REPORT No. 366

DYNAMIC AND FLIGHT TESTS ON RUBBER-CORD AND OLEO-RUBBER-DISK LANDING GEARS FOR AN F6C-4 AIRPLANE

By WILLIAM C. PECK

SUMMARY

This investigation was conducted by the National Advisory Committee for Aeronautics at the request of the Bureau of Aeronautics, Navy Department, for the purpose of comparing an oleo-rubber-disk and a rubber-cord landing gear, built for use on an F6C-4 airplane. The investigation consisted of drop tests under various loading conditions and flight tests on an F6C-4 airplane. In the drop tests the total work done on each gear and the work done on each of the shock-absorbing units were determined. For both drop tests and flight tests the maximum loads and accelerations were determined.

The comparative results showed that the oleo gear was slightly superior in reducing the ordinary landing shocks, that it had a greater capacity for work, and that it was very superior in the reduction of the rebound. The results further showed that for drops comparable to very severe landings, the rubber-cord gear was potentially more effective as a shock-reducing mechanism. However, due to the construction of this chassis, which limited the maximum elongation of the cords, this gear was incapable of withstanding as severe tests as the oleo gear. The action of the oleo gear during the tests was greatly inferior to the action of an ideal gear. The maximum accelerations encountered during the flight tests for severe landings were 3.64g for the rubber-cord gear and 2.27g for the oleo gear. These were less than those experienced in free drops of 7 inches on either gear.

INTRODUCTION

Since an airplane must be designed to withstand the shocks incurred in landing and taxying, a saving in structural weight is effected by incorporating shock-reducing devices in the landing gear. The relative merits of different types of landing gears, which in themselves do not add undue weight or prove otherwise objectionable, are judged primarily by their ability to reduce these shocks to a minimum. It is important, therefore, that the shocks and resulting forces incurred in the use of the different types of gears under similar conditions be determined by actual measurement.

The oleo type of landing gear is generally believed to be more effective in the reduction of landing shocks than the rubber-cord type. Quantitative measurements, however, from which a definite comparison of these two types can be made, are lacking.

The present investigation was undertaken to determine, for a typical case, the relative merits of these two types of landing gears. The shock-absorbing system for one of these gears consisted of rubber cords and balloon tires; for the other it consisted of oleo cylinders, rubber disks, and the balloon tires. Static, dynamic or drop, and flight tests were made. The static tests were made primarily to furnish deflection versus load data for use in the calculation of the results obtained in the other tests. In the dynamic tests the maximum forces developed and the distribution of work among the shock absorbing units were determined for various heights of drop and different loads. The flight tests were made to determine the forces developed in landing and taxying and the relation of various types of landings to heights of drop.

APPARATUS AND METHODS

APPARATUS

Landing gears.—Two deck-type landing gears, both for the F6C-4 airplane (Curtiss Fighter), were used in this investigation. One was of the rubber-cord type and the other of the oleo-rubber-disk type. These gears were standard in all respects, no changes being made with the exception of the removal of the fairings to allow the installation of measuring instruments. Wire wheels with 30 by 5, 4-ply, smooth tread, airplane balloon tires, were used on both landing gears throughout the investigation. Throughout all the tests an inflation pressure of 50 pounds per square inch was maintained in the tires.

The rubber-cord gear used (Curtiss Aeroplane and Motor Corporation Drawing Number EX40512) is shown in Figure 1. The gear was so constructed that the rubber cords could elongate approximately 4 inches before the axle would come in contact with a stop at the top of the axle guide.

The oleo gear (Curtiss Aeroplane and Motor Corporation Drawing Number EX41305) is shown in Figure 2 and diagrammatically in Figure 3. The working parts of the gear are shown best in the latter

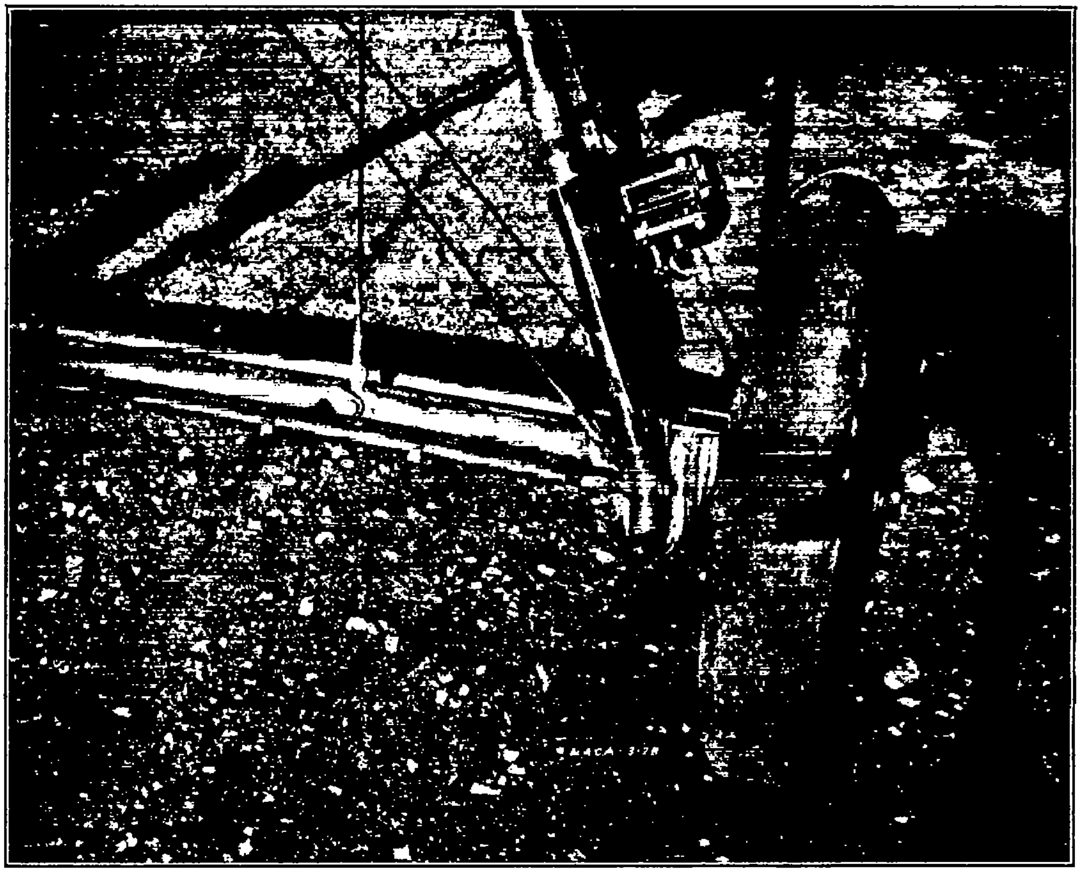

FIGURE 1.—Rubber-cord shock absorber type of landing gear

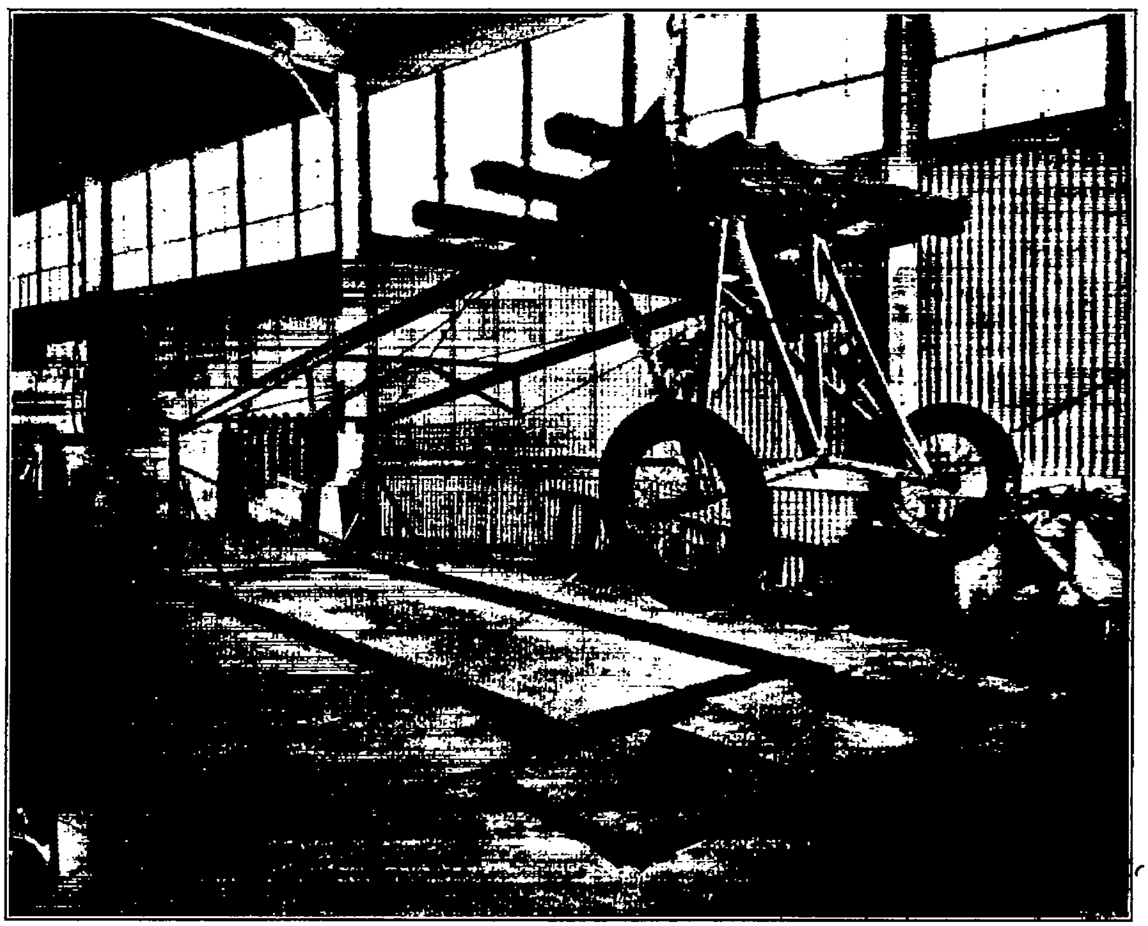

FIGURE 2.—Oleo-rubber-disk shock absorber type of landing gear on test rig

figure. They consisted of an oleo cylinder and piston and a number of rubber disks; the former for the purpose of absorbing the main shock of landing and the latter primarily for the shocks subsequent to the initial contraction of the units and those experienced during the taxi runs of the airplane.

The action of the valve mechanism, which is shown in Figure 3, was as follows: When the landing gear was elongating or when there was no relative motion between the oleo piston and cylinder, the valve was off the seat approximately one-eighth inch. In this condition, the oil could flow from the piston through the space between the valve and its seat into the cylinder. When the landing gear was contracting the difference in pressure below and above the valve caused it to seat, and the flow of the oil from the cylinder into the piston was restricted to the small orifice in the valve.

The effective area of the piston was 2.01 square inches and the strokes of the cylinders were 4.40 inches from the point of complete extension of the landing gear to that point at which the cylinders made contact with the rubber-disk compression collar; the gear employed 10 rubber disks 3½ inches outside diameter, 1⅝ inches inside diameter, and ½ inch thick. Metal spacers were used between the fourth and fifth, and seventh and eighth disks (counting from the top).

Dynamic test rig.—As previously mentioned, one part of the investigation consisted of drop tests of the landing gears. The apparatus used for these tests (the dynamic test rig) is shown in Figure 2. It consisted of a lower portion (hereafter referred to as the base) and an upper portion (hereafter referred to as the frame). The frame was constructed so as to rotate about an axis through the two uprights at the rear of the base. Two landing platforms were secured to the forward end of the base and were placed so that the tires of the landing gear, under test, would impinge approximately at their centers. The platforms were made in two units; the bottom unit consisted of heavy planking banded together with angle iron and covered with sheet steel; the top unit consisted of heavy plywood (6-ply) faced on its lower side with sheet steel. To allow an unrestricted lateral motion of the top units with respect to the bottom ones, steel rollers were placed between the two units.

Instruments.—With each gear tests were made that may be briefly described as (1) static tests; (2) dynamic or drop tests; and (3) flight tests. The actual test procedure will be described in detail later.

The static tests required no recording instruments. In the dynamic tests, with the rubber-cord gear, it was necessary to measure the elongation of the cords and accelerations developed versus time, and with the oleo gear, the relative motion of the oleo cylinders and pistons, the accelerations developed, the compression of the rubber disks, and the pressure in the oleo cylinders versus time. In the flight tests these same variables were measured, and in addition, the attitude and the air speed of the airplane at landing.

For measuring the elongation of the cords, the compression of the rubber disks, and the relative motion of the oleo cylinders and pistons, two control position recorders (Reference 1) were used. Steel wire was used to transmit the movement of the shock absorbing units to the instruments rather than the cord ordinarily used, due to the appreciable change in length of the cord under tension. With both landing gears these instruments were mounted on the platform of the dynamic test rig for the drop tests and on brackets secured to the side struts (fig. 1) for the flight tests.

An N. A. C. A. recording accelerometer (Reference 2) was used to record vertical accelerations. For the drop tests this instrument was mounted on the platform near the centroid of the effective load. For flight tests it was mounted as close as practicable to the center of gravity of the airplane.

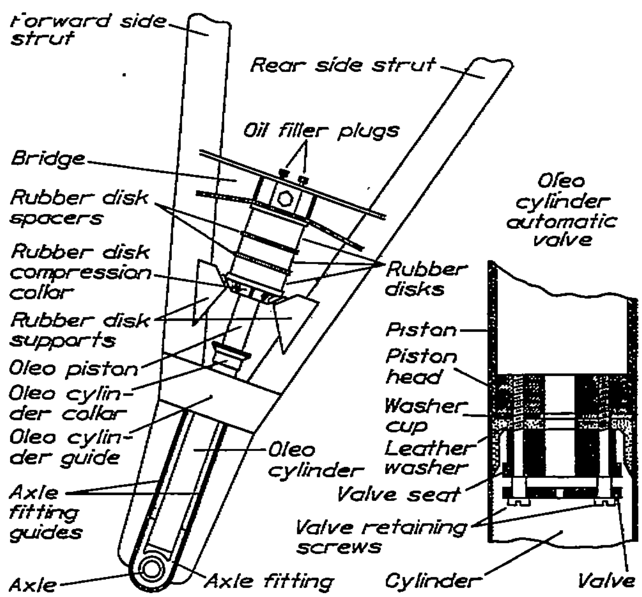

FIGURE 3.—Oleo-rubber-disk landing gear shock absorbing system

The pressure built up in the oleo cylinders was measured by a 2-unit recording manometer similar to the N. A. C. A. recording air-speed meter (Reference 3), but different in that two special high-pressure cells were used in place of the single cell. These cells were capable of measuring pressures up to 2,000 pounds per square inch with a maximum movement of the center of the diaphragm of 0.002 inch. The cells of the instrument and the oleo cylinders were connected by copper tubing filled with oil. To keep the tubing leads as short as possible, the instrument was mounted on the landing gear as shown in Figure 2 for all of the tests.

The attitude of the airplane at landing was recorded by means of a spring-driven motion-picture camera capable of taking 32 exposures per second. This camera was mounted in the airplane just aft of the pilot's cockpit with the lens axis parallel to the lateral axis of the airplane. The attitude was determined from the angle between the horizon on the picture and the frame of the picture.

The air speed of the airplane at landing was obtained by an N. A. C. A. recording air-speed meter (Reference 3) connected to a swiveling Pitot-static head mounted on a front strut of the airplane.

All records were synchronized by means of timing lines controlled by a chronometric timer adjusted to indicate ⅕-second intervals.

Special film drums, internally geared so that the film speed was 2½ inches per second were used on the control position recorders, pressure recorder, and accelerometer. These drums were statically and dynamically balanced in an attempt to eliminate the effect of accelerations on their rotation.

METHODS

TESTS

Static tests.—The static tests consisted of applying load in increments of approximately 400 pounds and making the following measurements with each increment of load: With the rubber-cord gear, the elongation of the rubber cords, the change in the tread of the gear, and the depression of the tires; with the oleo gear, the compression of the rubber disks, the position of the landing-gear parts with respect to the vertical and with respect to each other, the depression of the tires, and the variance in the tread of the gear. After a static load equal to about three and one-half times the normal load had been placed on the landing gear, the load was then removed in the same increments and corresponding measurements taken. In order to simulate the vibration that occurs in actual landing, which reduces the friction effect of the moving parts of the gears, the gears were tapped lightly before any of the above-mentioned measurements were made.

Dynamic tests.—The dynamic tests consisted of a series of free drops on each landing gear with five different conditions of loading. The free drop of the landing gear was considered that portion of the total vertical displacement of the landing gear wherein the downward or vertical motion of the test rig was unrestrained.

With the rubber-cord gear the effective loads (i. e., the static loads on the tires) used were 684, 1,183, 1,782, 2,258, and 2,616 pounds. With each loading condition free drops were made in increments of approximately 3 inches from a height of 2 inches above datum to the greatest height from which it was thought safe to drop the landing gear. With the 684-pound load the greatest drop was 20 inches, since with this drop a very violent rebound was experienced. With the 1,183, 1,782, 2,258, and 2,616 pound loads the maximum heights of drop were 24, 24, 17, and 11 inches, respectively. The 24-inch drop was the height specified by the Department of Commerce in their test regulations under normal load conditions for a landing gear to be used on this type of airplane. The 17 and 11 inch drops were the largest allowed by the strength of the rubber cords as wrapped, since with these drops they allowed the axles to hit the stops at the top of the guides.

With the oleo gear the loads used were 672, 1,179, 1,787, 2,320, and 2,685 pounds. As before, the drops under each loading were increased in increments of approximately 3 inches. With this gear, however, the initial drop was made with the oleo cylinders in contact with the rubber-disk collar and the tires merely touching the landing platforms. From this point the height of drop was increased up to a 17-inch free drop with the 672, 1,179, and 1,787 pound loads, 26 inches with the 2,320-pound load, and 11 inches with the 2,685-pound load. With the 2,320-pound load the height of drop was carried to 26 inches to extend the data beyond the 24-inch free drop specified by the Department of Commerce.

During the drop tests on the rubber-cord gear records were made of the elongation of the rubber cords and the accelerations developed for each drop. For the oleo-gear records were obtained of the relative motion of the pistons and oleo cylinders, the compressions of the rubber disks, the accelerations developed, and the pressures built up in the oleo cylinders.

An attempt was made to obtain an independent set of measurements of the accelerations developed during the drop tests by means of a high-speed motion-picture camera which took approximately 160 exposures per second. This, however, proved too slow to measure the variables with sufficient accuracy to calculate accelerations.

Flight tests.—The flight tests consisted of normal, 2-point and pancake landings, take-off and taxying runs with the landing gears mounted on an F6C–4 airplane. In all these tests the airplane was fully loaded and weighed 2,582 pounds. In the take-off runs the airplane was flown off the ground rather than "pulled off." The taxying runs were made at a ground speed of approximately 15 m. p. h. into and with the wind. The proper level of oil in the oleo cylinders was maintained for all of the tests except three of the flight tests in which, through oversight, there was insufficient oil. As a consequence, some interesting information was obtained on the action of the oleo gear without the oleo cylinders functioning.

Measurements similar to those taken in the drop tests were taken in the flight tests with the addition of a motion-picture record of the attitude of the airplane in the take-off and landing and a record of the air speed.

PRECISION

The control position recorders used to record the deflections of the shock-absorbing units were found to have no appreciable lag. The accuracy with which deflections could be measured by this means was found to be within ±0.05 inch.

Maximum accelerations indicated by the recording accelerometer may have been somewhat in error due to the necessity for damping the movement of the indicating mechanism of the instrument to eliminate the effect of vibrations of the instrument mounting. A comparison of the results obtained indicated that this error did not exceed 5 per cent.

The diaphragms of the pressure recorders used to determine oleo-cylinder pressures had a maximum movement at their centers of 0.002 inch. The movement of the oil in the pressure-transmission tubing was, therefore, small and practically limited to that caused by the compression of the oil and the expansion of the tube. Tests indicate that the lag of the pressure recorders was negligible. The effect of the impulse waves in the pressure lines was eliminated by drawing smooth curves of pressure through the records. The pressure results are, therefore, believed to be of satisfactory accuracy.

Difficulty was experienced in obtaining the desired accuracy because of fluctuations in the angular velocity of the high-speed film drums used on the recording instruments. This caused inaccuracy in determining the variation of the measured quantities with time. This trouble was not entirely eliminated by balancing the drums statically and dynamically. The best indication of the accuracy of the results, particularly of work versus height of drop, seems to be the consistency with which the experimental points follow the smooth curves of the variation. From this standpoint the results obtained with the rubber-cord gear appear to be good. For the oleo gear, however, the results are somewhat erratic. The experimental points in this case appear to be subject to an error of less than ±10 per cent. It is believed, however, that the inconsistency of the results is partially due to the erratic action of the automatic valve in the oleo cylinders.

COMPUTATION OF RESULTS

For each drop test of both landing gears the maximum forces developed in and the work done on each complete gear and on each component part of each gear were calculated. For each of the flight tests the maximum forces developed and the resulting forces in each of the structural members of both landing gears were calculated. In addition, an estimate of the energy absorbed by each unit of each gear for one loading condition was made.

To compare the two types of landing gears it was necessary to know their reactions when an equal amount of work was done upon them. This was possible when the total vertical displacement of the gears for similar loading conditions was used as a basis of comparison. The total vertical displacement was taken as the vertical displacement of a point on the test rig lying in a plane passing through the center line of the axle of the landing gear and normal to the longitudinal axis of the test rig. This displacement was the sum of the free drop, the maximum depression of the tires, the vertical displacement of the test rig due to the movement of the shock-absorbing units, and the distortions of the structural members of the landing gear and test rig. The distortions were found to be so small, during the static tests, that they were negligible. The free drop was determined by the position of the test rig prior to each drop. The vertical displacement of the point on the test rig due to the movement of the shock-absorbing units was determined from the instrument records of these movements and a calibration obtained from the static tests showing the relation between the aforesaid movements and the vertical displacement of that point.

The depressions of the tires during the dynamic tests were not measured. In order to calculate these depressions, it was assumed that the depressions of the tires were the same with a dynamic force as with a static load of equal magnitude. It is realized that this assumption is an approximation, but is one that will give results within the accuracy of the tests, as will be shown later. To obtain the depression of the tires for any drop test, the force on the tires was computed from the recorded accelerations and the depression for this force found from the static calibration of the tire depression versus load on the tires.

The work done on the complete landing gear was computed for each test. This work was equal to the product of the effective load and its total vertical displacement during the test.

The forces developed on the rubber cords were found as the products of the instantaneous values of acceleration (in terms of g) and the effective static load on the cords. The work done on the rubber cords could be found by two methods: (a) By finding the integral of the curve of force on the cords (as determined above) versus the elongations of the cords; (b) by assuming that the elongation of the cords was the same for a dynamic force and a static load of equal magnitude and by taking the integral of the curve of static load versus cord elongation (as determined from the static test) between the limits of load equal to zero and load equal to the maximum force developed on the cords. For a number of the drop tests the work done on the cords was computed by the two methods. It was found that the results of the two agreed within 10 per cent. As it is probable that the precision of measurement is of about this same order of magnitude (see Precision), and although method (b) was based upon an assumption that is admittedly only an approximation, it was used in order to avoid a great deal of tedious work. The force and the work done on the tires of both gears and on the rubber disks of the oleo gear were calculated in a manner similar to that employed for the calculations on the rubber cords.

For the oleo cylinder, the force developed was found as the product of the pressure on the piston and the effective piston area. The work done on the oleo cylinder was equal to the integral of the curve of piston force versus cylinder movement.

The percentage of work done on each unit was found by dividing the work done on each unit by the total work done on the landing gear.

While no specific measurements were made to obtain the energy absorbed by the landing gears, an approximate idea of the energy absorbed for one condition of loading can be obtained from the static-load curves. If it is assumed that the deformation of the tires, disks, and rubber cords is the same for a static load and an equal dynamic force, and the amount of energy absorbed by them is the same for equal deformations irrespective of the time interval, then the curves of increasing loads and decreasing loads versus deformation can be used to find the approximate energy absorbed. The area under the curve of increasing load versus deformation represented the work done on that unit during that part of the static calibration wherein the load was being increased. The area under the curve of decreasing load versus deformation represented the work that was returned by the unit during that portion of the test wherein the load was being decreased. The difference between the two areas represented the energy absorbed by the unit. This difference divided by the area under the increasing load curve gave the ratio of the energy absorved to the work done on the unit. Knowing the distribution of the work on the units of the landing gear and the percentage each unit absorbed, the percentage that the complete landing gear absorbed was roughly computed.

In the flight tests the whole credit for arresting the downward motion of the airplane was given the landing gear. Actually, of course, the tail skid arrested a portion of this downward motion; however, crediting the landing gear with the whole work puts the resultant calculated forces on the safe side for design considerations. The maximum force in the landing gear was determined as the product of the maximum acceleration developed and the total weight of the airplane. The maximum force on each of the structural members was determined by a resolution of this maximum force into the proper components.

RESULTS

The results are presented in curve form for the drop tests and in tabular form for the flight tests. In all of the curves the results obtained with the various loads used have been plotted against total vertical displacement of the landing gear. The curves show the maximum acceleration on the landing gears (figs. 4 and 5); the maximum forces developed on the tires (figs. 6 and 7); the work done on the complete landing gears (figs. 8 and 9); on tires (figs. 10 and 11); on rubber cords (fig. 12); on rubber disks (fig. 13); and on oleo cylinders (fig. 14); the percentage of the total work done on the landing gear that is done on the tires (figs. 15 and 16); on the rubber cords (fig. 17); on the rubber disks (fig. 18); and on the oleo cylinders (fig. 19).

Table I shows the maximum accelerations experienced and the maximum forces on the cords during the initial stroke of the landing gear and the subsequent ground runs in the flight tests with the rubber-cord landing gear. Table II shows the maximum accelerations experienced, the maximum forces developed on the rubber disks, and the maximum cylinder pressures generated during the flight tests on the oleo gear. Tables III and IV show the maximum forces developed on the structural members of the rubber cord and the oleo gear, respectively, during the flight tests.

Curves showing the relation between the total drop of the landing gear and the free drop are given in Figures 20 and 21. The curves of the deformation of the shock absorbing units versus the increasing and decreasing static loads are shown in Figure 22.

Additional information on the action of the oleo gear is given in Figures 23 to 29, inclusive, which show the pressures built up in the oleo cylinders during some of the drop tests. Figure 30 gives the maximum pressures generated in the cylinders during the tests, and Figure 31 shows the maximum resisting forces in terms of normal static load developed by the oleo cylinders and rubber disks during the drop tests under the normal static loading conditions.

As a means of directly comparing the maximum forces or the accelerations developed in the two gears during the drop tests, curves of maximum accelerations for the two gears under an approximate static load of 2,300 pounds are shown in Figure 32.

DISCUSSION OF RESULTS

Comparison of gears.—The results of these tests show the shock reducing qualities of the two gears, the abilities of the gears to absorb work and thereby reduce the rebound, the comparative capacities of the gears, and the height of drop equivalent to landings. They also show the degree to which the operation of the oleo cylinders approached the ideal operation. The results also show the effects of variation in loading conditions on both gears. These, however, will be but briefly discussed while the major discussion will be on the results of the drop tests under the approximate loading of 2,300 pounds and on the landing tests. The results of the drop tests will be discussed on the basis of total vertical drop, and those of the landing tests on a basis of similar types of landings.

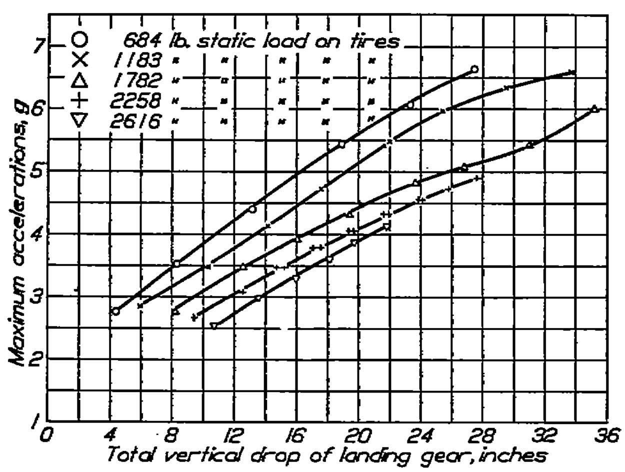

FIGURE 4.—Maximum accelerations experienced by rubber cord gear during drop tests

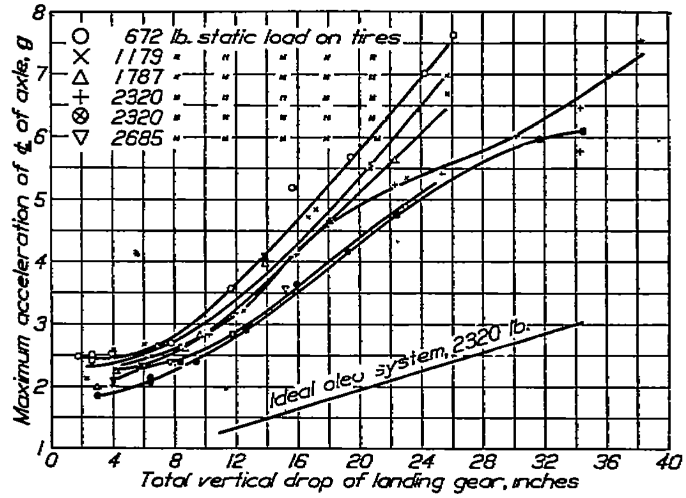

FIGURE 5.—Maximum accelerations experienced by oleo gear during drop tests

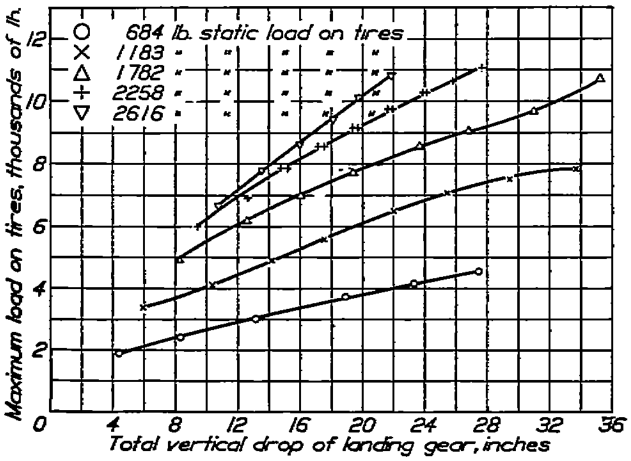

FIGURE 6.—Maximum tire loads on rubber cord gear during drop tests

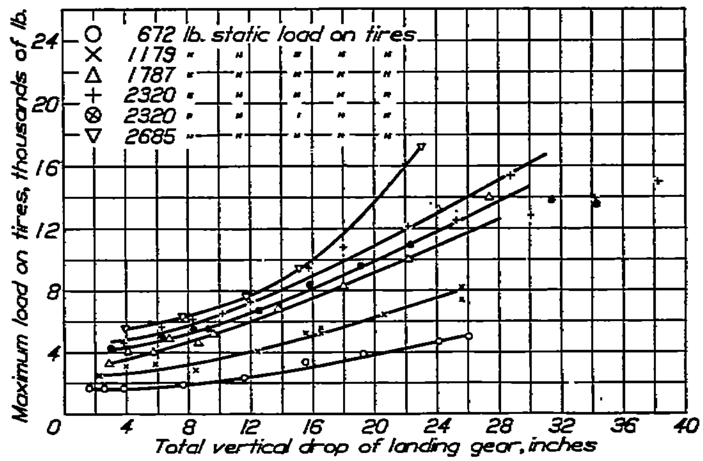

FIGURE 7.—Maximum tire loads on oleo gear during drop tests

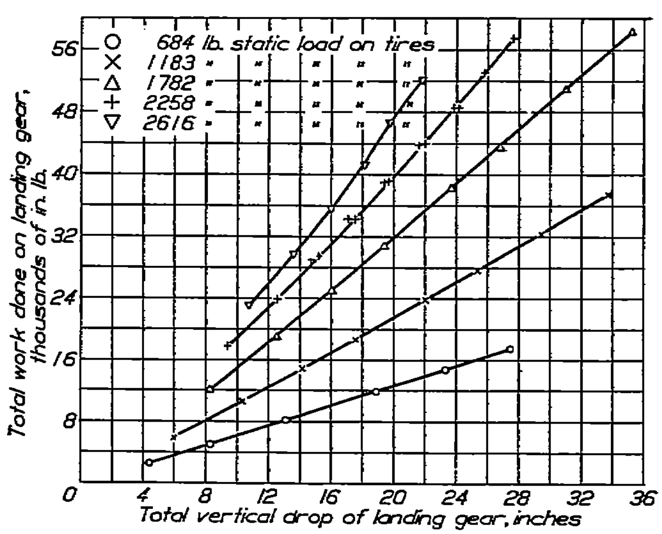

FIGURE 8.—Work on rubber cord gear during drop tests

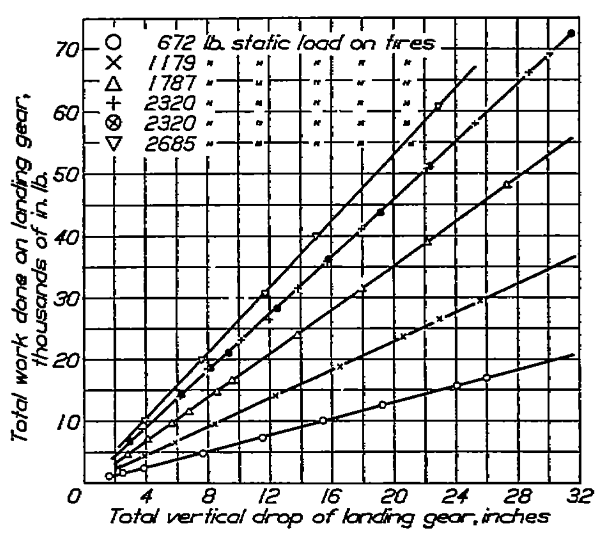

FIGURE 9.—Work on oleo gear during drop tests

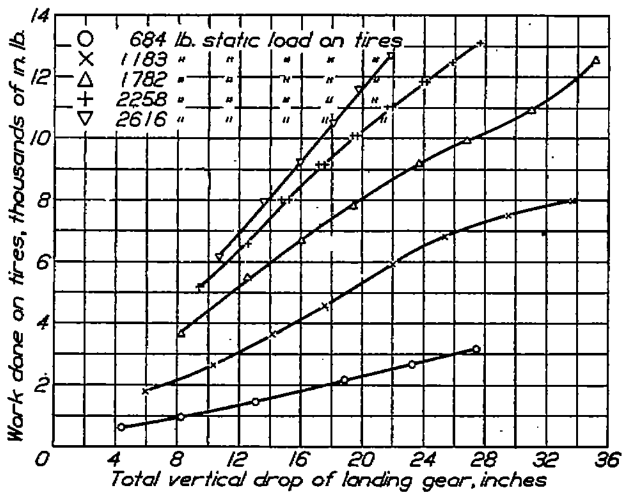

FIGURE 10.—Work on tires of rubber cord gear during drop tests

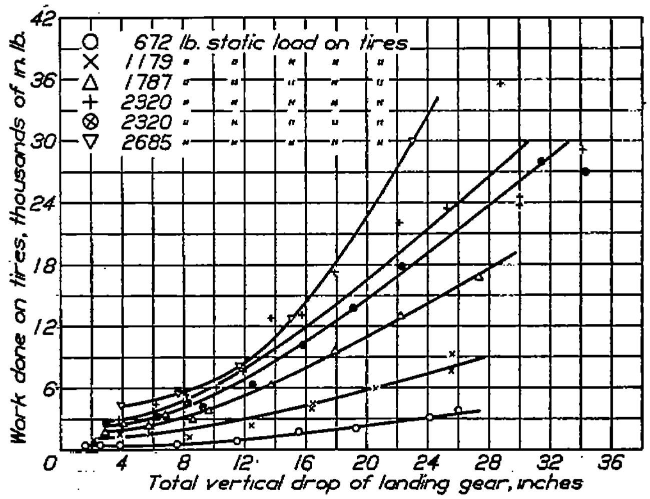

FIGURE 11.—Work on tires of oleo gear during drop tests

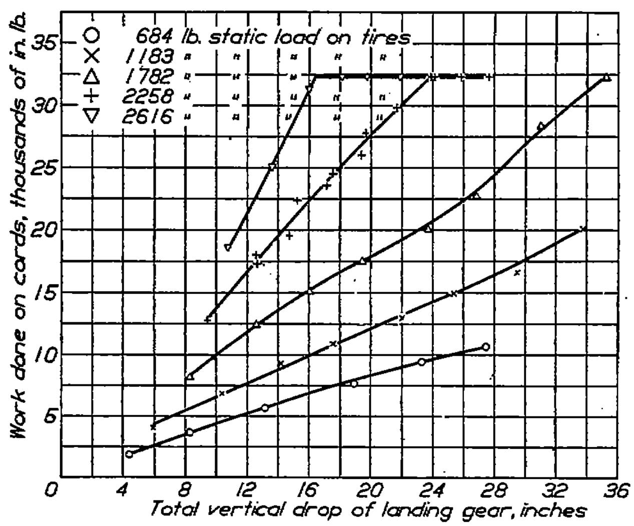

FIGURE 12.—Work on cords of rubber cord gear during drop tests

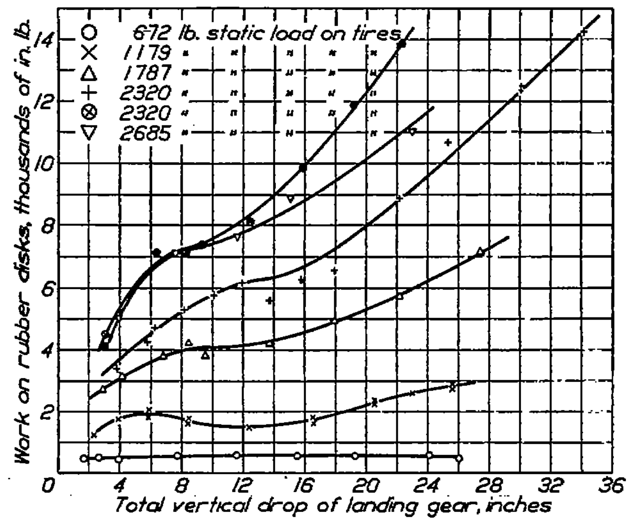

FIGURE 13.—Work on rubber disks of oleo gear during drop tests

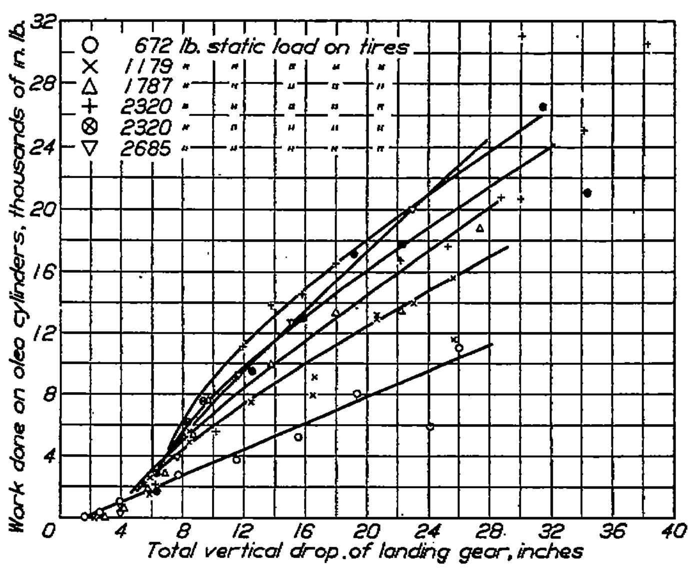

FIGURE 14.—Work on oleo cylinders during drop tests

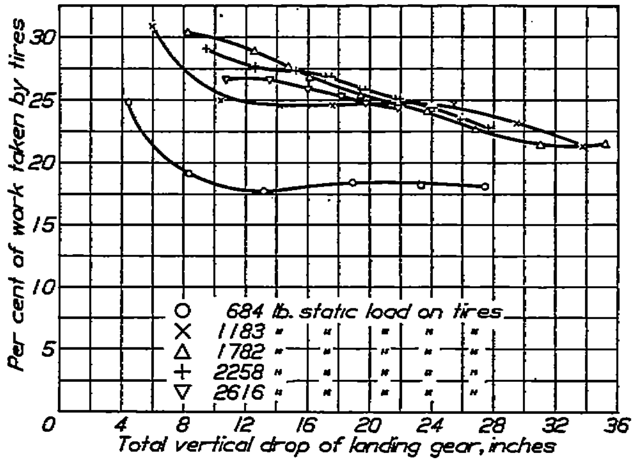

FIGURE 15.—Per cent of total work on rubber-cord gear that is taken by tires

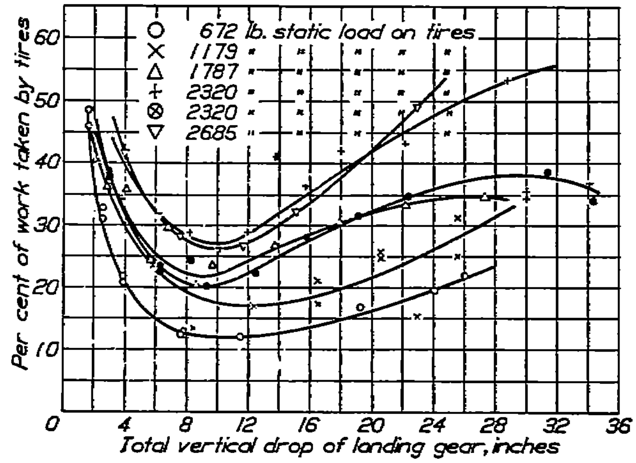

FIGURE 16.—Per cent of total work on oleo gear that is taken by tires

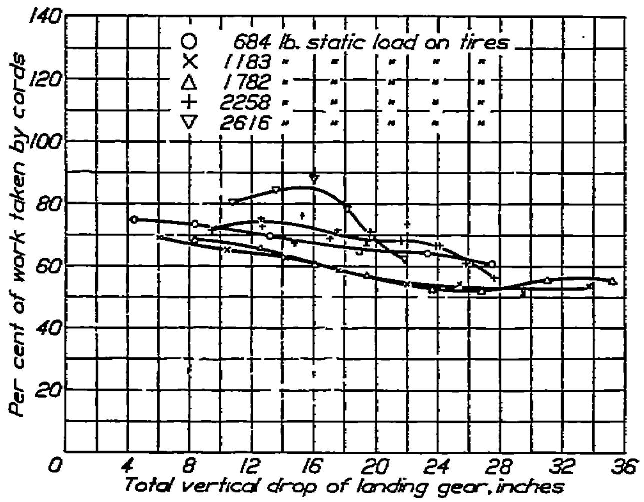

FIGURE 17.—Per cent of total work that is taken by cords

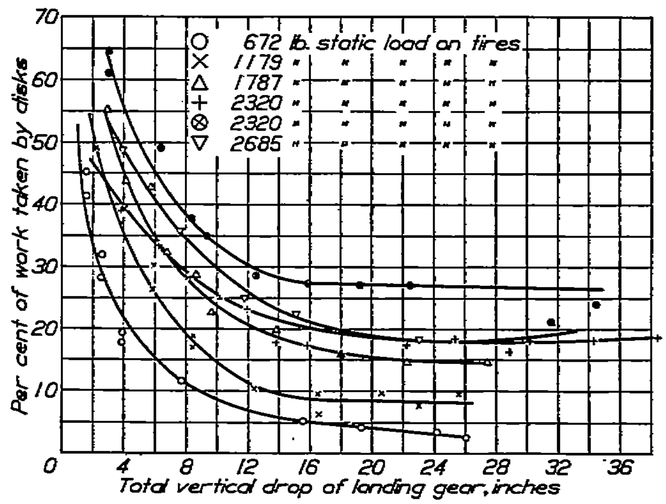

FIGURE 18.—Per cent of total work that is taken by rubber disks

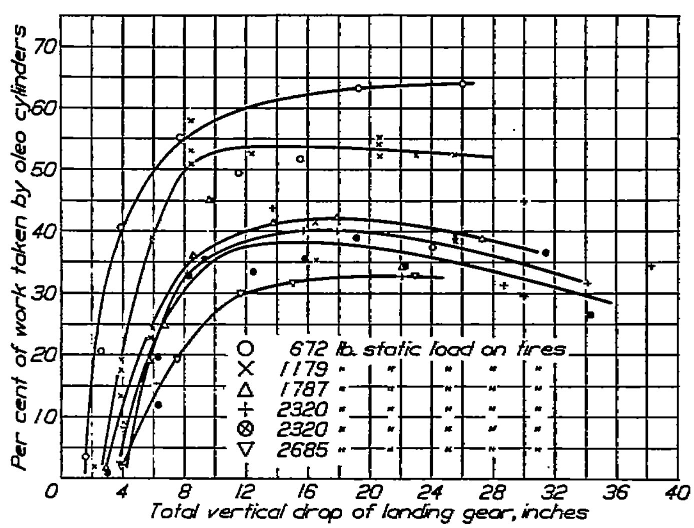

FIGURE 19.—Per cent of total work that is taken by oleo cylinders

Incidentally, from the experience gained in keeping the gears in proper operating condition during the investigation, some idea was obtained of the relative amount of labor required for maintenance of the two gears under service conditions.

A very important phase of the comparison of the two gears is that of the maximum accelerations experienced with the gears under the same or similar test conditions. The results show that the oleo gear was slightly superior to the rubber-cord gear in the drop tests under a 16-inch total vertical drop, or in the average type of landings. In the more severe drop tests the rubber cord was potentially more effective as a shock reducing unit than the oleo, but due to the manner in which the action of the rubber cords was

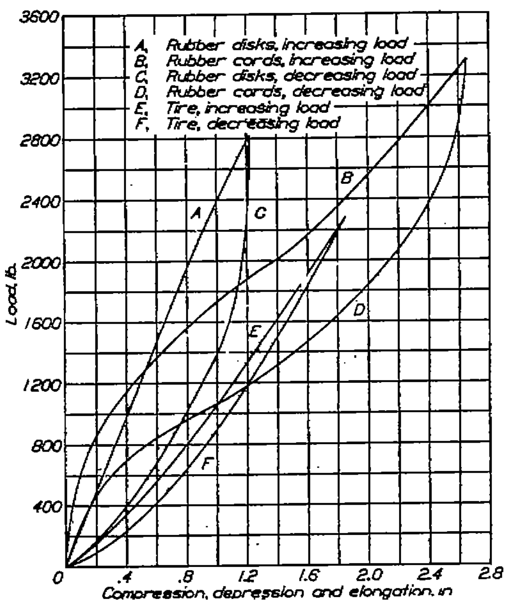

FIGURE 22.—Hysteresis curves of tires, rubber disks, and rubber cords

limited by the construction of the gear, the oleo was superior in the very severe tests. This is clearly shown by a perusal of the results. Figure 32 shows the maximum accelerations experienced during the drop tests, and Tables I and II show the accelerations developed in the landing tests. It will be noted that the maximum accelerations experienced by the oleo gear in the drop tests were slightly less than those experienced by the rubber-cord gear up to a total drop of 16 inches for which the acceleration was $3.6g$ for either gear. Beyond this and up to the drop where the rubber cords elongated to such a degree as to allow the axles to hit the stops, the rubber-cord gear developed the lower maximum accelerations. The tests were not carried beyond this drop on the rubber-cord gear as it is obvious that excessive forces would be developed. The tests on the oleo gear were, however, carried to a free drop of 26 inches. The flight test results substantiated those obtained from the drop tests in that the accelerations developed in the oleo gear in the initial contact with the ground were slightly less than those experienced by the rubber-cord gear. In the ground runs, wherein the oleo cylinders were not effective, the accelerations experienced on both gears were approximately the same. This also is the case in the landing tests wherein there was an insufficient amount of oil in the oleo cylinders. In these last-mentioned tests, the oil level was so low in the oleo units that no pressure developed in the cylinders during the landings.

The tendency of a landing gear to cause rebound or bouncing is also an important consideration in its use. This tendency is controlled by the distribution of the work among the units of the gear and the amount of energy each unit absorbs or dissipates. The work done on each unit and the percentage of the total work that was taken by each of the units is shown in Figures 8 to 19, inclusive. Unfortunately, in drop and flight tests no measurements were taken of the amount of energy absorbed or of the rebound. An estimate from the results of the static tests (fig. 22) shows, however, if it is assumed that the work done on the units under static loadings was the same as the work that would be done under similar dynamic loads, that the rubber-cord gear returned about 75 per cent of the work done on it to cause bouncing. To the pilot, the rubber-cord gear appeared to be "stiff," and its use made it exceedingly difficult to land the airplane without bouncing. The oleo gear, on the other hand, permitted landings which "felt smooth" and only in the most severe cases caused rebound of the airplane. This difference in the tendency to cause rebound was very pronounced in the drop tests. The rubber-cord gear caused a very appreciable bounce in all of the tests, but the rebound of the oleo gear seldom caused the wheels to leave the landing platforms.

The previous discussion showed that from the consideration of the tendency of the gears to cause rebound, the oleo gear was very superior to the rubber-cord gear. From the consideration of the shock-reducing qualities, however, the oleo gear was only slightly more effective than the rubber-cord gear in the range of the average types of landings and superior to the rubber cord for very severe landings, due to the limited movement of the rubber-cord gear rather than to the merits of the oleo. In the ground runs and in the cases wherein there was insufficient oil in the oleo cylinders, causing the oleo cylinders to be inoperative, the oleo gear was approximately as effective as the rubber cord. This showed that as far as the shock-reducing qualities of the gear were concerned for ordinary landings the oleo cylinders did not have a very great effect.

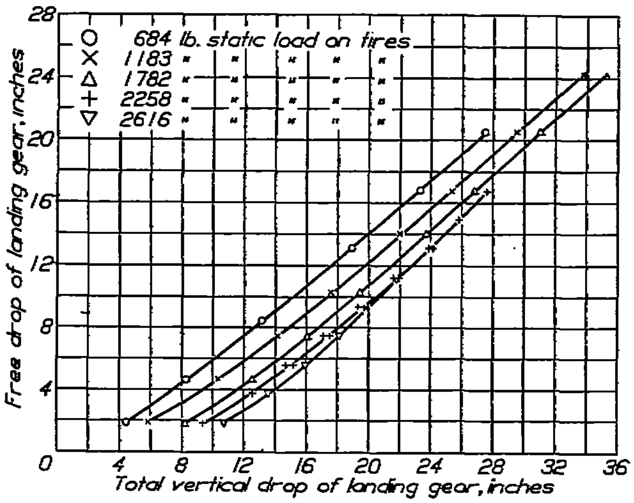

FIGURE 20.—Relation between total drop and free drop for rubber-cord gear

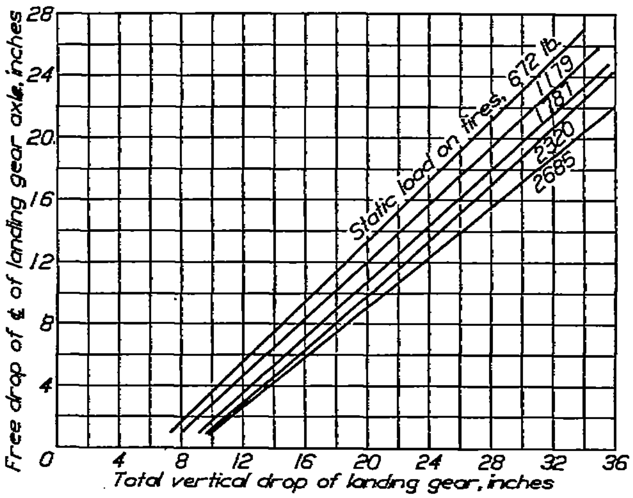

FIGURE 21.—Relation between total drop and free drop for the oleo gear

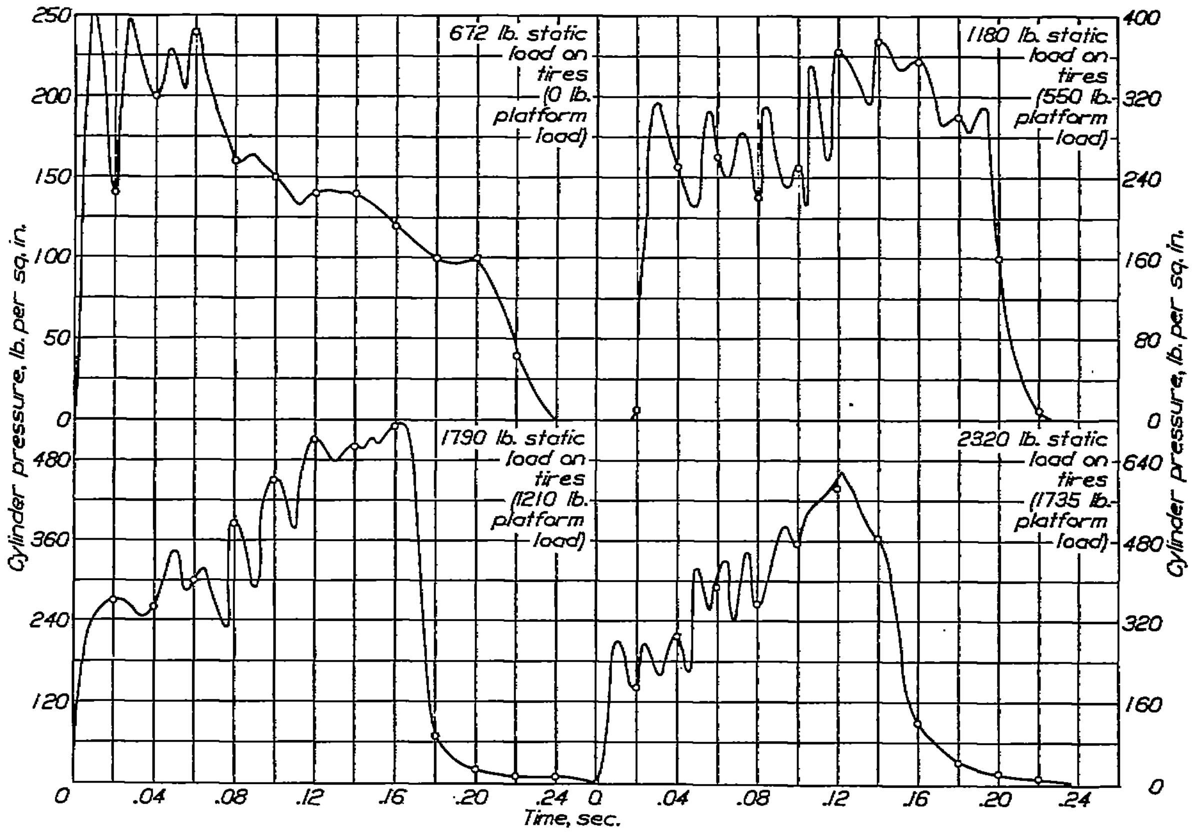

FIGURE 23.—Pressure histories for oleo cylinders; 1¾-inch free drop

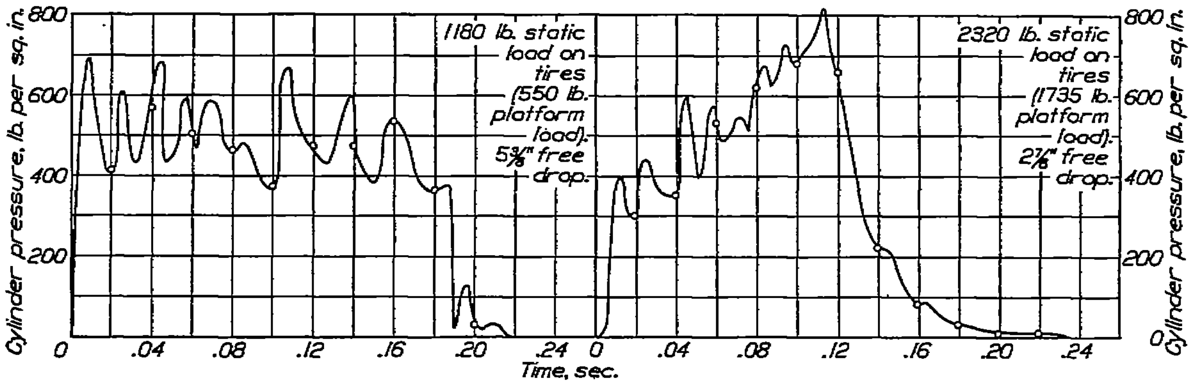

FIGURE 24.—Pressure histories for oleo cylinders

89300—32——7

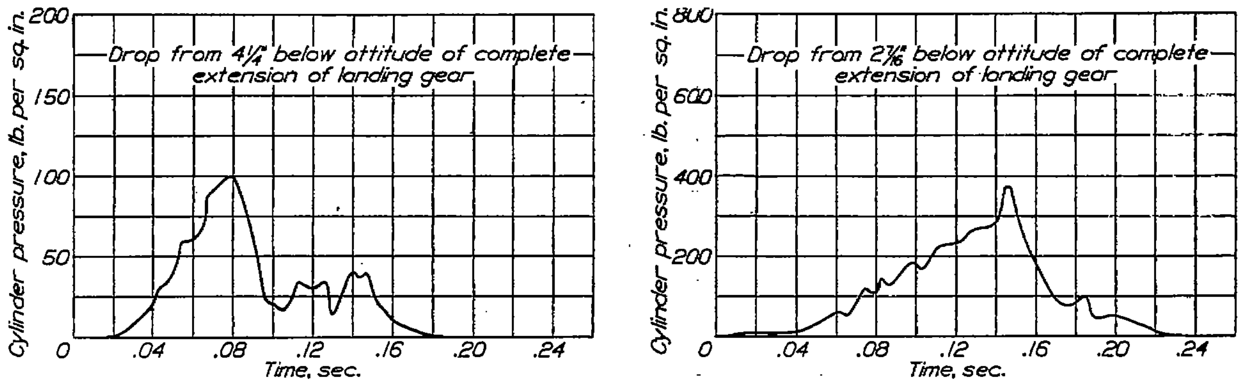

FIGURE 25.—Pressure histories for oleo cylinders; 2,320-pound static load on tires

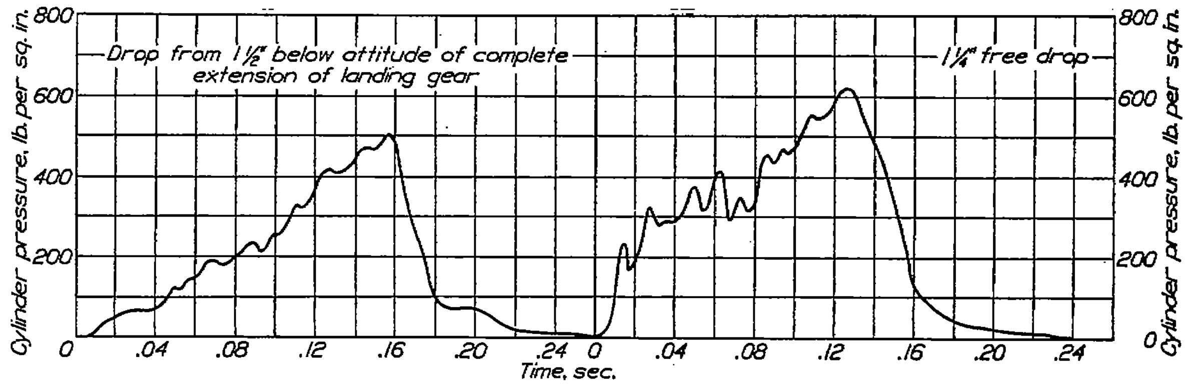

FIGURE 26.—Pressure histories for oleo cylinders; 2,320-pound static load on tires

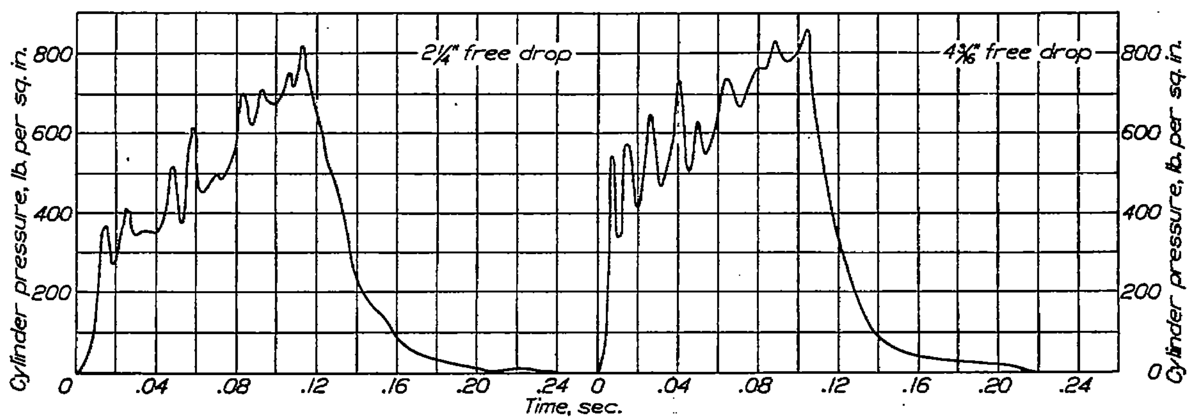

FIGURE 27.—Pressure histories for oleo cylinders; 2,320-pound static load on tires

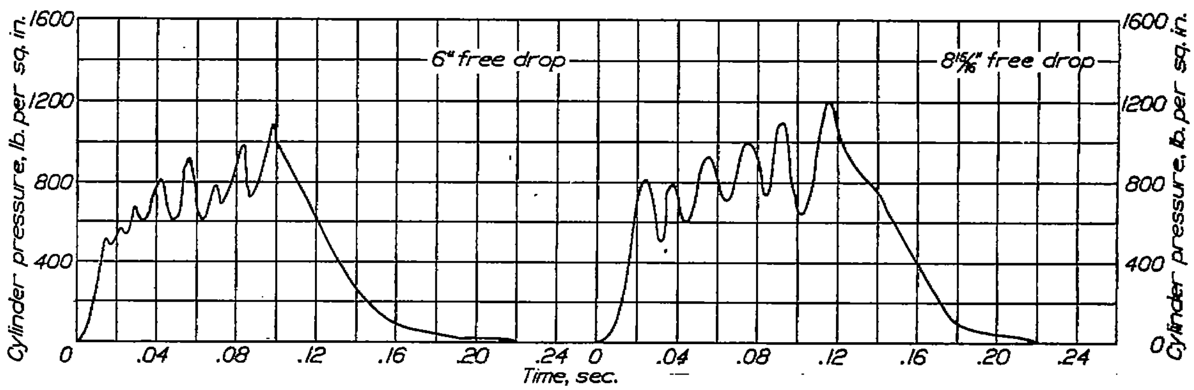

FIGURE 28.—Pressure histories for oleo cylinders; 2,320-pound static load on tires

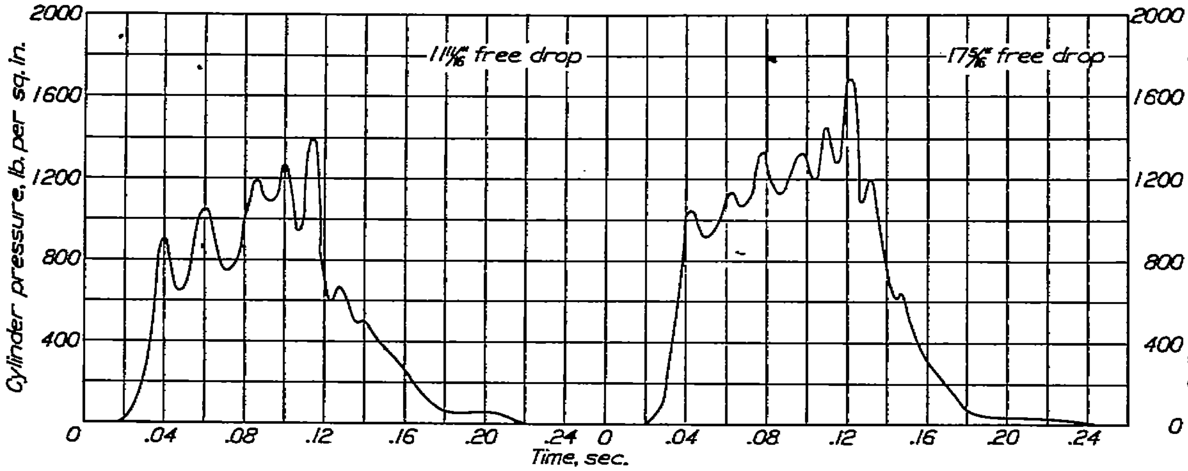

FIGURE 29.—Pressure histories for oleo cylinders; 2,320-pound static load on tires

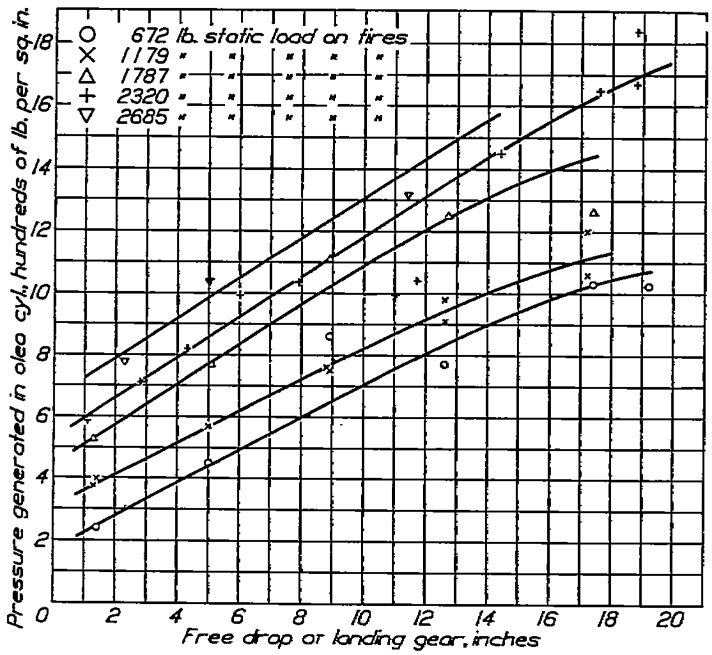

FIGURE 30.—Maximum pressures developed in oleo cylinders during drop tests

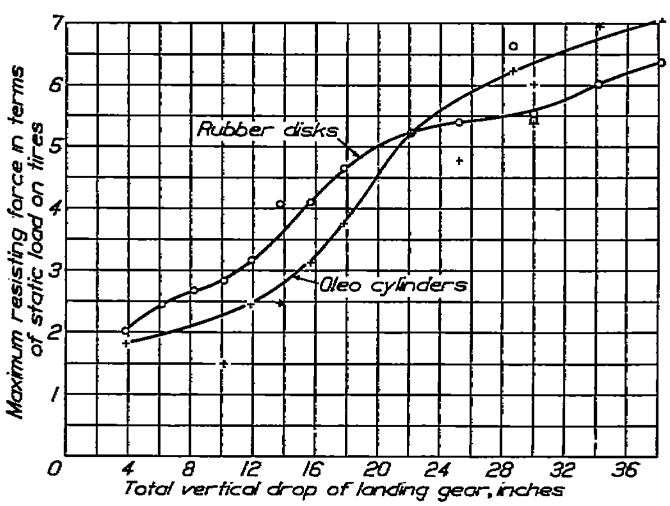

FIGURE 31.—Maximum forces developed in rubber disk and oleo units during drop tests; 2,320-pound static load on tires

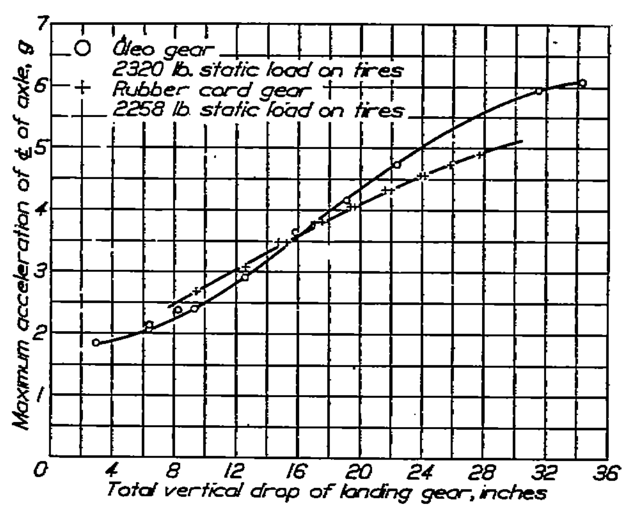

FIGURE 32.—Maximum accelerations developed on gears during drop tests

Oleo gear.—The lack of effective operation of the oleo gear is further brought out by comparing the accelerations developed in it during the drop tests with those that would be developed by an "ideal system" having a stroke which would allow the same restrained vertical motion of the load, as the oleo gear, for the same respective total drops. This comparison can be made by noting Figure 5. On this figure, a curve of the theoretical accelerations for a 2,320-pound loading on an ideal unit with the stroke meeting the conditions set forth above, is shown. It will be noted that in all of the drops the maximum acceleration developed by the oleo gear was in excess of twice that which would be developed by the ideal, whereas the maximum accelerations should have approached those of the ideal. This wide difference from the ideal case clearly shows that the oleo gear was not as effective as it should have been, due either to improper action of the oleo unit or improper design of the landing gear.

The failure of the oleo gear to operate efficiently is further brought out by comparing the maximum accelerations developed with its use with those that would be developed with the use of an "ideal" shock-absorbing system.

By an "ideal" system is meant a theoretical one which offers a uniform retarding force throughout its entire stroke of such magnitude and character that at the end of the stroke, it has absorbed and completely dissipated sufficient energy to have completely arrested the downward motion.

This comparison can be made by noting Figure 5, which contains curves of the maximum accelerations recorded during the drop tests on the oleo gear, and a curve of the theoretical accelerations that would be developed by an "ideal" system having the same stroke as that of the oleo gear under 2,320-pound loading condition. It will be noted that the theoretical curve starts at $1g$ with a total drop of the gear of 7.6 inches.

The reason for the break in the "ideal" curve at $1g$ and 7.6 inches total vertical drop may be somewhat obscure. For the purposes of comparison, the stroke of the "ideal" system has been assumed to be the same as that of the oleo gear, so until the drop is greater than 7.6 inches, the "ideal" system has not been completely extended. For drops in the range of 0 to 7.6 inches, the units of the system act instantly upon release of the load before it has had an opportunity to attain a velocity. Since the requirement for the "ideal" system is that it offers a uniform retarding force that will completely arrest the downward motion, the retarding force instantly built up will equal the force tending to produce motion which, in all cases, is the force of gravity. When the drop is greater than 7.6 inches, the load has attained a velocity, and consequently possesses some kinetic energy before the retarding force is applied. In addition, then, to overcoming the force of gravity, the retarding force must offer sufficient resistance to completely absorb this kinetic energy, and consequently, the retarding force must be in excess of $1g$.

In an elastic system, in which the initial retarding force is zero, and in which the force during the stroke is directly proportional to the displacement of the units, the maximum retarding force is twice that obtained with the use of an "ideal" system having the same stroke. This may be shown mathematically as follows:

Let E_1 = the energy absorbed by the "ideal" system.
E_2 = the energy absorbed by the elastic system.
F_1 = the retarding force of the "ideal" system.
F_2 = the instantaneous retarding force of the elastic system.
X_1 = the stroke of the "ideal" system.
X_2 = the stroke of the elastic system.

In the "ideal" system, the force F_1 is a constant, but in the elastic system, the force is proportional to X_2 or $F_2 = kX_2$.

The general expression for the amount of energy absorbed by the system is $E = \int F dx$. Thus the energies taken by the systems are

$$E_1 = F_1 X_1 \text{ and } E_2 = \tfrac{1}{2}k X_2^2$$

In order to make a comparison of the two systems, it is assumed that they have the same stroke and absorb the same amount of energy. Accordingly, $F_1X_1 = \tfrac{1}{2}kX_2^2$

But

$$F_2 = kX_2 \text{ and } X_1 = X_2$$

Therefore,

$$F_1X_1 = kX_2\ (\tfrac{1}{2}X_2) = \tfrac{1}{2}F_2X_2$$

or

$$F_1 = \tfrac{1}{2}F_2$$

It has been shown that the minimum retarding force offered by the "ideal" system is $1g$. Therefore, the smallest maximum acceleration that could be expected with the use of an elastic system, in which the retarding force varies from zero to the maximum in direct proportion to the displacement of the units, would be $2g$.

Again, referring to Figure 5, it will be noted that the smallest maximum accelerations recorded for the oleo gear tend to approach $2g$, which indicates that in the very small drops, its action was similar to the above-described elastic system, and that the retarding force of the cylinders, during the small drops, was negligible. It will also be noted that in all of the drops the maximum accelerations experienced with the use of the oleo gear were in excess of twice those of the theoretical system.

It is realized that the conditions set forth for the "ideal" system can not be realized in practice, but they may be more closely approached than was the case with this oleo gear (Reference 4.) The marked difference between the action of this oleo gear and the action of some other oleo units, with respect to the theoretical system, indicates that this oleo gear was not as effective as it might have been, due either to improper action of the oleo gear or improper design of the landing gear.

Another poor feature of the oleo units was the breather plugs in the tops of the oleo pistons. When a free drop exceeding 5 inches or a very severe landing was made, oil would be thrown from these plugs and would eventually flow onto the rubber disks. This resulted in the disks becoming so impregnated with oil that after 75 per cent of the investigation had been completed the disks had to be replaced with new ones. The change in the disks completely changed the action of that unit and other units, so that entirely separate sets of results were obtained for the tests prior and subsequent to this replacement, as shown in the figures. The curves designated by the symbol + are from the tests made prior to the replacement, and those indicated by the symbol ⊗ are from the tests made subsequent to it. The disks that were used as replacements were supposed to be exactly similar to those in the gear at the onset of the tests, and were so as regards size. From inspection they also appeared to be of the same quality; however, from the change in the test results it is obvious that they were not. This shows that even a small difference in the quality of a unit has a very appreciable effect on the action of that unit and the complete shock-absorbing system.

Maintenance.—A comparison of the care required by the two gears during the tests is interesting, as it presents a very good example of the maintenance that would be required for continued use of them. At the onset of the tests both landing gears were completely overhauled, the rubber-cord gear being rewrapped and the oleo gear realigned so that there would be no binding between its moving parts. During the investigation no maintenance was required for the rubber-cord gear, while the following was necessary for the oleo gear:

1. Examination of the oil level after every three tests.
2. Complete replacement of the rubber disks after 75 per cent of the investigation had been completed.
3. Disassembling of the oleo cylinders to remove scorings caused by foreign particles being worked in between the cylinders and pistons.

Comparison of flight and drop tests.—It is interesting to compare the results of the flight and drop tests. It will be noted from the results that the accelerations developed on contact with the ground in the good examples of normal and 2-point landings were less than those experienced in the subsequent ground runs, and that the accellerations experienced in the taxi and take-off runs were comparable to those experienced in these ground runs. Also, the maximum accelerations experienced in the tests were smaller in the initial contact with the ground on the oleo gear than on the rubber-cord gear and approximately the same as those experienced for both gears in the subsequent ground runs. The accelerations developed in initial contact, in the tests for the average normal and 2-point landings, were less than those experienced in the drop tests of 1-inch free drop on the rubber cord gear and less than any free drop on the oleo gear. In the flight tests wherein poor normal or 2-point landings or average pancake landings were made the maximum accelerations experienced were less than those experienced with a 3-inch free drop on the rubber cord gear or a 1-inch free drop on the oleo gear. In a very severe pancake landing made on the rubber-cord gear the acceleration experienced was comparable to that developed in a 7-inch free drop. In a pancake landing made on the oleo gear during the period in which there was insufficient oil in the oleo cylinders, a maximum acceleration was experienced which was comparable to that experienced in an 8-inch free drop on the oleo gear with the cylinders properly filled with oil.

Operation under various loadings.—The discussion of the operation of the landing gears under the various loading conditions will be confined to indicating some of the salient points. It will be noted in Figures 4 and 5 that for the lighter conditions the rate at which the maximum accelerations increase with increased total drop varies with loading. Since the minimum rate of increase in accelerations with the loading indicates the load for which the landing gear was most effective in reducing shocks, these curves may be used to indicate the loads for which each gear was most effective. From this standpoint, the rubber-cord gear appears to be most effective with the 1,800-pound load, and the oleo gear with the 2,300-pound load. Further consideration substantiates the indication that 1,800 pounds was the proper loading for the rubber-cord gear. Figure 12, work done on the cords versus total drop, shows that with the heavier loads the work that the cords were capable of taking reached the limit set by the construction of the gear prior to the realization of the 24-inch free drop specified by the Department of Commerce for this type of landing gear. With the 1,800-pound loading the limit of the work the cords were capable of taking appears to have been reached at the 24-inch free drop. It is, therefore, believed that the proper loading for the rubber cord gear was approximately 1,800 pounds and for the oleo gear 2,300 pounds.

CONCLUSIONS

A comparison of the results obtained with the rubber-cord and the oleo types of landing gears used in this investigation show:

1. The oleo gear was slightly superior in its ability to reduce the shocks incurred in ordinary landings and total vertical drops up to 16 inches for which the maximum acceleration was 3.6g with either gear.

2. The rubber-cord gear was increasingly superior in the above respect, as the height of total drop was increased above the 16 inches until the further elongation of the cords was limited by stops at a total drop of 22 inches.

3. At greater total drops than 22 inches the superiority of the oleo was again evidenced by its ability to withstand a total drop of 37 inches which corresponded to a free drop of 26 inches for this gear.

4. The oleo gear with only the rubber disks acting was approximately as effective as the rubber-cord gear for ordinary landings and ground runs.

5. The oleo gear is greatly superior to the rubber-cord gear in its ability to absorb energy, and thereby reduce the tendency to rebound.

6. The results obtained with the oleo gear show that the action of the oleo cylinders was far from that for an ideal cylinder, and leaves room for considerable improvement in the design of the units and the gear.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *May 20, 1930*

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TABLE I

RESULTS OF TESTS ON RUBBER-CORD DECK LANDING TYPE OF LANDING GEAR ON AN F6C-4 AIRPLANE

Test No.	Type of test	Initial contraction of landing gear			Major impact in ground run			Remarks
		Cord loads (pounds)		Accelera-tion g	Cord loads (pounds)		Accelera-tion g	
		Right	Left		Right	Left		
1	Taxying				1,850		2.07	Wind gusty. Taxi into wind.
2	Do				1,420	2,150	1.55	Normal taxi into wind.
3	Do				2,010	3,015	1.63	Normal taxi with wind. Field wet and soft.
4	Do				3,420	4,890	2.32	Normal taxi with wind. Field wet but firm.
5	Take-off				1,500	2,210	1.79	Smooth take-off. Wind gusty.
6	Do				2,380	3,010	2.02	Smooth take-off. Good section of field.
7	Normal landing		3,520	1.84				Field wet in spots. Wind very gusty.
8	Do	1,300	1,525	1.58		1,370	1.30	Field fairly firm. Wind very gusty.
9	Do			1.48			1.58	Field firm. Tail low 2-point.
10	Do	1,330	1,920	1.92	1,300	2,430	1.97	Rough landing. Plane bounced.
11	Do	2,720	1,920	2.17	1,900	1,920	1.69	Rough 3-point landing.
12	Do	1,590	2,150	2.02	1,770	1,870	1.69	Fairly rough landing. Engine missing.
13	Two-point	1,370	1,540	1.58	1,730	1,750	1.73	Fast landing. Good 2-point landing.
14	Do	1,170	1,710	1.68	2,480	2,940	1.88	Very good 2-point landing.
15	Do	2,940	3,420	2.55	4,670	3,470	3.33	Very severe landing (2-point).
16	Pancake	4,010	4,600	2.90	3,730	3,470	2.46	Rather severe landing. Field firm.
17	Do	2,490	2,500	2.17	1,980	1,620		Fairly smooth landing. Field firm.
18	Do	3,810	2,210	2.75	2,770	2,200	1.83	Landing not very severe. Field good.
19	Do	1,685	2,050	1.58				Smooth landing. Very slight pancake.
20	Do	2,825	2,050	1.87	3,630	2,440	2.02	Fairly smooth landing.
21	Do	3,960	5,640	3.64	3,730	3,560	2.41	Good pancake landing.

NOTE.—Pilots did not make very severe pancake landings due to the manner in which this type of landing gear caused the plane to bounce.

TABLE II

RESULTS OF TESTS ON OLEO WITH RUBBER DISKS LANDING GEAR (DECK LANDING TYPE) ON F6C-4 AIRPLANE

Test No.	Type of test	Initial contraction of landing gear: Disk loads (pounds) Right	Disk loads (pounds) Left	Oleo pressures (lbs./sq. in.) Right	Oleo pressures (lbs./sq. in.) Left	Acceleration g	Major impact in ground run: Disk loads (pounds) Right	Disk loads (pounds) Left	Oleo pressures (lbs./sq. in.) Right	Oleo pressures (lbs./sq. in.) Left	Acceleration g	Remarks
22	Taxying						2,120	3,000			1.68	Very low oleo pressures.
23	Do						2,850	2,790			2.02	Do.
24	Take-off						2,670	3,280	210	385	1.98	
25	Do						3,180	2,890			1.68	Pressures too low to measure.
26	Normal landing			575	605	1.45			440	160	1.98	Smooth landing. Field good.
27	Do	2,220	1,400	345	260	1.45	2,800	2,580	450	160	1.58	Smooth landing. Field firm.
28	Do	2,120	2,030	990	450	2.25	2,220	2,300	535	100	1.84	Fair landing. Field firm.
29	Do	1,810	1,580			1.15	2,420	1,820			1.38	Good landing. Cross wind.
30	Do	2,010	1,920			1.58	2,220	2,300			1.69	Do.
31	Do			1,190	230	1.25	1,910	2,400	240	570	1.53	Wobbly landing. Field firm.
32	Two-point	1,370	2,030	440	330	1.53	1,480	1,580	200	140	1.29	Slight pancake. Field firm.
33	Do	2,220	1,470	220	500	1.38	2,110	1,920	450	310	1.58	Fast landing. "Floater."
34	Do	2,800	3,190	375	440	1.73	1,480	2,580	160	210	1.28	Fast landing. Tended to take-off.
35	Do	1,910	1,700	560	730	1.47	2,320	3,190	160	230	1.63	Very consistent 2-point.
36	Pancake	2,670	2,410	(1)	(1)	2.22	3,180	2,300	85	480	2.17	Stalled 2-point landing.
37	Do	3,710	3,120	(1)	(1)		2,850	2,890			2.07	Good 2-point landing.
38	Do	3,480	3,770	(1)	(1)	2.83	2,850	4,020			2.85	Severe landing, bounced.
39	Do	2,480	2,890	660	760	2.17	1,870	3,770	335	115	1.73	Not severe landing.
40	Do	2,590	3,470	200	200	1.38	2,120	4,060	305	165	1.68	Field wet and soft.
41	Do	2,300	3,590	1,150	1,150	2.27	2,670	3,470	160	310	1.68	Fairly severe. Field wet and soft.

[1] Oil out of cylinders.

NOTE.—Remarks taken from visual observation of flight tests with the exception of notes covering pressures generated in the oleo cylinders of the landing gear.

TABLE III

LOAD DISTRIBUTION ON RUBBER-CORD LANDING GEAR MOUNTED ON AN F6C-4 AIRPLANE

Maximum loads in members during initial stroke of landing gear shock-absorber units

Test No.	Type of test	F_5	F_4	F_6	F_7	F_{tires}	F_{cords}
7	Nornal landing	1,980	1,850	2,820	1,400	2,530	3,530
8	Do	920	840	1,370	810	1,210	1,525
10	Do	1,130	1,040	1,660	940	1,480	1,920
11	Do	1,250	1,150	1,840	1,040	1,630	2,150
12	Do	1,570	1,440	2,300	1,310	1,990	2,720
13	Two-point	890	830	1,240	570	1,220	1,540
14	Do	980	920	1,370	630	1,340	1,710
15	Do	1,900	1,790	2,660	1,230	2,450	3,420
16	Pancake	2,630	2,410	4,110	2,560	3,210	4,600
17	Do	1,470	1,350	2,300	1,430	1,850	2,500
18	Do	2,090	1,910	3,210	2,110	2,710	3,810
19	Do	1,240	1,110	1,870	1,230	1,560	2,050
20	Do	1,680	1,510	2,540	1,660	2,060	2,825
21	Do	3,170	2,900	4,710	2,780	3,850	5,640

Maximum loads in members after initial stroke of landing gear or during ground run

Test No.	Type of test	F_5	F_4	F_6	F_7	F_{tires}	F_{cords}
1	Taxying	1,120	1,010	1,690	1,090	1,410	1,850
2	Do	1,320	1,170	2,010	1,400	1,630	2,150
3	Do	1,800	1,620	2,720	1,790	2,200	3,015
4	Do	2,920	2,620	4,420	2,930	3,440	5,290
5	Take-off	1,300	1,190	1,930	1,140	1,660	2,210
6	Do	2,070	1,900	3,080	1,820	2,570	3,010
8	Normal landing	910	830	1,380	820	1,190	1,370
10	Do	1,440	1,310	2,230	1,390	1,810	2,430
11	Do	1,130	1,020	1,750	1,090	1,440	1,870
12	Do	1,160	1,050	1,790	1,120	1,480	1,920
13	Two-point	1,030	950	1,510	960	1,350	1,750
14	Do	1,690	1,560	2,480	1,410	2,140	2,940
15	Do	2,630	2,420	3,850	2,190	3,240	4,670
16	Pancake	1,610	1,460	2,490	1,550	1,960	3,730
17	Do	1,180	1,070	1,830	1,140	1,500	1,980
18	Do	1,630	1,480	2,520	1,570	2,030	2,770
20	Do	2,120	1,920	3,270	2,040	2,590	3,630
21	Do	2,180	1,970	3,360	2,090	2,650	3,730

F_5 is the compressive load in the forward side strut of the landing gear.
F_4 is the compressive load in the middle side strut below the junction of this strut and the rear side strut.
F_6 the compressive load in the middle side strut above the junction of this strut and the rear side strut.
F_7 the tensile load in the rear side strut.
F_{cords} maximum load on the rubber cords on one leg of the landing gear.
F_{tires} maximum load on one tire of the landing gear.

NOTE.—In the above load-distribution tabulation only the vertical loads on the tires were considered. The above is, therefore, only an approximation and is indicative of the true values due to disregarding the horizontal component of the load.

TABLE IV

LOAD DISTRIBUTION ON OLEO-RUBBER-DISK LANDING GEAR MOUNTED ON AN F6C-4 AIRPLANE

Maximum loads in members during initial stroke of landing gear shock-absorber units

Test No.	Type of test	Loads on struts, axle, and tires in pounds: F_h	F_{tires}	F_{3-4}	F_1	F_2	F_{1a}	F_{2a}	Disk loads
27	Normal landing	1,170	2,080	440	4,170	1,920	2,930	2,970	2,220
28	Do	1,150	1,980	420	3,940	1,780	2,730	2,780	2,120
29	Do	950	1,700	360	3,400	1,560	2,430	2,470	1,810
30	Do	1,040	1,870	390	3,730	1,690	2,600	2,600	2,010
32	Two-point	1,050	1,900	400	3,870	1,800	2,730	2,770	2,030
33	Do	1,050	1,880	400	3,250	970	1,990	2,020	2,220
34	Do	1,550	2,790	590	5,060	1,790	3,260	3,310	3,190
35	Do	940	1,680	360	3,110	970	2,030	2,060	1,910
36	Pancake	1,390	2,500	530	4,960	2,240	3,460	3,510	2,670
37	Do	2,000	3,590	760	7,280	3,520	5,200	5,260	3,710
38	Do	2,030	3,640	770	7,390	3,570	5,280	5,360	3,770
39	Do	1,580	2,850	600	5,930	3,000	4,300	4,370	2,890
40	Do	1,860	3,320	700	6,690	3,170	4,750	4,820	3,470
41	Do	1,880	3,390	710	6,780	3,130	4,760	4,880	3,590

Maximum loads in members after initial stroke of landing-gear or during ground run

Test No.	Type of test	F_h	F_{tires}	F_{3-4}	F_1	F_2	F_{1a}	F_{2a}	Disk loads
22	Taxying	1,620	2,910	610	6,020	2,970	4,330	4,400	3,000
23	Do	1,500	2,690	570	5,430	2,540	3,830	3,890	2,850
24	Take-off	1,700	3,060	650	6,090	2,750	4,250	4,310	3,280
25	Do	1,600	2,880	600	5,460	2,220	3,670	3,720	3,180
27	Normal landing	1,480	2,630	550	5,260	2,420	3,690	3,750	2,800
28	Do	1,700	3,060	650	6,100	2,750	4,220	4,310	3,280
29	Do	1,270	2,280	480	4,550	2,090	3,250	3,300	2,420
30	Do	1,190	2,140	450	4,290	1,930	2,980	2,950	2,300
31	Do	1,250	2,320	490	4,820	2,380	3,450	3,520	2,400
32	Two-point	820	1,480	310	3,010	1,400	2,120	2,150	1,580
33	Do	990	1,790	370	3,070	920	1,890	1,920	2,110
34	Do	1,230	2,210	470	4,010	1,420	2,590	2,630	2,530
35	Do	1,570	2,810	590	5,190	1,620	3,400	3,450	3,190
36	Pancake	1,660	2,980	640	5,900	2,670	4,120	4,150	3,180
37	Do	1,560	2,790	590	5,770	2,740	4,060	4,110	2,890
38	Do	2,170	3,880	820	7,980	3,810	5,640	5,720	4,020
39	Do	2,070	3,720	780	7,780	3,910	5,620	5,700	3,770
40	Do	2,190	3,910	820	7,870	3,780	5,580	5,660	4,060
41	Do	1,820	3,280	690	6,550	3,030	4,600	4,670	3,470

F_h is the tension in the axle due solely to the tendency of the side struts to move outward. The tension due to bending is not included.

F_{tires} is the maximum load on one tire during the portion of the landing test as noted.

F_{3-4} the tensile load on the center V struts. In this determination no side load was considered. The maximum loads as given are due solely to the downward load of the axle.

F_1 compressive load in the forward side strut above the bridge supporting the oleo piston.

F_2 tensile load on rear side strut above oleo-piston bridge support.

F_{1a} compressive load on forward side strut below oleo piston support.

F_{2a} tensile load on rear side strut below oleo-piston support.

NOTE.—In the above tabulation only the vertical loads on the tires were considered. The values as given are, therefore, only approximate and indicative, as the horizontal component has not been considered.