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THE SHOCK-ABSORBING SYSTEM OF THE AIRPLANE LANDING GEAR

By Pietro Gallerio

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THE SHOCK-ABSORBING SYSTEM OF THE AIRPLANE LANDING GEAR\*

By Pietro Callerio

A discussion is given of the behavior of the shock-absorbing system, consisting of elastic struts and tires, under landing, take-off, and taxiing conditions, and a general formula derived for obtaining the minimum stroke required to satisfy the conditions imposed on the landing gear. Finally, the operation of some typical shock-absorbing system is examined and the necessity brought out for taking into account, in dynamic landing-gear tests, the effect of the wing lift at the instant of contact with the ground.

1. In numerous examples of airplane landing gear, the gear consists of a rigid structure to which is attached a deformable member to which in turn is attached the wheel, clearly indicating the modern practice of having the entire shock-absorbing system within the landing gear. The importance of such a system is evident; It is only necessary to consider the constantly increasing landing speeds, a consequence of the high wing loads assumed by modern airplanes, and the steep flight-path inclinations permitted by present high-lift devices (reference 1). The tendency toward glide landings without leveling off near the ground - a tendency whose principal reason is found in the greater difficulty which is experienced in leveling off on landing with high-lift devices and which assumes particular importance for aircraft designed for blind flying - brings into prominence again the problem of the determination of the shock-absorber characteristics. It is sufficient to consider the fact that an airplane which lands at a speed of 120 kilometers per hour with a flight-path inclination of 1:9, if not properly leveled off by the pilot before the wheels touch ground, develops the same stresses as if it fell from a height of 70 centimeters.

2. The principal purpose of a shock-absorbing system is that, by means of the considerable deformation of the

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\*"Sul sistema ammortizzatore dei carrelli d'aeroplano." L'Aerotecnica, vol. XIX, no. 6, June 1939, pp. 625-640.

elastic member embodied in the structure, to permit the vertical velocity of the airplane to be reduced gradually to zero on landing, in such a manner that the forces produced on the structures should not exceed the stress values designed for those structures. After the velocity has been reduced to zero, if the shock-absorbing system consisted of a perfectly elastic member the stored-up energy would be restored more or less suddenly giving rise to a rebound which, if not controlled, might be not only disagreeable but even dangerous. In order to avoid this difficulty, the shock-absorbing system should be capable of dissipating, with the aid of suitable arrangements, a large part of the energy possessed by the aircraft in landing and of damping the return motion due to the stored-up potential energy of deformation of the system - permitting, however, the shock absorber to assume its initial position sufficiently rapidly that it may be ready to operate in case of an immediately subsequent shock. In addition to this most important and essential function of the shock-absorbing system, it is necessary to consider its operation during taxiing and take-off. When the airplane taxis at low speed the shock absorber should simply permit the wheels to follow the irregularities of the ground and to damp the shocks produced by them. Since, on the other hand, these shocks are not generally of a character to give rise to dangerous stresses on the structure, too great a travel would be not only useless but unfavorable because it would hinder the maneuverability during taxiing. The energy dissipation provided by the tires may be assumed sufficient in this case, particularly if they are of the low-pressure type.

When the airplane runs on the ground to take off, after a first interval during which it is under conditions similar to those of taxiing, a certain velocity is reached, beyond which aerodynamic forces on the wings come increasingly into play. The load on the wheels gradually decreases until finally, having attained the velocity of take-off, the load decreases to zero. Even though the shock absorber (because of its mechanical nature or characteristics) cannot be successfully designed to accommodate both high and low vertical velocities and is therefore designed to accommodate the high vertical velocities, the low ones being chiefly damped by the aerodynamic forces; nevertheless, it is necessary that there be a certain amount of travel of the shock absorber between the position that corresponds to static load and the position of zero load in order that the wheels follow the profile of the ground.

thus preventing the reaction on the wheels from being subjected to abrupt variations in intensity.

Too small a shock absorber travel (between static and zero load positions) would in such a case lead to the phenomenon schematically illustrated in figure 1. While in position A the weight is supported by the elastic reaction on the shock absorber, at position B - due to the unevenness of the ground - there would be a further deformation of the shock-absorber elastic system. The mass  $m$ , which tends to remain in its position, is thrust upward as a result of the compression of the spring and, if the shock absorber does not permit a sufficient distention, the wheel at a certain point may lose contact with the ground, with a consequent succeeding shock.

From what has been said above, it is seen therefore that the shock absorber should possess the following requirements:

1) It should permit landing with a sufficiently large (landing gear) travel.

2) It should dissipate a large part of the energy possessed by the airplane due to the vertical velocity, and damp the return travel due to the energy absorbed elastically.

3) It should permit a limited travel above and below the position of static load during taxiing at low and high velocity.

3. Although the above considerations refer particularly to the landing gear (so called), they apply to a "shock-absorbing system" in general - which term was meant to include also the part referring to the tail wheel. Since the behavior of both (units) is entirely similar, however, we may limit our considerations to the shock-absorbing system of the landing gear (main wheels), in which the greatest stresses occur and which, in a particularly important case - namely, that of a two-wheel landing - takes all the load.

Let us therefore consider this landing condition and assume that outside of the shock-absorbing system, the other parts of the airplane have no elasticity. This assumption is equivalent to the statement that all the points of the airplane undergo the same acceleration in landing.

Actually, with increasing distance away from the landing gear, the acceleration gradually decreases due to the work of deformation of the interposed structures, but this decrease is absolutely negligible. According to some American investigations, the elastic work of deformation may be considered to vary from 0.0115 to 0.0230 kg m for each kilogram of the structure, and this corresponds to a sufficiently small percent of the energy to be absorbed that it is not worth while to consider it.

4. From the theoretical point of view the damping system is studied, in general, by neglecting the elasticity of the wheel (fig. 2), assuming all the mass  $m$  concentrated at the center of gravity and possessing the vertical velocity  $V_0$  and apparent weight  $\alpha P^*$ ; assuming, moreover, that the reaction of the shock absorber is given by the simple expression

$$R = cs + Kv \quad (1)$$

where  $cs$  is the elastic reaction, and  $Kv$  is a dissipative term proportional to the velocity.

From the above assumptions there can easily be derived the equation of motion, considering the equilibrium between the applied forces and the forces of inertia. This study, however, would not present any great practical interest because the conclusions arrived at by this mathematical treatment are considerably modified because of the fact that the dissipative term is taken proportional to the velocity instead of the square of the velocity as it normally actually is, and because other elements are neglected (friction, viscosity of the damping liquid, etc.), and particularly, because the shock absorber operates jointly with the tires.

It may merely be pointed out that, according to whether the damping is large or small, there is obtained an aperiodic motion or an oscillatory damped motion, and that in the case in which the coefficient  $\alpha$  is equal to zero, the motion is the same as that of a horizontally oscillating mass whose damping is proportional to the velocity. In the case of strong damping there are obtained curves of the type of those of figure 3, which show qualitatively

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\*The apparent weight  $\alpha P$  is the difference between the weight  $P = mg$  and the lift ( $\alpha = 1$  for low velocity, zero aerodynamic forces;  $\alpha = 0$  at the velocity of take-off).

the variation of the force  $R$  as a function of the displacement and the time.

5. The problem becomes considerably more complicated if the shock absorber is considered as consisting of two distinct elastic systems operating simultaneously - an assumption which corresponds to the actual conditions since the wheel tires must be considered in addition to the shock absorber. In this case, illustrated by the sketch of figure 4, calling  $R_1$  the reaction of the wheel, and  $R_2$  the corresponding force on the shock absorber, we have:

$$R_2 = a R_1$$

where  $a$  is a coefficient which depends on the geometric characteristics of the landing gear under consideration. The value of  $a$  may be constant or variable for the different positions assumed by the landing-gear struts during deformation. In this case, since the variations are always rather small, a mean constant value may be assumed for  $a$ . Making, in addition, the simplifying assumptions:

$$R_1 = C_1 S_1$$

$$R_2 = C_2 S_2 + Rv_2$$

the mathematical treatment leads to differential equations (reference 2) which are much more complicated than those obtained for the case of the shock absorber alone, referred to above. These equations, on account of false assumptions made in deriving them, cannot correspond to the actual conditions.

On account of the uncertainties of the mathematical procedure, we shall leave the theory aside and consider instead the practical problem that presents itself to the designer, namely, what displacement is necessary in order that the stresses on the structure should not exceed safe values. The regulations prevailing in various countries prescribe in general that the shock-absorbing system should be capable of absorbing the kinetic energy due to a certain vertical landing velocity  $V_0$ , or that due to a drop of the airplane from a certain height without any forces arising on the structure that exceed  $n$  times the weight. Although, instead of the velocity  $V_0$ , the corresponding drop height  $H = V_0^2/2g$  may be used interchangeably, we shall refer to the drop velocity  $V_0$ .

We may observe here that the initially prescribed load factor  $n$  permits the computation of the structure on the basis of a simple study of the landing gear as a whole before any special study of the shock absorber is carried out, which may be done subsequently. It is necessary, however, even for a preliminary study, to know the stroke of the shock absorber in order to define the extreme positions assumed by the wheels and by the landing-gear struts in take-off and in landing. These positions must be considered both for strength calculations and for the determination of the minimum distance of the propeller blades from the ground during taxiing - which distance must not be below a certain value.

The advantage of reducing the travel of the shock absorber to a minimum is evident not only for weight economy but also in certain types of landing gear for preventing the wheels from assuming too great a deviation between the positions of maximum and zero deformations.

Having, by some method, chosen a value of the coefficient  $n$  that should not disagree with that prescribed by the regulations, it is necessary that the travel be determined so as to guarantee that under the most unfavorable landing conditions, this value is not exceeded.

Let us now consider the airplane in landing. We assume that we have already carried out the preliminary investigation of the landing gear sketched in figure 5: Making use of the previously given notation, we indicate by  $R_1$  the force on the wheel, by  $R_2$  that on the shock absorber, and by  $\alpha P$  the apparent weight of the airplane at the instant of landing, which weight may be considered constant for the brief period of the landing shock. The following relations may be written:  $R_2 = a R_1$  (force on the shock absorber is  $a$  times that on the wheel)

$M \frac{d^2 s}{dt^2} - R_1 + \alpha P = 0$  (equilibrium between applied forces and force of inertia); from these we have:

$$R_1 - \alpha P = \frac{R_2}{a} - \alpha P = M \frac{dv}{dt}$$

Considering a time  $dt$  in which the center of gravity is lowered by  $ds$  while the tire is deformed by  $ds_1$  and the shock absorber by  $ds_2$ , we have:

$$R_1 ds_1 + R_2 ds_2 = - M \frac{dy}{dt} ds + \alpha P ds$$

and since  $ds = v dt$ :

$$R_1 ds_1 + R_2 ds_2 = - M d \left( \frac{v^2}{2} \right) + \alpha P ds$$

After the time  $t$  required for the vertical velocity to be reduced to zero (the center of gravity will be lowered by the amount  $s = h$ , the tire deformed by  $S_1$ , and the shock absorber by  $S_2$ ), we have:

$$\int R_1 ds_1 + \int R_2 ds_2 = M \frac{v_0^2}{2} + \alpha P h \quad (1)$$

a relation which states that the shock absorber should absorb an amount of energy corresponding to the sum of the kinetic energies possessed by the airplane due to the vertical component of the velocity and the potential energy due to the displacement  $h$  of the center of gravity of the airplane after contact with the ground.

We assume now that we know the curves  $R_1 = f(s_1)$  and  $R_2 = \varphi(s_2)$  obtained simultaneously (fig. 6). In order that the forces on the structure should not exceed  $n$  times the weight, the maximum value of  $R_1$  should be equal to  $nP$ , and hence the maximum of  $R_2$  should be  $a n P$ . Denoting by  $K_1$  and  $K_2$  the ratios

$$K_1 = \frac{\int R_1 ds_1}{S_1 n P}$$

$$K_2 = \frac{\int R_2 ds_2}{a S_2 n P}$$

relation (1) becomes:

$$K_1 S_1 n P + a K_2 S_2 n P = \frac{P}{g} \frac{v_0^2}{2} + \alpha P h \quad (1a)$$

from which, dividing by  $P$  and remembering that the total displacement  $h$  of the center of gravity is

$$h = S_1 + a S_2$$

there is obtained

$$n K_1 S_1 + a n K_2 S_2 = \frac{V_0^2}{2g} + \alpha h$$

Hence, knowing the deformation  $S_1$  of the tire at the coefficient  $n$ , the shock absorber travel is given by

$$S_2 = \frac{\frac{V_0^2}{2g} - S_1 (n K_1 - \alpha)}{a (n K_2 - \alpha)} \quad (2)$$

If, instead of the velocity  $V_0$ , the corresponding drop height is considered,  $H = V_0^2/2g$ , there is obtained

$$S_2 = \frac{H - S_1 (n K_1 - \alpha)}{a (n K_2 - \alpha)} \quad (2a)$$

This relation, in the case in which the shock absorber alone is considered to operate, may be written:

$$S_2 = h = \frac{H}{a n K_2 - \alpha} \quad (2b)$$

which is the formula usually given for the shock-absorber travel and is seen to be independent of the weight of the airplane.

7. Let us consider what are the possible values that may be assumed by the coefficients  $K_1$  and  $K_2$  of formula (2). As regards the tire, although there are not many data on which to base a judgment, it may be assumed on the basis of recent tests (reference 3) that the deformations and the loads are connected by a relation of the type

$$R_1 = A s_1^m \quad (m > 1) \quad (3)$$

If, instead of static loads, dynamic loads are considered - which, for example, are obtained by measuring the forces due to the accelerations determined from the drop of masses resting on the tire - similar diagrams are obtained, except for greater curvature, in the sense that the tire behaves for low dynamic loads as if it were less rigid, and for the other dynamic loads as if it were more rigid

than if static loads were applied. The relation (3) is still valid, but the exponent  $m$  increases to an appreciable extent.

Figure 7, obtained with a low-pressure tire 8.50 x 10 (640 x 205) for two different tire pressures, shows clearly - in addition to what we have said - that the divergence between static and dynamic loads is more marked the less the inflation pressure of the tire.

On examining some tire depression curves obtained with dynamic loads, it is found that the value of  $K_1$  for the usual pressures and deformations permitted in practice, fluctuates between 0.32 and 0.35 for low- and medium-pressure tires, and between 0.40 and 0.43 for high-pressure tires. In any case, since the dynamic behavior is markedly different from the static behavior, it is necessary to carry out a systematic series of dynamic compression tests on tires of uniform size, so that it may be possible to deduce, with sufficient approximation, the values of the exponent  $m$ , and hence, of the coefficients  $K_1$  required for the determination of the energy effectively absorbed by the tires.

As regards the coefficient  $K_2$ , it naturally varies greatly from one type to another. While it has a value approximately equal to 0.5 in the case in which the shock absorber consists simply of a spring without initial tension (a very rare case, of course), it has a value between 0.80 and 0.85 for the oleopneumatic and oleoelastic types that have received much study. Theoretically, a value of  $K_2$  might be obtained equal to 1, but on account of the large number of not easily determinable factors that enter into the phenomenon (drop height, velocity of deformation, viscosity of the liquid, etc.), it is best not to assume for the shock absorber - at least, for the preliminary study - a value exceeding 0.85. We may observe that while it is wise to assume rather low values for the coefficients  $K_1$  and  $K_2$ , it is of no advantage if they be too conservative. In the case in which the shock-absorber stroke has been computed on the basis of too low values of  $K_1$  and  $K_2$ , the work that the deformable system can perform is greater than the work necessary to reduce the vertical velocity to zero, and therefore either the shock absorber does not reach the end of its stroke or, having reached it, determines forces on the structure that are less than those for which they have been designed. In either case, the utilization of the shock absorber is not logically the best.

Naturally, the opposite occurs and with consequences that may be very serious if the values of  $K$  are chosen too high (i.e., if travel is insufficient). In this case, even in landings that do not correspond to the maximum velocity assumed for the computation, stresses may be produced greater than any provided for, and these may cause failure of some part of the landing gear or fuselage.

The appreciable difference between the energy-absorption characteristics of the tire and shock absorber shows that for equal total travel  $h$  of the center of gravity, the amount of energy absorbed is greater, the greater the shock-absorber travel in comparison with that of the tire.

8. In this connection, the fact should be brought out that, according to the regulations at present in force, it would not be possible to assign the shock-absorbing function to the tires alone, even when restricted to the low-pressure type, without introducing inadmissible landing loads.

In the case of the tires alone, equation (1a) becomes

$$K_1 S_1 n P = \frac{P}{g} \frac{V_0^2}{2} + \alpha P S$$

and dividing by  $P$ , substituting for  $V_0^2/2g$ , the corresponding height  $H$ , and remembering that for the drop test  $\alpha = 1$ :

$$n K S = H + S$$

$$S = \frac{H}{n K - 1}$$

Even assuming that tires are available that can deflect by an amount  $S_1 = 0.75 H^*$ , by taking for  $K_1$  a value of 0.35, there is obtained

$$0.75 H = \frac{H}{n \times 0.35 - 1}$$

from which  $n = 6.7!$  Aside from the prescribed regulations, moreover, it is not logical to expect good results from a shock absorber that has such a low work characteristic and which therefore can be employed only for very low vertical velocities.

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\*The minimum value for  $H$ , permitted by the R.I.N.A., is 30 centimeters.

9. Let us consider a typical example of shock absorber, consisting of a spring without initial tension which, on compressing, forces the oil contained in the chamber A to flow through a constant orifice, and let us neglect for the moment, consideration of the tire (fig. 8). Relation (1) in this case may be written:

$$\frac{m V_0^2}{2} + \alpha P h = \int R ds$$

where  $R$ , neglecting the friction, may be expressed by the relation

$$R = c_1 s + \mu V_0^2$$

In the above formula the first term represents the work performed by the spring of elastic constant  $c_1$ , the second is the dissipative term,  $\mu$  being the resistance coefficient of the liquid flow through the orifice. We assume that  $R$  may be considered constant during the entire stroke  $h$  and equal to the maximum allowable value  $a n P$ . Since the force is constant, the acceleration is also constant, so that the velocity varies linearly from  $V_0$  to zero. We thus have the relations:

$$v = V_0 - a t$$

$$s = V_0 t - \frac{a t^2}{2}$$

from which, eliminating the time  $t = \frac{V_0 - v}{a}$ , there is readily obtained

$$v^2 = V_0^2 - 2 a s$$

The above equation states that  $v^2$  varies linearly with the deformation  $s$ , from the maximum value  $V_0^2$  to zero. The variation of  $v^2$  with  $s$  is indicated in figure 8.

Since the values of the elastic reaction increase at the same time from 0 to the final value  $a n P$ , it is sufficient that

$$\mu V_0^2 = c_1 h = a n P$$

in order that the resultant  $R$  remain constant during the stroke. In this case, therefore, the above-defined coefficient  $K_2$  would come out equal to 1 and the shock-absorber stroke given by formula (2b) would be the minimum, namely,

$$h = \frac{H}{a n - \alpha} \quad (4)$$

In a manner analogous to this simple case, it may readily be seen that by suitably varying the size of the orifice of the escaping oil, there may theoretically be obtained a constant internal force also for other types of shock absorber, as oleoelastic and oleopneumatic. Such a condition can practically be obtained by making the oil flow through an annular opening determined by a hollow cylinder, in which is situated a calibrated rod or piston of suitably varying cross section so that at each instant

$$\mu V^2 = a n P - f(s)$$

where  $f(s)$  is the reaction of the elastic part of the apparatus.

The conditions are entirely different when the tires are also taken into account. In this case the reaction of the shock absorber cannot be constant during the entire duration of the landing because at each instant we must have  $R_2 = a R_1$ , and  $R_1$  naturally varies from zero to the final load  $nP$ . Only in the case in which the load is above that for which the tire is completely compressed does the shock-absorbing system function as if the tire were absent; hence, for the stroke in which the shock absorber acts alone, it can operate with constant internal force.

We may point out, in order to complete our observations on the operation of the shock absorber, that in the case in which the latter has an initial load  $R_{20}$  during the first interval of the shock, there occurs only the deformation of the tire until the load  $R_{10} = R_{20}/a$  is reached, after which the two systems work simultaneously. In any case, it appears evident that when the shock absorber and tire operate together, the coefficient  $K$  can never attain the value 1, which is possible with the shock absorber working alone.

10. A fact that should be particularly brought out is

that the addition of the tire, by producing variations in the velocity in the dissipative term  $\mu V^2$ , may have considerable effect on the behavior of the two acting together. For this reason, the tests which are usually carried out on the shock absorber alone, should be carried out instead on the tire shock-absorbing system. If the shock absorber is mounted on the landing gear in such a manner that the force on it is equal to that acting on the wheel (landing gear with forked shock absorber, for example), the tests do not require any particular attention. In the case, however, that the value of  $a$  in the relation  $R_2 = a R_1$  is different from 1, it is necessary to bear in mind the following considerations.

The subscript  $p$  will refer to the test conditions.

For the set-up indicated in figure 10, we have for equilibrium:

$$M_p \frac{d^2 S_p}{dt^2} - R_1 + \alpha P = 0$$

while for the actual conditions, we have:

$$M \frac{d^2 S}{dt^2} - R_1 + \alpha P = 0$$

Since  $R_1 = R_2/a$ , we obtain, by keeping the value of  $R_2$  the same in the two cases:

$$M = \frac{R_2}{a (S'' + \alpha g)}$$

$$M_p = \frac{R_2}{S_p'' + \alpha g}$$

from which

$$M_p = M \frac{a (S'' + \alpha g)}{S_p'' + \alpha g} \quad (5)$$

Moreover, for the actual case, we have:

$$S = S_1 + a S_2 \quad (6)$$

while for the test,

$$S_p = S_{1p} + S_a \quad (7)$$

Setting

$$S_{1p} = \frac{S_1}{a}$$

which can be obtained with sufficient approximation by varying the tire pressure, there is obtained:

$$\frac{S}{S_p} = a$$

With the aid of (6) and (7), we also have:

$$\frac{S'}{S'_p} = \frac{S''}{S''_p} = a$$

Equation (5) then becomes:

$$M_p = M_a \frac{a S''_p + \alpha g}{S''_p + \alpha g}$$

In the case where  $\alpha$  is sufficiently small to be neglected, we have:

$$M_p = M a^2$$

that is, the test can be carried out by employing a mass  $M_p = a^2 M$ . In this case, since the velocity of the test and the true velocity are connected by the relation

$$S' = a S'_p$$

it is necessary to consider for the drop test, instead of the velocity  $V_0$ , a velocity  $V_0/a$ ; or, instead of the drop  $H$ , a drop  $H/a^2$ .

11. From the preceding considerations, an apparently curious fact is derived which we shall illustrate by a numerical example: To fix our ideas, assume we have an airplane of 1,800 kilograms, provided with wheels having tires  $8.50 \times 10$  (640 x 105 mm) inflated to  $1.75 \text{ kg/cm}^2$ , for which the regulations fix a maximum load factor of  $n = 3$  for a drop of 40 cm. The maximum permissible load on a wheel is  $900 \times 3 = 2,700 \text{ kg}$ , to which corresponds a static

deformation of 138 mm and a dynamic deformation of 128 mm, and a coefficient  $K_1 = 0.33$ . Not considering the contribution of the tire, and assuming the shock-absorber force to be constant, for which  $K_2 = 1$ ; and assuming further, for simplicity, that the coefficient  $a$  of the landing gear is equal to 1 (that is, that there exists the same load on the wheel as on the shock absorber), the stroke required in order not to exceed the factor  $n = 3$  from equation (4), in which  $\alpha = 1$ , since the effect of the lift is not considered in the test, is

$$S = \frac{H}{a n - 1} = \frac{40}{3 - 1} = 20 \text{ cm}$$

The shock absorber can therefore dissipate an amount of work

$$L = 3 \times 900 \times 20 = 54,000 \text{ kg cm}$$

corresponding to the energy due to the drop of 900 kg from a height of 40 cm, and of the work due to the travel of 20 cm permitted by the shock-absorber stroke, and is therefore suitable for the required drop test.

We now consider the tires also to be taken into account. Assuming for the moment that the shock absorber, even when working with the tire, still operates with the coefficient  $K_2 = 1$ , and that it is permitted to attain, as before, a value of  $n = 3$ , the travel of the shock absorber from (2a), in which  $\alpha$  and  $a$  equal 1, is found to be

$$S_2 = \frac{H - S_1 (nK_1 - 1)}{nK_2 - 1} = \frac{40 - 12.8 (3 \times 0.33 - 1)}{3 \times 1 - 1} = 20 \text{ cm}$$

that is, practically the same as before. Since, however, the value of  $K_2$  cannot be equal to unity, the stroke of 20 cm, which was sufficient with the tire not mounted, becomes insufficient. This means that the tire, in addition to impairing the operating conditions of the shock absorber, is not sufficient to absorb the energy due to the greater travel it permits the center of gravity of the airplane. In the case considered, for example, the deformation of 12.8 cm corresponds to an amount of work

$$L = 900 \times 12.8 = 11,520 \text{ kg cm}$$

while the energy absorbed by the tire is

$$L' = K_1 nPs = 0.33 \times 3 \times 900 \times 12.8 = 11,480 \text{ kg cm}$$

The 40-centimeter drop test with the addition of the tire would therefore give rise to accelerations greater than those obtainable with the shock absorber alone.

12. On the basis of the results obtained in the above example, it might be concluded that a landing on wheels without tires should be more gentle, or at least, less abrupt, for equal vertical velocity, than a landing on wheels provided with tires. Evidently there is some fundamental divergence between the conditions of the tests conducted according to present-day procedure and the true conditions.

As a matter of fact, it is the aerodynamic forces, which are not taken into account in the tests, that account for the above divergent results. The value of the coefficient  $\alpha$  in formula (2), in other words, is not to be considered equal to 1 as is usually assumed, but should be correctly evaluated and taken into account in carrying out the tests. Account must thus be taken of the fact that on landing of a mass  $m$  with velocity  $V_0$ , the weight is not  $P$  but only a fraction - normally small - of  $P$ , and hence that the work which the shock-absorbing system must perform is that defined by the second member of (1):

$$L = \frac{m V_0^2}{2} + \alpha P h$$

and not

$$L_1 = \frac{m V_0^2}{2} + P h$$

The difference is not at all negligible, especially for long-travel shock absorbers. The value of  $\alpha$  may be computed from the formula

$$\alpha = \frac{2}{1 + \sqrt{\beta}} \quad (8)$$

where  $\beta$  is a coefficient defined by Verduzio (reference 4) as the "landing characteristic"

$$\beta = B \frac{V_0}{v_0}$$

$B$  being the lift-drag ratio of the airplane in the landing attitude,  $V_0$  the minimum supporting velocity near the ground, and  $v_0$  the vertical velocity of descent. For the usual values of  $\beta$  as appears from figure 11, which gives the plot of equation (8), the value of  $\alpha$  varies from 0.2 to 0.3.

Considering in our numerical example a mean value  $\alpha = 0.25$ , it is seen that a travel of 20 cm permitted by the stroke of the shock absorber, and 12.8 cm permitted by the compression of the tire, corresponds effectively to a total amount of work  $0.25 \times 900 \times 32.8 = 7,380$  kg cm equal to 20.5 percent of the kinetic energy possessed by the airplane in landing, instead of

$$900 \times 32.8 = 29,520 \text{ kg cm}$$

equal to 82 percent of the total kinetic energy in a drop test where the lift is not taken into account.

When it is considered that the work of deformation of the tire is about 11,500 kg cm, it will be understood that the addition of the tire to the shock absorber improves appreciably the landing characteristics instead of impairing them as would occur in a drop test carried out according to the criteria actually prevailing.

The method of conducting the drop test, if the latter is to represent effectively a possible landing condition, must therefore be such that only the weight  $\alpha P$  performs work. There might therefore be used a set-up such as that shown in figure 12, or a similar one.

We may point out, finally, that instead of the drop height, it would be more suitable in the regulations to consider the equivalent vertical velocity  $V_0$ , and in determining the values to be imposed in computing the landing gear, to take account of the elements that influence this velocity, particularly the wing loading, and the presence of high lift devices.

Translation by S. Reiss,  
National Advisory Committee  
for Aeronautics.

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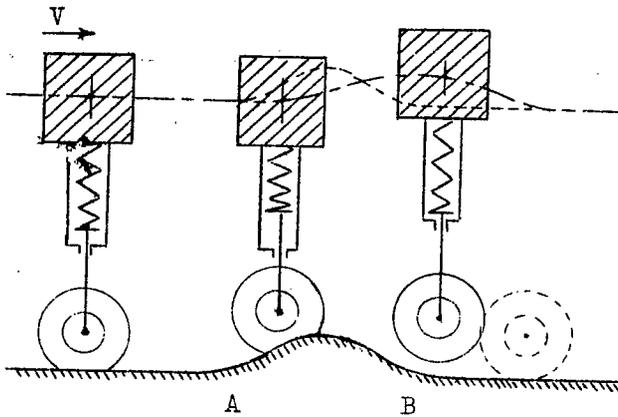


Figure 1.

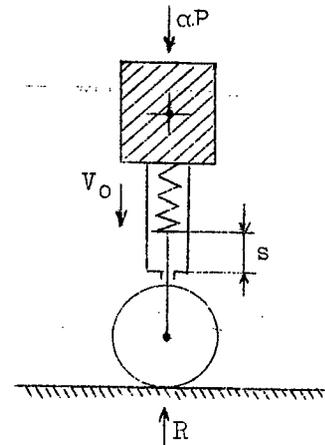


Figure 2.

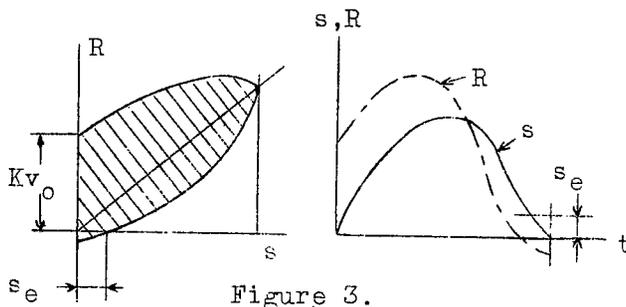


Figure 3.

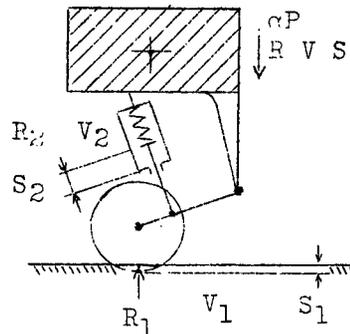


Figure 4.

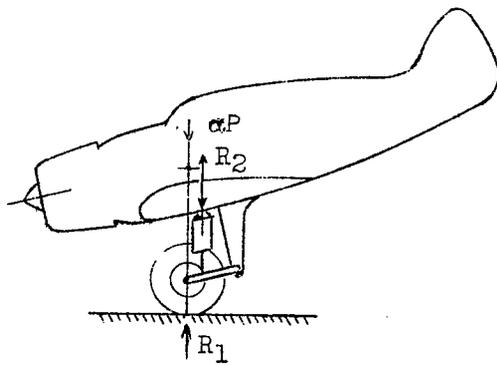


Figure 5.

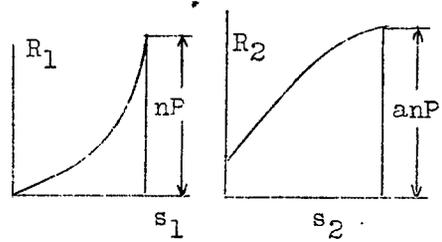


Figure 6.

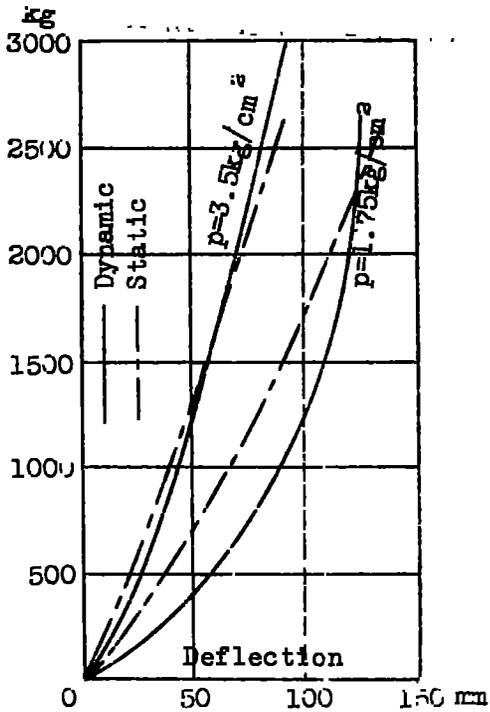


Figure 7.

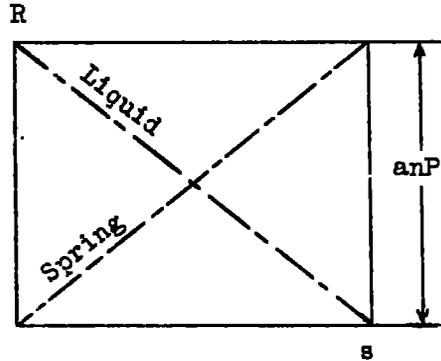


Figure 9.

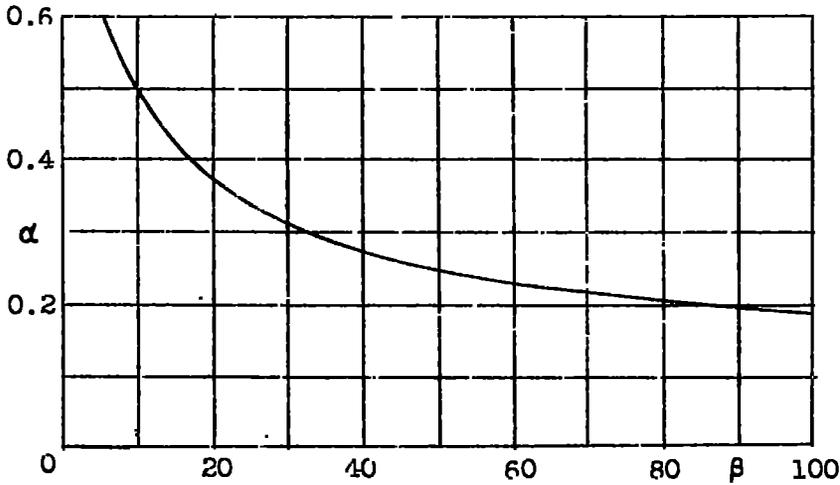


Figure 11.

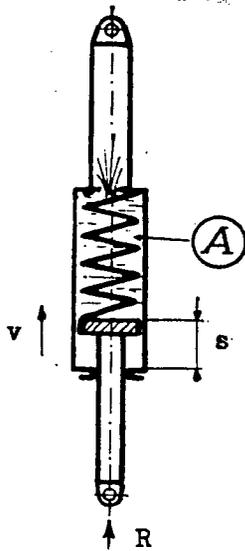


Figure 8.

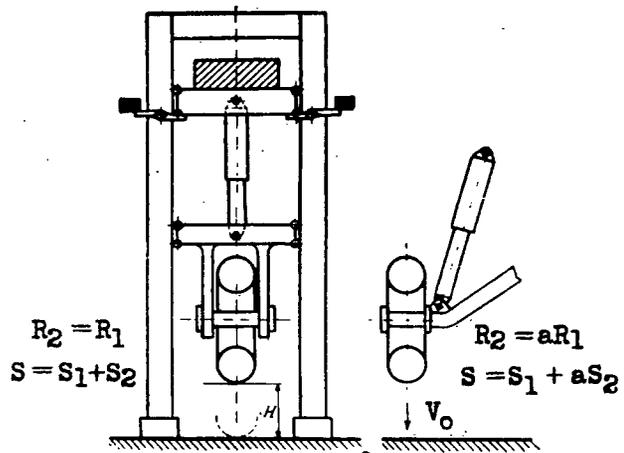


Figure 10.

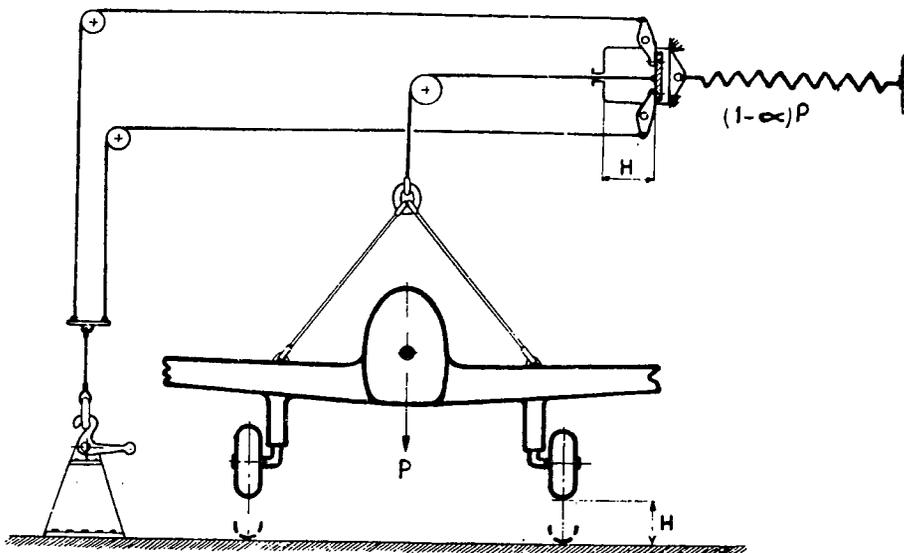


Figure 12.

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