REPORT No. 99

ACCELERATIONS IN FLIGHT

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
GOVERNMENT PRINTING OFFICE
1921

REPORT No. 99

ACCELERATIONS IN FLIGHT

By F. H. NORTON and E. T. ALLEN
Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

NOTE.—This report was prepared for the Bureau of Construction and Repair, Navy Department, and is published by permission of the Chief Constructor, U. S. Navy

15768—21

REPORT No. 99.

ACCELERATIONS IN FLIGHT.

F. H. Norton and E. T. Allen, National Advisory Committee for Aeronautics.

INTRODUCTION.

This work on accelerometry was carried out at the Langley Field Station of the National Advisory Committee for Aeronautics at the request of the Bureau of Construction and Repair, United States Navy, for the purpose of obtaining the magnitude of the load factors in flight and to procure information on the behavior of an airplane in various maneuvers.

When an airplane is flying on a straight and level course a spring scale with a 1-pound weight attached to it would record 1 pound. If, however, the plane is put into a turn or a zoom the scale will no longer record 1 pound, but may record 2 or even 3 pounds—that is, the apparent weight of objects on the airplane have increased two or three times. Should the control be suddenly pushed forward to nose the plane over, the spring scale may read zero—that is, an object on the plane would have no weight. When a spring scale is used in this way the pound graduations on the scale represent accelerations in terms of the acceleration of gravity g, which is in English units about 32 feet per second per second.

If the average loading of the wings is 10 pounds per square foot in level flight, during a maneuver in which the spring scale reads 3 the wings would then be carrying a load of 30 pounds per square foot. The readings of the accelerometer therefore give the loads that the airplane structure must undergo during a maneuver and also the load that the pilot and passengers experience. Every flier knows that he is pushed down into his seat during a tight spiral, for instance, and it is almost impossible to stand up or lift the feet from the floor. During violent stunts a 180-pound man may increase in weight to as much as 800 pounds.

The accelerometer records are of value to the designer, as they show him what stresses the airplane structure undergoes and how long these stresses last. The records also show clearly the pilot's ability, especially in stunts and in landings, so that an accelerometer should be an excellent means of examining a flier, as it gives a clear and unbiased record of his handling of a machine.

DESCRIPTION OF INSTRUMENT.

As the spring scale and weight described above would be undamped and would have such a long period that the shorter vibrations would not be recorded, an instrument working on the same principle was built, but having a much higher period and means for recording the accelerations on a moving film. The instrument consists mainly of a flat steel spring supported rigidly at one end, so that the free end may be deflected by its own weight from its neutral position by any acceleration acting at right angles to the plane of the spring. This deflection is measured by a very light tilting mirror, caused to rotate by the deflection of the spring, and thus reflecting a beam of light onto a moving film, giving an accuracy of about 0.01 g. The essential portions of this instrument are shown in Fig. 1 and photographs of it in Figs. 2 and 3.

The motion of the spring is damped by a thin aluminum vane, which vibrates with the spring between the poles of an electric magnet, and the amount of damping can be varied by altering the current passing through the magnet. The source of light consists of a low-voltage tungsten lamp very similar to a flash-light bulb, the image of its filament being focused after reflection from the mirror onto the moving film. This film is driven at constant speed by a governor-controlled clock having an electric brake for starting and stopping at a distance. In order to determine the constancy of the clock under accelerations it was mounted on a whirling arm and its rate was measured at several speeds of the whirling arm. In Fig. 4 is shown a curve of speed variation plotted against acceleration. It will be noticed that the point at zero g is shown considerably above the curve, this being due to the fact that the clock was tested on its side, giving zero g along the vertical axis but not along the horizontal axis, as it should be to make all parts weightless. By careful design of the governor it should be possible to keep the speed of the clock constant within 1 per cent under any acceleration that would occur in an airplane. A photograph of the clock is shown in Fig. 5. The natural period of the instrument is 70 vibrations per second, which is high enough to be above any motor vibrations that could occur, and yet a deflection of $\frac{3}{4}$ inch is obtained on the film for an acceleration of 1 g. In order to give a reference line from which to measure accelerations a second mirror is fixed in such a way that it reflects a steady beam of light on the film at the position of zero g.

In order to test the performance of the instrument it was mounted on a whirling arm having a horizontal axis. Upon rotating the arm the accelerations on the instrument changed through a range of 2 g. for each revolution, thus tracing a sine curve, the height of its medium line depend-

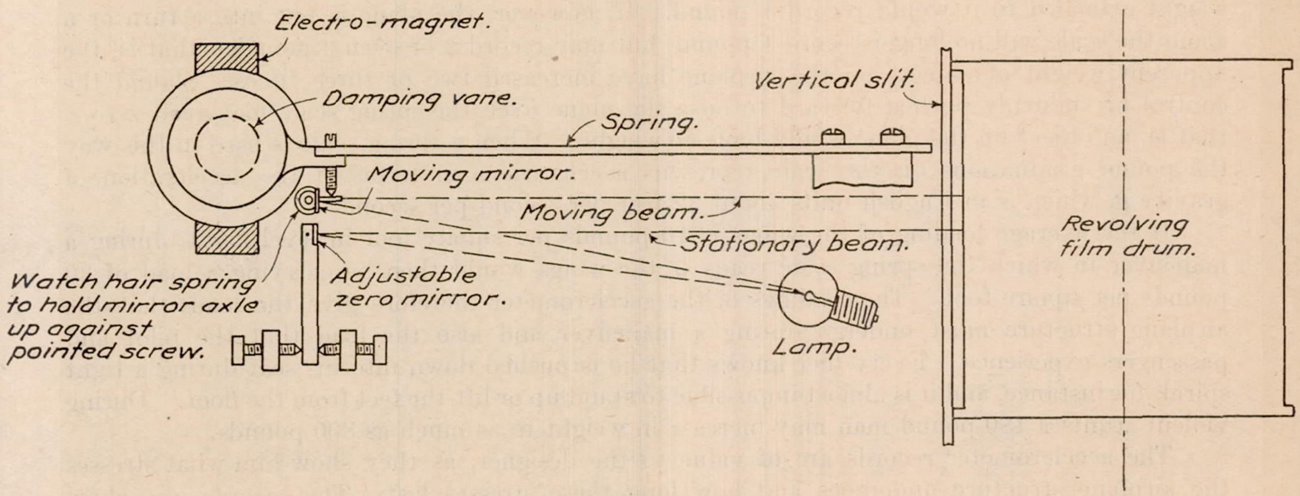

FIG. 1.

ing on the rate at which the whirling arm was revolved. A record taken in this way is shown in Fig. 26. It will be noticed that the curve is very smooth and with practically no instrumental vibrations. In order to test the instrument for vibrations of a high period, a rocking platform was constructed that could be oscillated at any frequency or amplitude by means of cams. The accelerometer was fastened to the table of this oscillator and a record taken as shown in Fig. 28. As one cam had a slight lead on the other there was a sharp knock experienced once every revolution, thus causing excessive vibration in the accelerometer record. The instrument was then mounted on about 1-inch of sponge rubber and another record taken in the same way, except that the film was run at a slightly greater speed, in order to separate the vibrations more clearly. This record is shown in Fig. 29, and it will be seen that the smaller vibrations are almost completely damped out by the rubber.

After the laboratory tests on the instrument were satisfactorily completed, it was mounted in the JN-4H airplane, on a sponge rubber mounting, which isolated it from the vibrations of the fuselage. The instrument was mounted in the front cockpit and was within a few inches of the center of gravity of the machine, and two switches were wired back to the pilot so that he could start the clock or turn on the light at any time. In the other airplanes on which records were taken it was necessary to carry the instrument in the rear cockpit, which is several feet behind the center of gravity, so that the accelerations recorded on these machines were

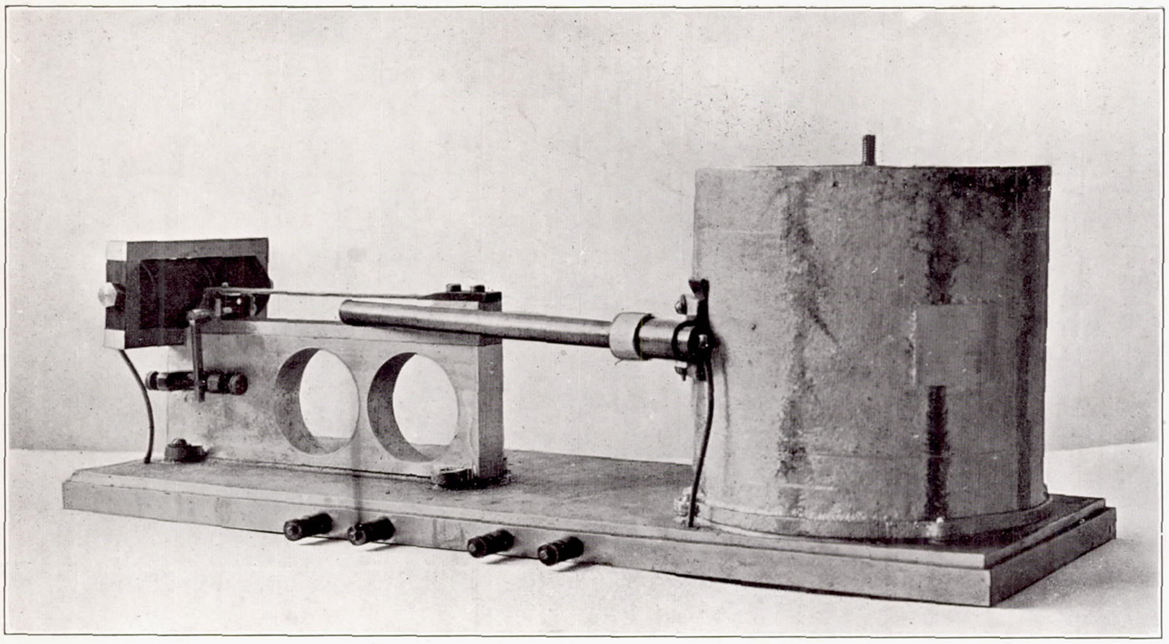

FIG. 2.—N. A. C. A. ACCELEROMETER WITH COVER REMOVED.

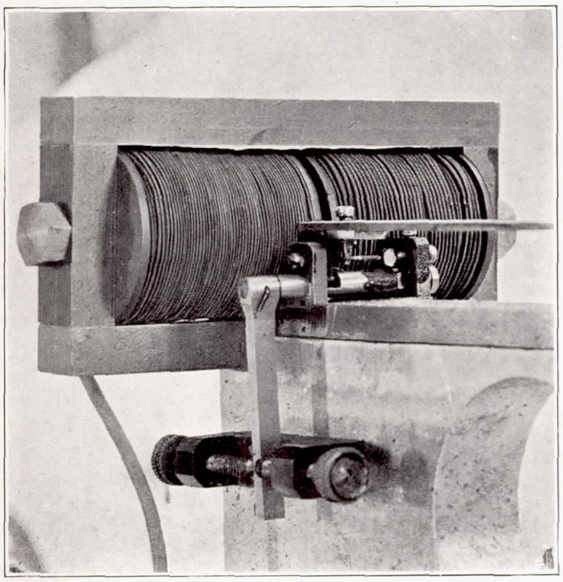

FIG. 3.—DETAIL OF MIRRORS AND DAMPING MAGNETS.

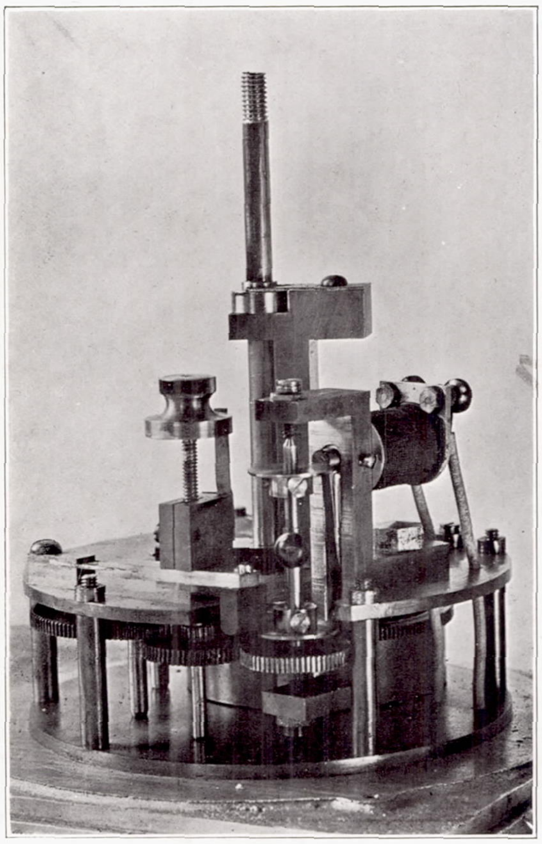

FIG. 5.—ACCELEROMETER CLOCK.

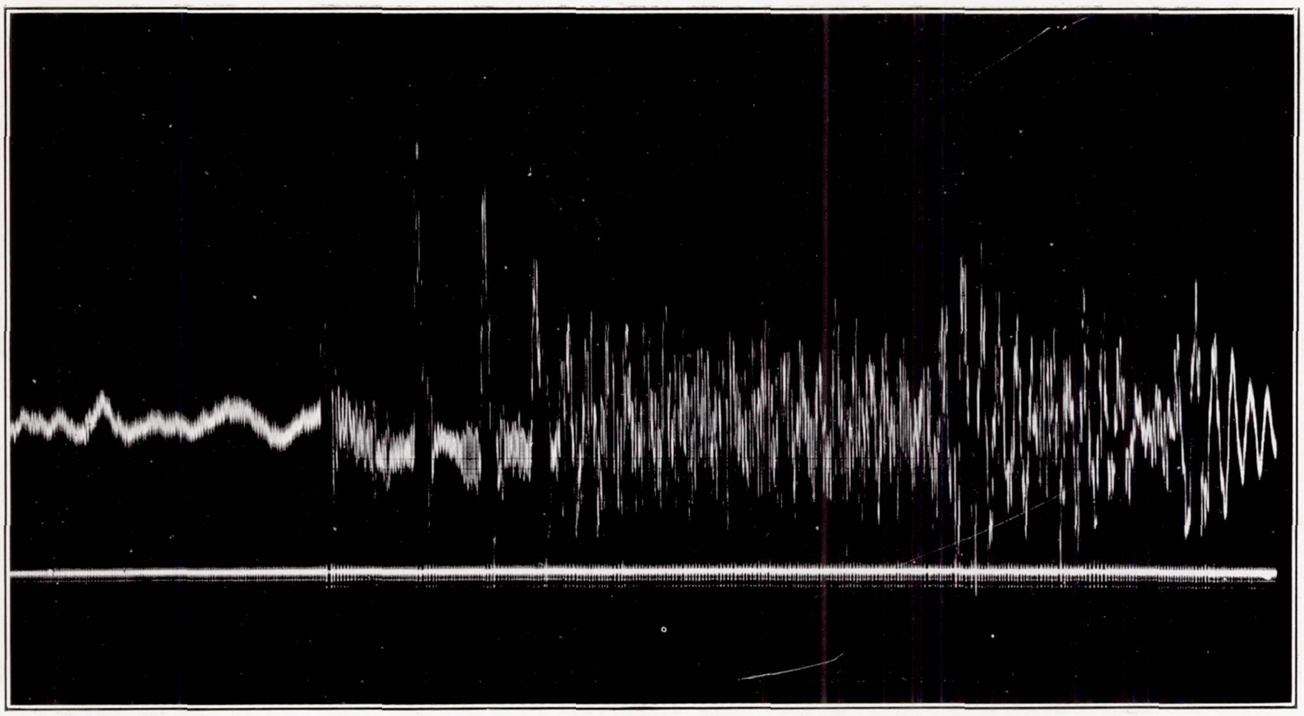

FIG. 6.—LANDING, JN4H, TAIL HIGH AND LITTLE LEVELING OFF. THE PROPELLER WAS NOT REVOLVING. THE MACHINE HAD PRACTICALLY STOPPED ROLLING AT END OF THE RECORD. MAXIMUM ACCELERATION IS 5.25 G.

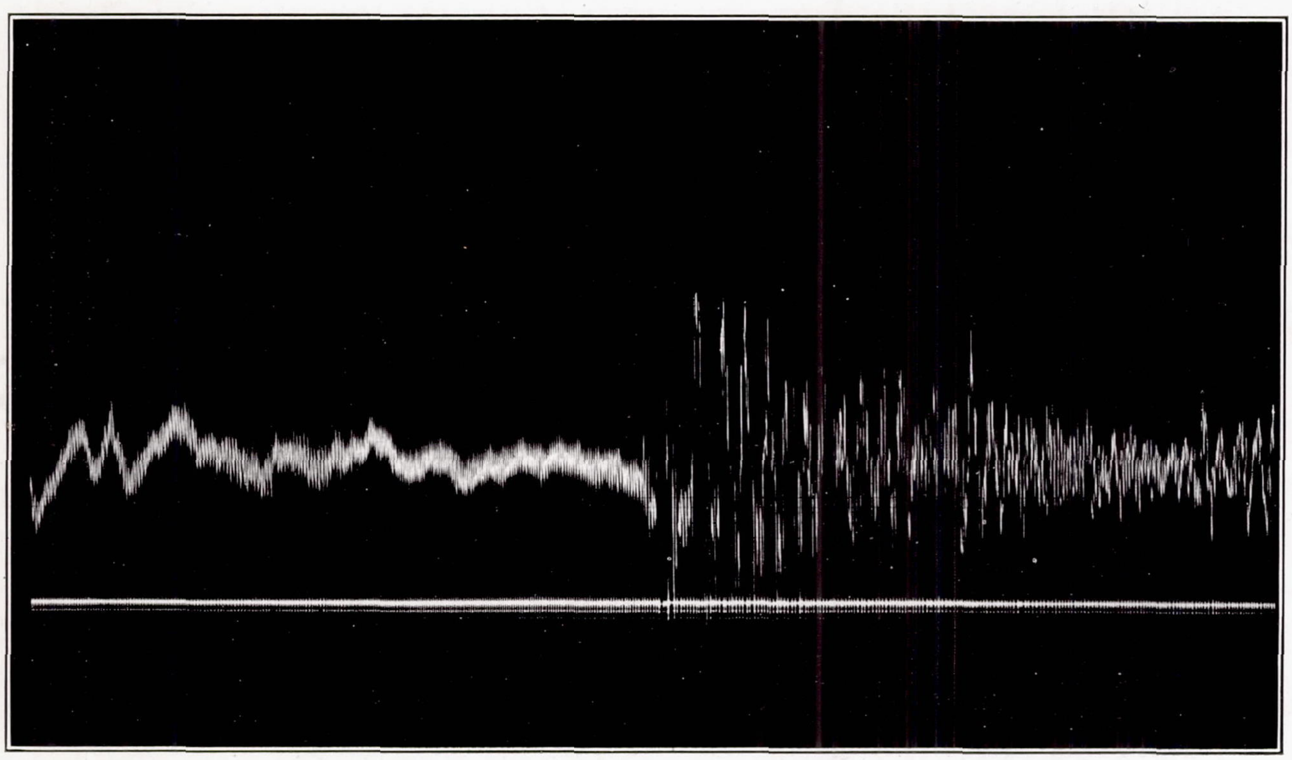

FIG. 7.—LANDING, JN4H, PANCAKED ABOUT 4 FEET. QUITE ROUGH. MAXIMUM ACCELERATION IS 4.95 G.

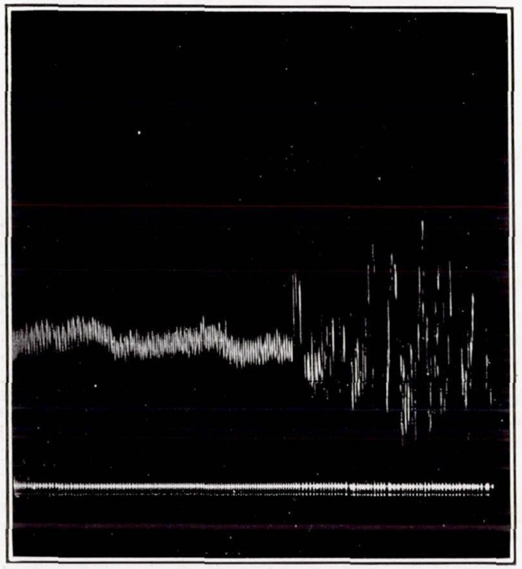

FIG. 8.—LANDING, JN4H, THREE POINT, QUITE SMOOTH. MAXIMUM ACCELERATION IS 2.20 G.

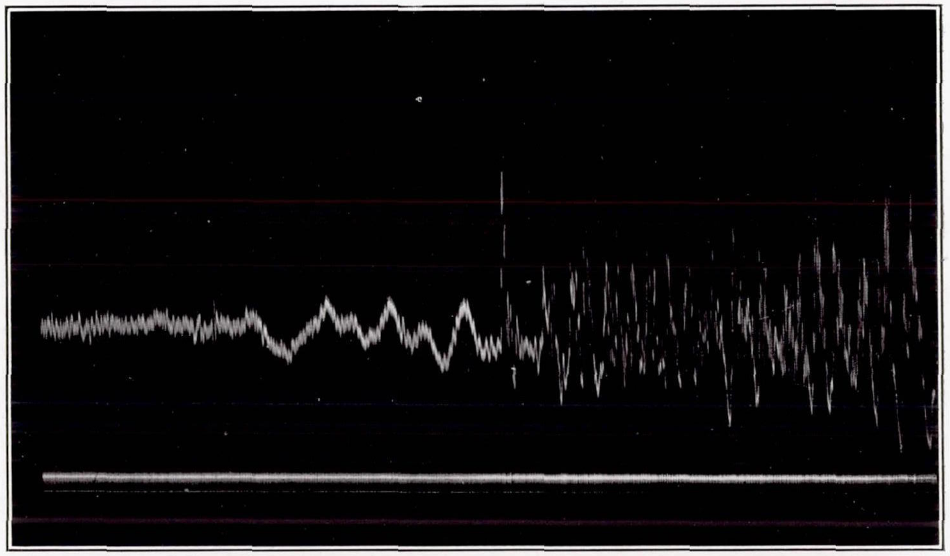

FIG. 9.—LANDING, DH4B, SMOOTH. MAXIMUM ACCELERATION IS 2.56 G.

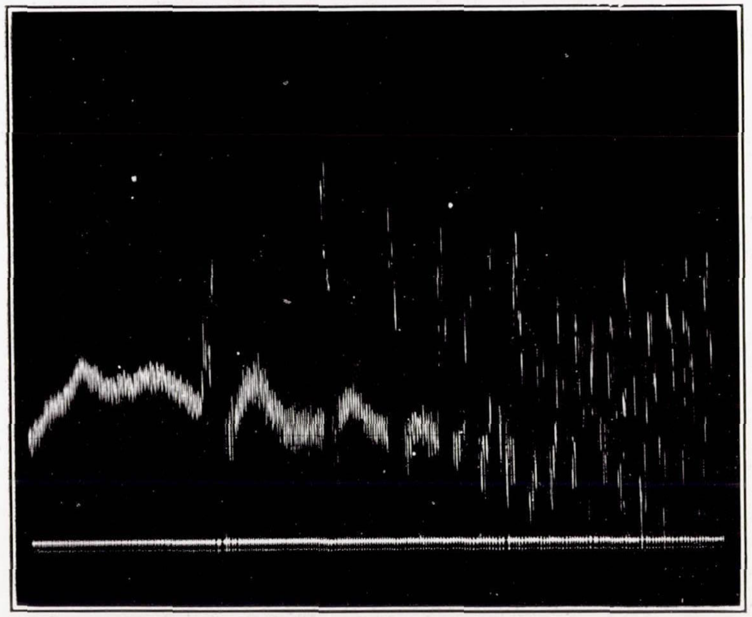

FIG. 10.—LANDING, JN4H, TAIL HIGH, BUT NOT VERY ROUGH. MAXIMUM ACCELERATION IS 3.14 G.

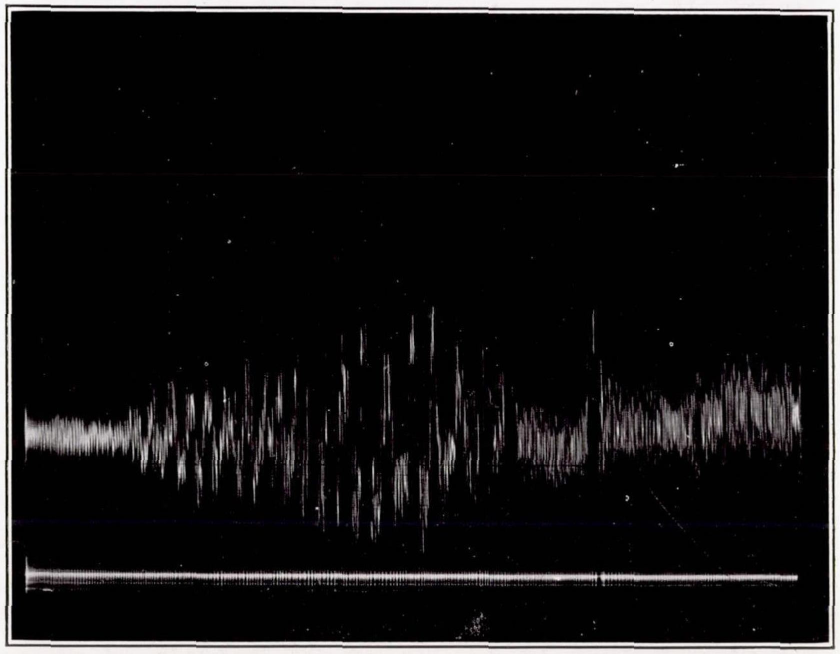

FIG. 11.—TAKE OFF, JN4H. FAIRLY SMOOTH GROUND, LAST BOUNCE MADE PURPOSELY, GIVING AN ACCELERATION OF 3.78 G.

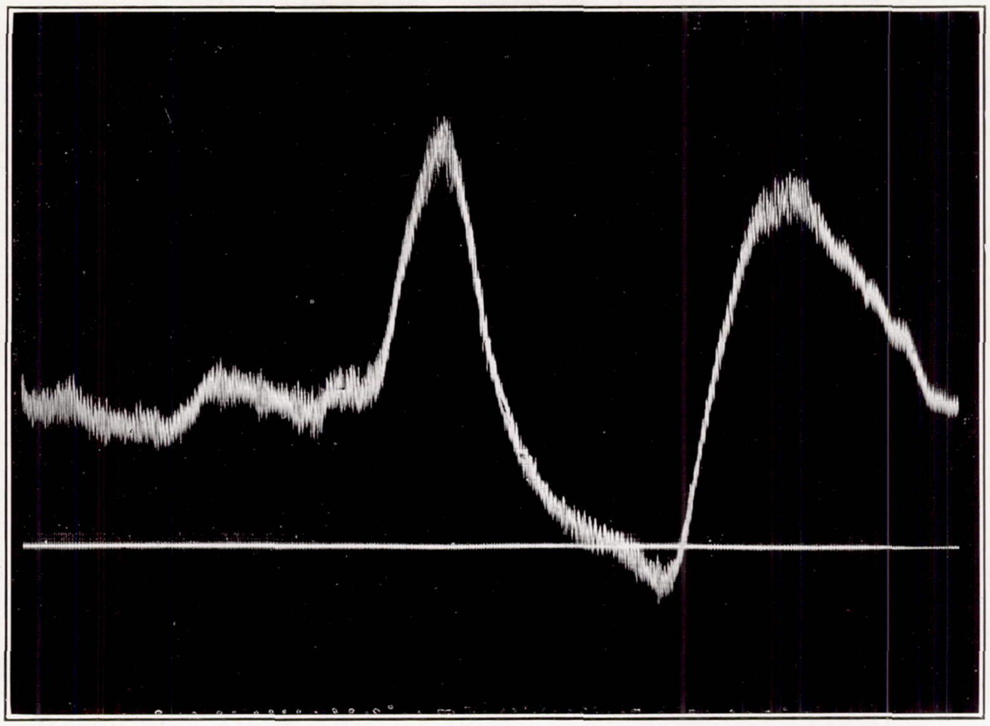

FIG. 12.—LOOP, JN4H. AIR SPEED AT START WAS 72 M. P. H. QUICK PULL UP, STALLED AT THE TOP AND FELL OUT SIDEWAYS. FIRST MAXIMUM IS 3.21 G. AND SECOND IS 2.75 G.

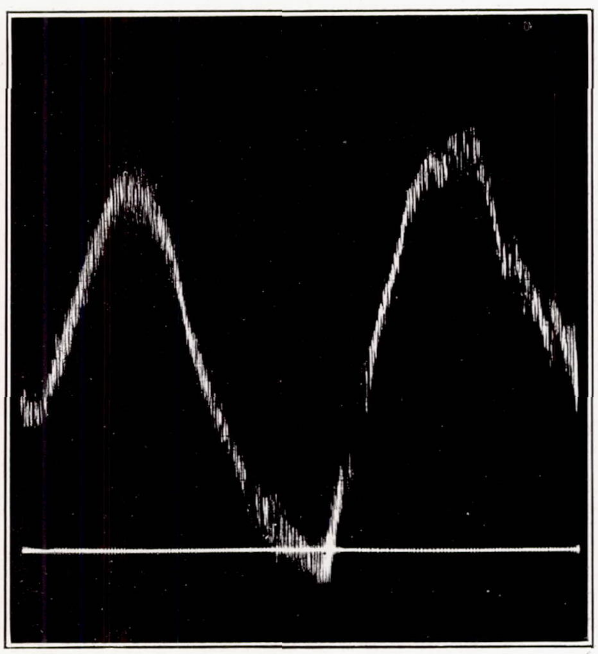

FIG. 13 —LOOP, JN4H. THE AIR SPEED AT START WAS 75 M. P. H., HUNG AT TOP. FIRST MAXIMUM IS 2.85 G. AND SECOND IS 3.22 G.

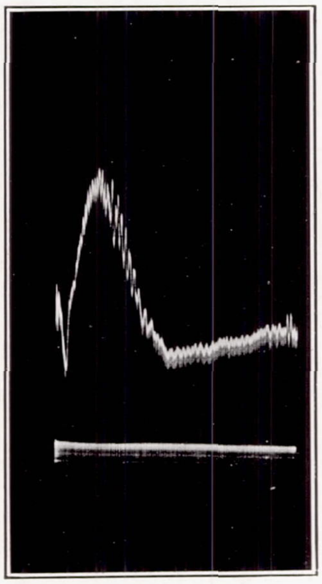

FIG. 14.—STICK PULLED BACK AS SUDDENLY AS POSSIBLE ON THE DH4B AT 75 M. P. H. MAXIMUM ACCELERATION IS 2.05 G.

somewhat in error, due to the effect of angular rotation of the whole machine. The records obtained begin at the left hand end of the film and run toward the right, and the film moves at the rate of 0.215 inch per second, and in all cases an acceleration of 1 g. corresponds to 0.70 inch, measured from the zero line. It will be noticed that even with the shock-absorbing rubber there is transmitted to the instrument a certain definite period of vibration from the fuselage of the plane, and that the period of this vibration is constant for any plane, no matter what the engine speed, but as the amplitude of this vibration is small it is quite easy to estimate a mean line which will represent the true accelerations on the machine as a whole. All accelerations are taken normal to the wing chord.

RECORDS OBTAINED IN FLIGHT.

Landings and take-offs.—In Fig. 6 is shown a record of a landing made in a JN–4H, with the tail high and with little or no leveling off from the glide, and it will be noticed that the first time the wheels struck the ground an acceleration of 5.25 g. was reached, then the machine bounced into the air for about two seconds, struck again with slightly less shock, and then rebounded twice more, each bounce being of shorter period and each shock of less magnitude, until the machine finally rested permanently on the ground. It is also evident that while taxi-ing even on a fairly smooth field, accelerations of as much as 2.5 g. are experienced, and a good landing will always give less acceleration than will the subsequent taxi-ing on anything except the smoothest of fields. In Fig. 7 the same machine was pancaked with a drop of about 4 feet, giving an acceleration at the time of striking of 4.95 g. and the rebound was very slight, and although this landing was intentionally made with a considerable drop it did not feel rougher than many routine landings. Fig. 8 is a record of a smooth three-point landing, where the acceleration on first striking is only 2.2 g., which is considerably less than some of the accelerations experienced shortly afterwards while taxi-ing. Fig. 9 shows a smooth landing in a DH–4B, the acceleration when first touching being only 2.56 g., representing an average landing for this type of machine. In Fig. 10 is shown a tail-high landing in a JN–4H, when the machine porpoised considerably, and three well-marked bounces are evident in the record. The maximum acceleration was 3.14 g. and the landing did not seem exceptionally heavy. Fig. 11 shows a take-off in a JN–4H over fairly smooth ground, and the last bounce was purposely made, which gave an acceleration of 3.78 g. It is quite noticeable that the vibrations of the plane when the motor is wide open on a climb are of greater amplitude, but of the same period, than when the machine is gliding.

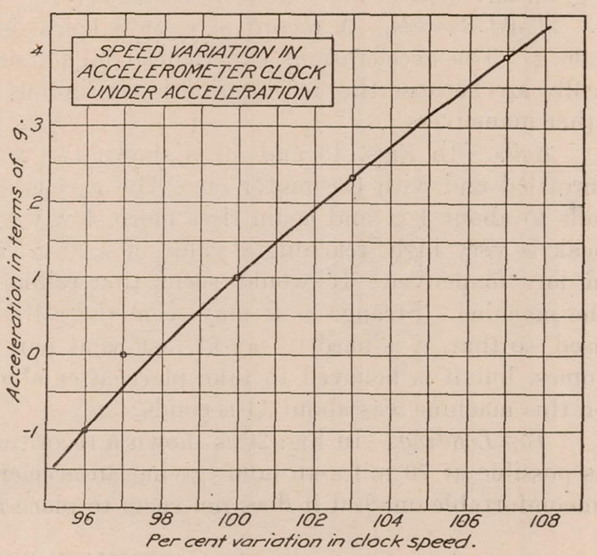

FIG. 4.—Speed variation in accelerometer clock under acceleration.

Looping.—Fig. 12 shows a slow loop with a JN–4H in which the machine fell out at the top, a slow loop usually being characterized by sharp peaks in the acceleration curve. Fig. 13 is another slow loop where the machine hung at the top, but the maximum acceleration on pulling out reached 3.22 g., due to a rather long dive at the end. Fig. 15 shows a loop started at 100 miles per hour, the machine being pulled up slowly and going over very smoothly, and the record approaches very nearly a sine curve except for the small irregularities in the last end of the record, which are believed to be due to the machine entering its own wake, as this fact is often noticed in vertical banks as well as loops. Even with the high initial speed the maximum acceleration was only 3 g. in this loop. Fig. 16 is another loop taken at 92 miles an hour. Fig. 17 is a loop made at 105 miles an hour and shows a very smooth record, although the machine was pulled around rather rapidly and a maximum acceleration of 3.68 g. was reached. The length of time taken to complete a loop in a JN-4H varied between 14 and 17 seconds, depending not so much on the air speed as on the rate at which the machine was pulled around.

Spins.—Fig. 24 is a spin in a JN-4H, which was stalled into it suddenly in order to set up the maximum amount of oscillation. These oscillations evidently tend to damp out and if the spin was continued long enough would probably disappear. At the beginning of the record the acceleration dropped below 0 g. as the machine fell off from the stall, and after the record that follows very closely a sine curve, but the period of the oscillation is not dependent on the rate of spinning—that is, one oscillation does not necessarily come in one turn of the spin. Another spin on the same machine is shown in Fig. 25, which was a much smoother spin, but the damped oscillations are still evident and an acceleration of 3.12 g. was experienced in pulling out of this spin. The oscillations are practically absent in the spin in a DH-4B (Fig. 22), damping out after the first oscillation. In the same way (Fig. 23) in a record taken of a Bristol fighter there appears to be only one oscillation, and after that the curve is quite smooth and continuous. These records show that there are no large accelerations experienced in the spin itself and unless the machine is dived rapidly in pulling out accelerations should never exceed 3 g. on any type of machine in this maneuver.

Tight Spirals.—A record of a tight spiral is shown in Fig. 21, giving an acceleration of 2.06 g. The accelerations experienced in a tight spiral seem to the pilot greater than they really are because the acceleration is continuous rather than lasting only a few seconds, as in other maneuvers.

Rolls.—In Figs. 18 and 19 is shown the record of a roll of the JN-4H with the motor throttled and with the motor on. The acceleration rises very rapidly to a sharp peak, then falls to about 1 g. and again rises more slowly to a lower peak. The acceleration in the first peak is very high, reaching a value of 4.20 g., which is the highest acceleration experienced in any maneuver. It would seem that rolling would place an exceedingly high stress on the machine. Strange as it may seem the roll is executed with the rudder, and no aileron is used, so that, it is hard to say at just what part of the maneuver the maximum acceleration comes, but it is believed to take place after about 90° of roll. The time for a complete roll on this machine was about 11 seconds.

Top Loading.—In Fig. 20 is shown a record where the stick was pushed forward as rapidly as possible at 70 miles an hour, giving an acceleration of -0.53 g. This maneuver is a very uncomfortable one but it does not seem to place much load on the plane.

SUMMARY OF RECORDS.

The following table gives the maximum acceleration found in each maneuver:

Maneuver.	Machine.	Maximum acceleration.
Porpoise landing	JN-4H	5.25 g.
Pancake, 4-foot drop	JN-4H	4.95 g.
Loop	JN-4H	3.68 g.
Roll	JN-4H	4.20 g.
Spin, maximum in pulling out	JN-4H	3.12 g.
Spin	DH-4B	2.78 g.
Do	Bristol	2.72 g.

From these figures it would seem that in no reasonable stunt would the air load ever exceed 4.5 g. A normal landing should not give more than 3 g., and a very rough landing will seldom exceed 5.5 g. It is quite possible that on a high-speed scout machine, higher loadings than these would be experienced in stunting, but the accelerometer records taken by the Bristol in mock fights show no loads in excess of 4.5 g. An attempt was made to obtain records on an S. E. 5, but the present instrument was so bulky that it had to be attached to the outside of

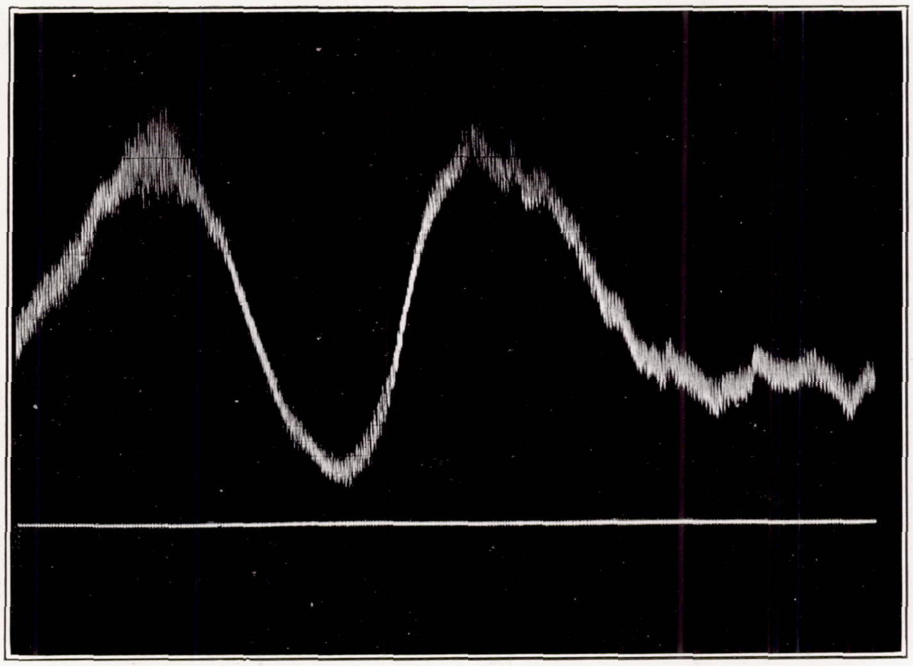

FIG. 15.—LOOP, JN4H. AIR SPEED AT START 100 M. P. H. SLOW, SMOOTH PULL UP NOTICEABLE BUMP WHEN PULLING OUT, DUE TO ENTERING OWN WAKE. FIRST MAXIMUM IS 3.00 G. AND SECOND IS 2.88 G.

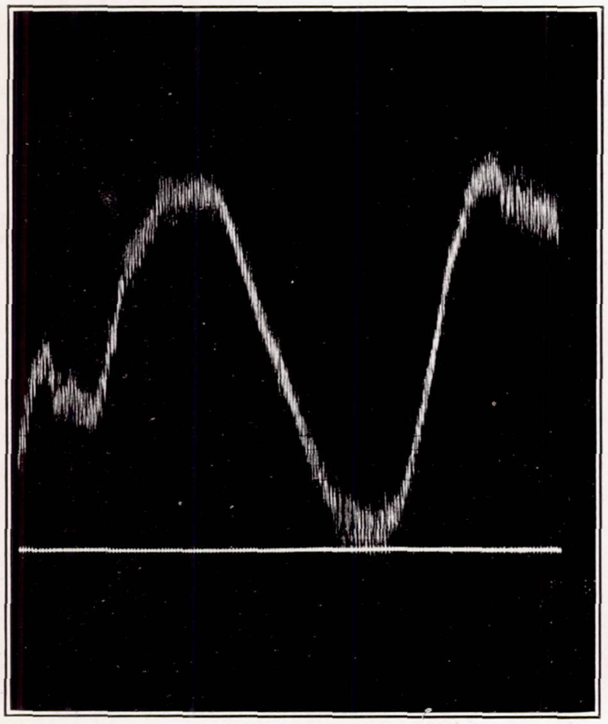

FIG. 16.—LOOP, JN4H. AIR SPEED AT START 92 M. P. H. SMOOTH ALL THE WAY AROUND. FIRST MAXIMUM IS 2.85 G. AND SECOND IS 2.97 G.

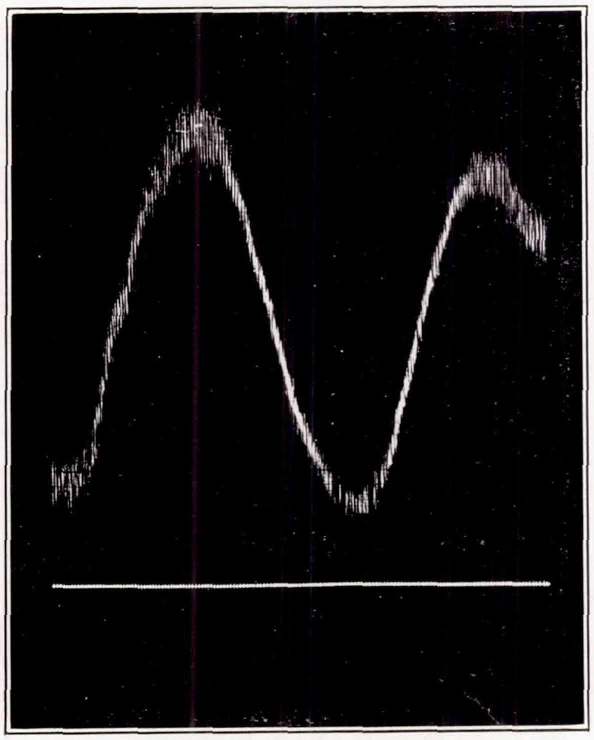

FIG. 17.—LOOP, JN4H. AIR SPEED AT START WAS 105 M. P. H. SLOW PULL UP. FIRST MAXIMUM IS 3.68 G. AND THE SECOND IS 3.26 G.

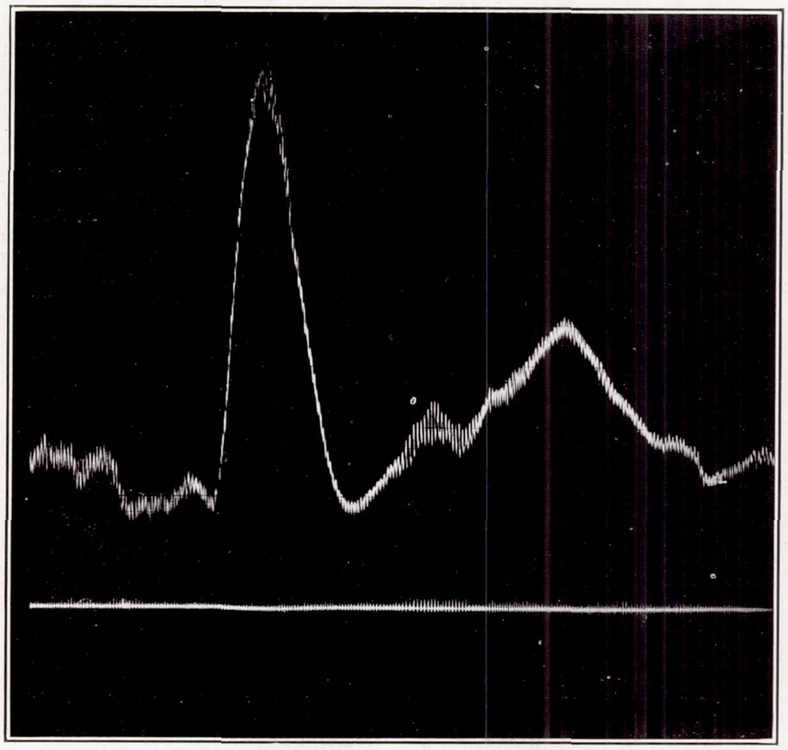

FIG. 18.—ROLL TO LEFT, MOTOR THROTTLED IN JN4H. MAXIMUM ACCELERATION IS 4.20 G., THE HIGHEST FOUND IN ANY MANEUVER. AIR SPEED AT BEGINNING WAS 100 M. P. H.

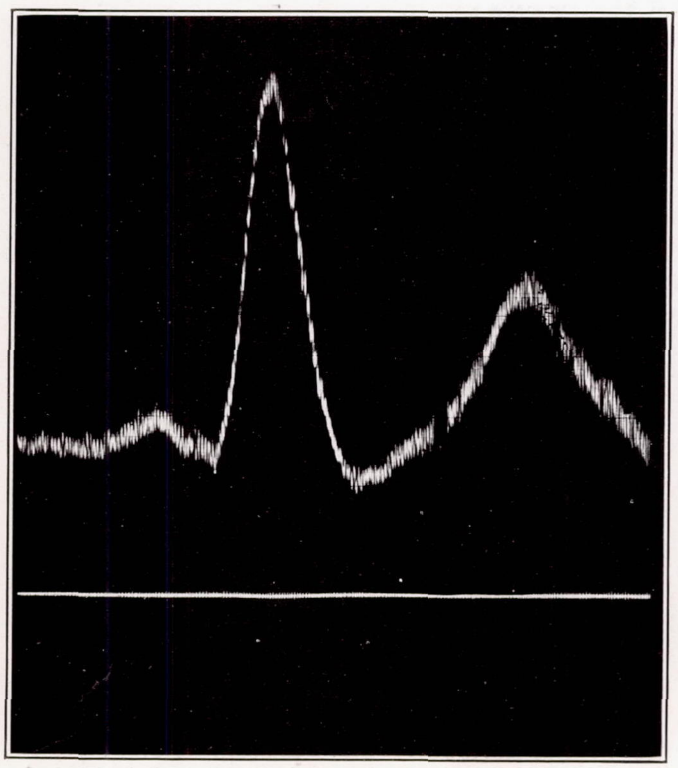

FIG. 19.—ROLL IN JN4H, TO THE LEFT. MOTOR ON. MAXIMUM ACCELERATION IS 4.15 G. AIR SPEED AT BEGINNING WAS 100 M. P. H.

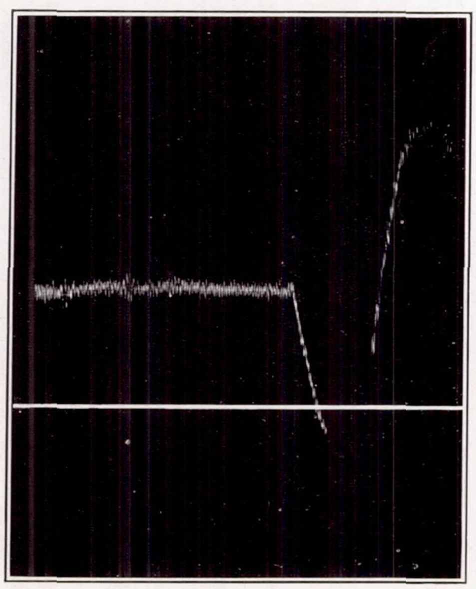

FIG. 20.—TOP LOADING JN4H, STICK PUSHED FORWARD AS QUICKLY AS POSSIBLE AT 70 M. P. H. MAXIMUM NEGATIVE ACCELERATION IS —0.53 G.

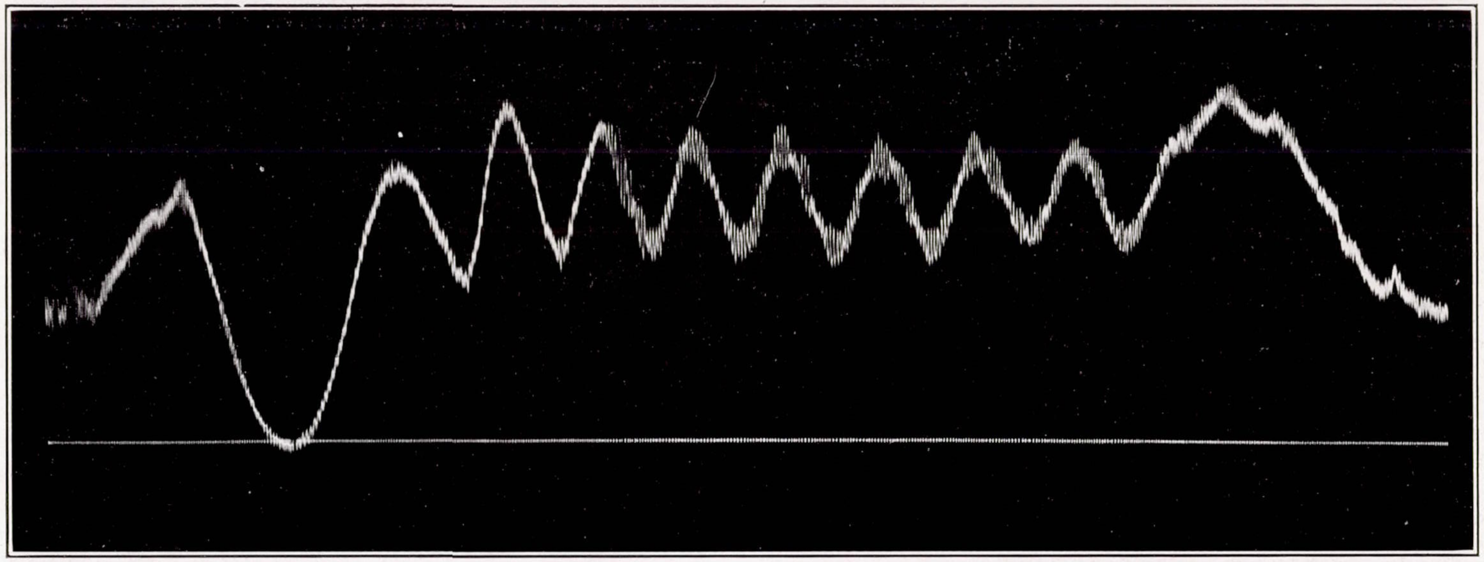

FIG. 24.—SPIN OF 9½ TURNS, JN4H. QUICK PULL UP INTO STALL, MOTOR THROTTLED. DESCENDED 1,700 FEET. MAXIMUM ACCELERATION IN THE SPIN WAS 2.57 G. AND WHEN PULLING OUT 2.70 G.

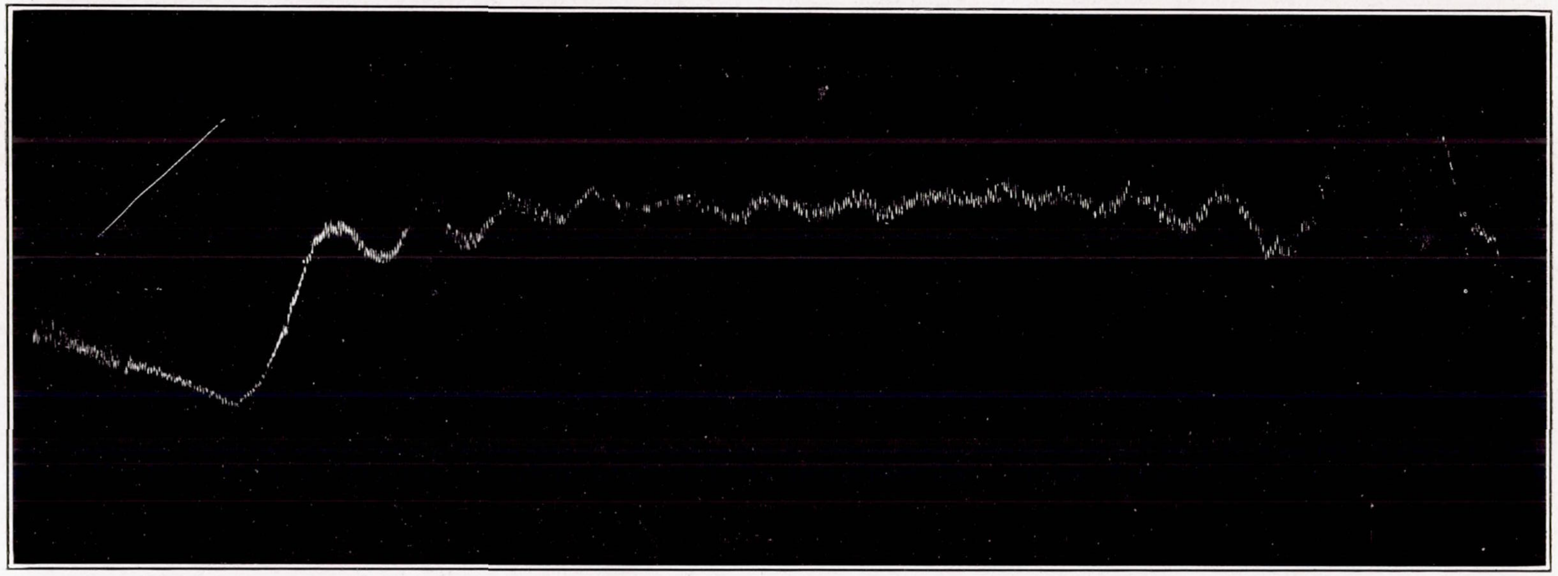

FIG. 25.—SPIN OF 7 TURNS, SMOOTH, JN4H. MAXIMUM ACCELERATION IN THE SPIN IS 2.21 G. AND IN PULLING OUT 3.12 G.

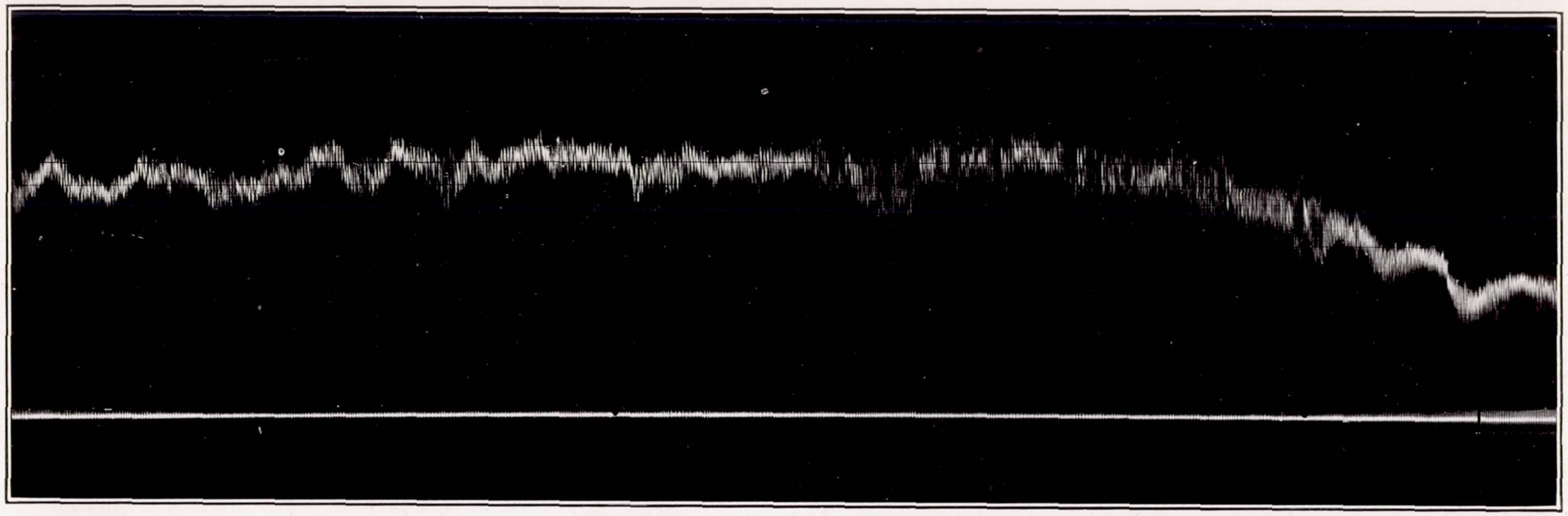

FIG. 21.—TIGHT SPIRAL, MOTOR ON JN4H. MAXIMUM ACCELERATION IS 2.06 G.

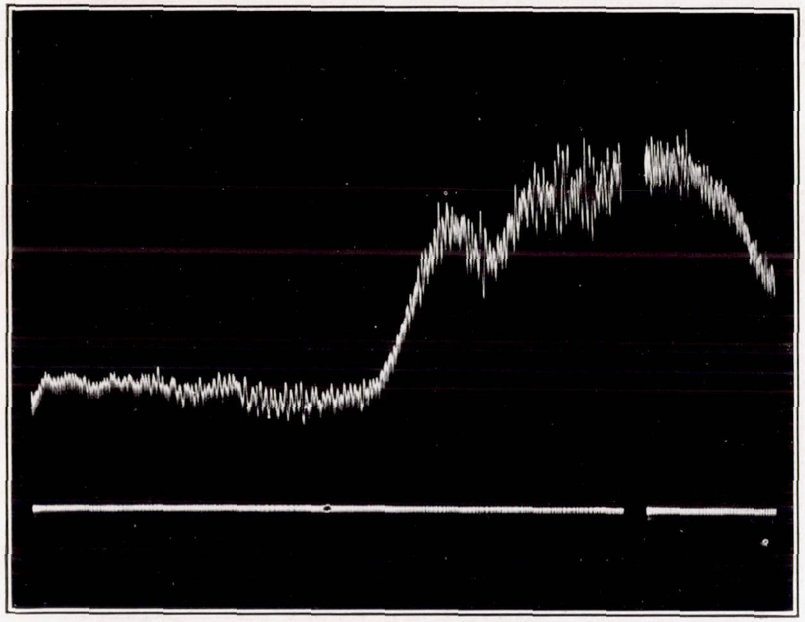

FIG. 22.—SPIN, DH4B, SMOOTH. MAXIMUM ACCELERATION IS 2.78 G. AS THE SPIN WAS A LONG ONE, THE FILM WAS STOPPED FOR A SHORT TIME IN THE MIDDLE OF THE SPIN.

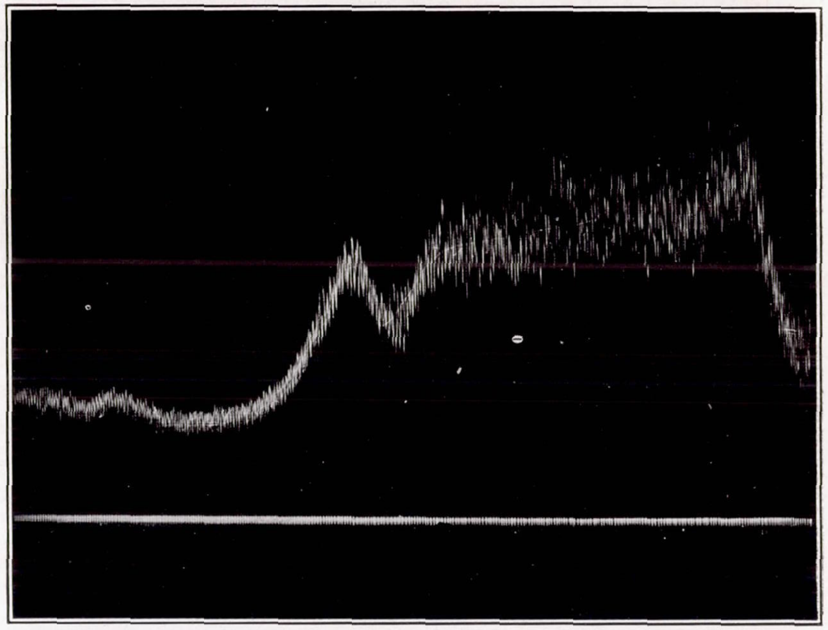

FIG. 23.—SPIN, BRISTOL FIGHTER (ENG.) MOTOR THROTTLED. THE MACHINE CAME OUT OF THE SPIN ITSELF. MAXIMUM ACCELERATION IS 2.72 G.

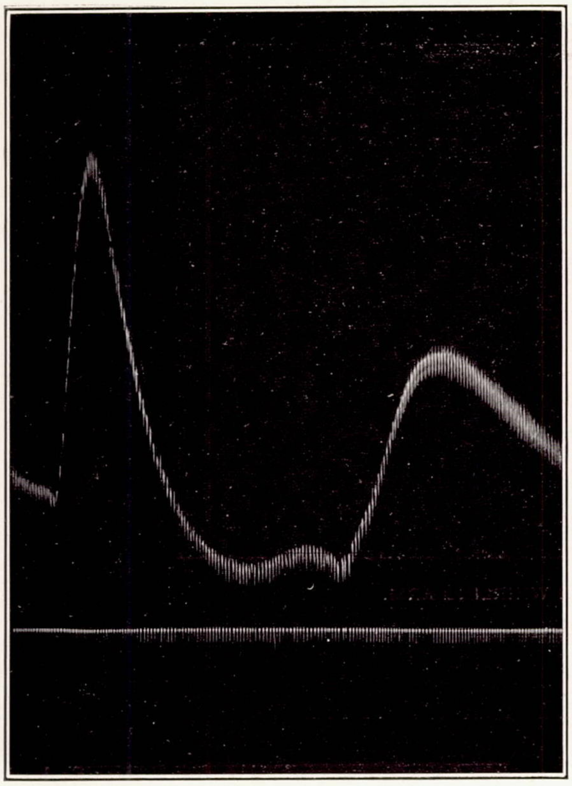

FIG. 30.—STICK PULLED BACK SUDDENLY AT 80 M. P. H. ON JN4H. MOTOR THROTTLED. MAXIMUM ACCELERATION IS 3.52 G.

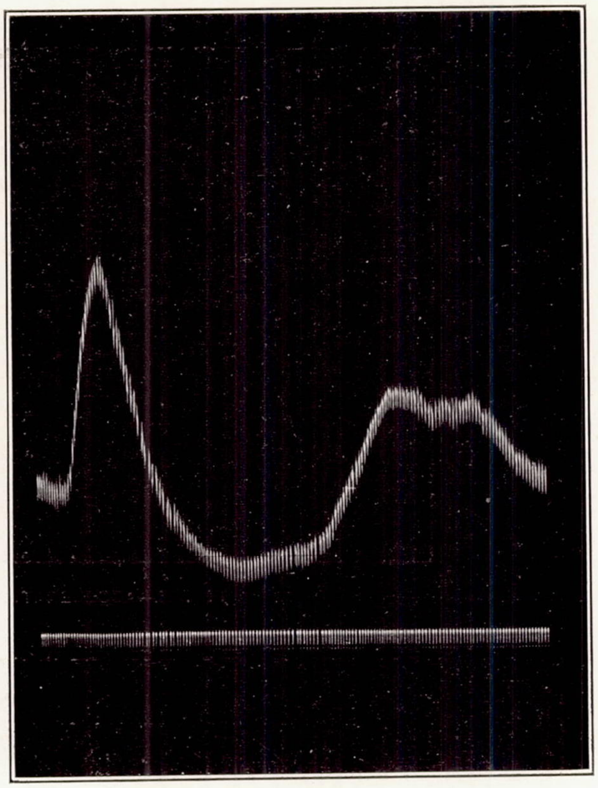

FIG. 31.—STICK PULLED BACK SUDDENLY AT 70 M. P. H. ON JN4H. MOTOR THROTTLED. MAXIMUM ACCELERATION IS 2.76 G.

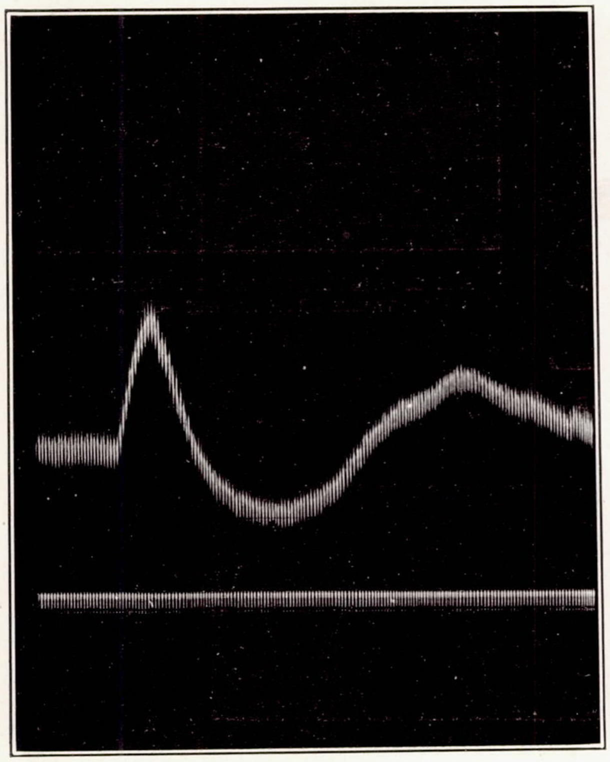

FIG. 32.—STICK PULLED BACK SUDDENLY AT 60 M. P. H. ON JN4H. MOTOR THROTTLED. MAXIMUM ACCELERATION IS 2.01 G.

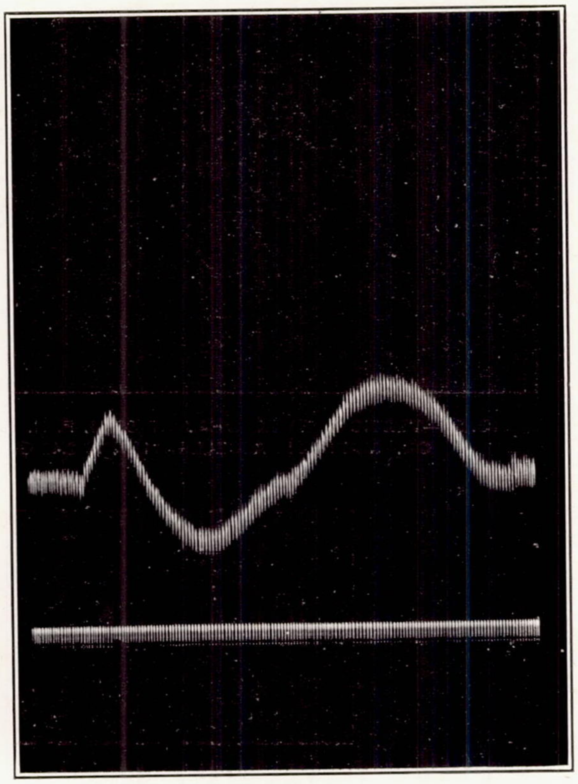

FIG. 33.—STICK PULLED BACK SUDDENLY AT 50 M. P. H. ON JN4H. MOTOR THROTTLED. MAXIMUM ACCELERATION IS 1.46 G.

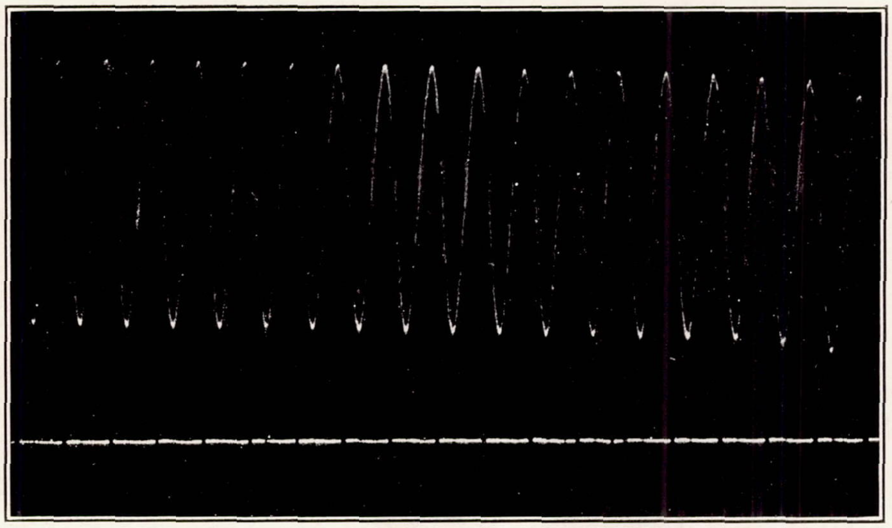

FIG. 26.—ACCELERATIONS ON WHIRLING ARM.

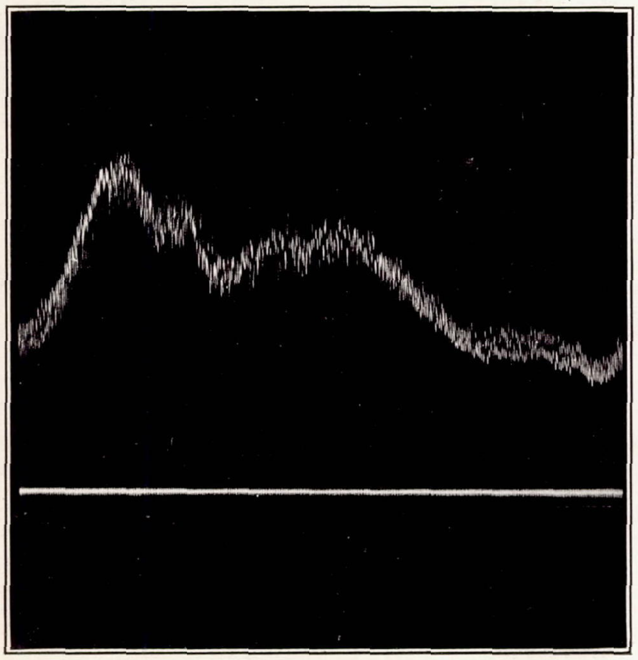

FIG. 27.—VERTICAL BANK, DH4B AT 95 M. P. H. MOTOR ON. MAXIMUM ACCELERATION IS 2.42 G.

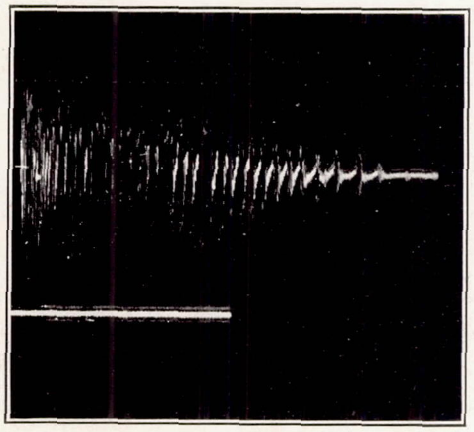

FIG. 28—ACCELERATIONS ON ROCKING TABLE WITH NO RUBBER.

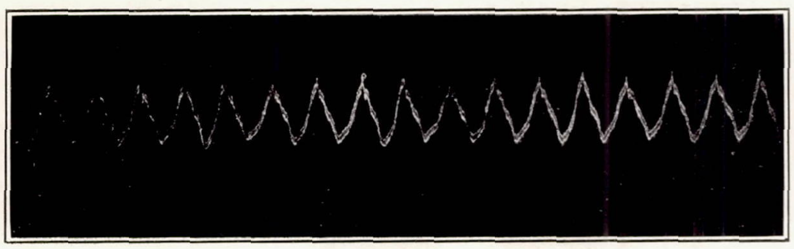

FIG. 29.—ACCELERATIONS ON ROCKING TABLE WITH SPONGE RUBBER UNDER INSTRUMENT.

the fuselage, and although it was partly protected from the propeller blast, the vibrations set up were so great as to obscure the record. A much smaller instrument of the same type is now being constructed and it is hoped to get records on a machine of this type in the near future.

ACCELERATIONS IN PULLING OUT OF A DIVE.

In Figs. 30 to 33 are shown the records obtained when pulling back as suddenly as possible on the stick of a JN–4H at 50, 60, 70, and 80 miles per hour. The records show that the same time elapses for reaching the maximum acceleration regardless of the speed of the plane, and that this maximum is reached approximately 0.85 second after the stick is pulled back. Accelerations obtained from these records are plotted in Fig. 34 against the air speed of the plane, and to check them up a second set of runs were taken under the same conditions and their values plotted on the same curve, and the coincidence of the points is excellent. On the same sheet is also a curve of theoretical accelerations that would be experienced if the plane was instantly turned to its angle of maximum lift without losing any speed. This theoretical curve, as would be expected, lies slightly above the experimental curve, but the difference between the curves is much less than would be supposed, so that the stresses determined from theoretical considerations should give very closely the true accelerations when the controls are suddenly pulled back at any speed. By extending the experimental curve to higher speeds, which can certainly be done with very little error, it is possible to estimate the exact loading experienced in pulling out of a dive at any speed. It was not thought advisable to carry the experimental points up to any higher speeds with the machine at hand although it probably would have stood a loading as high as 8.

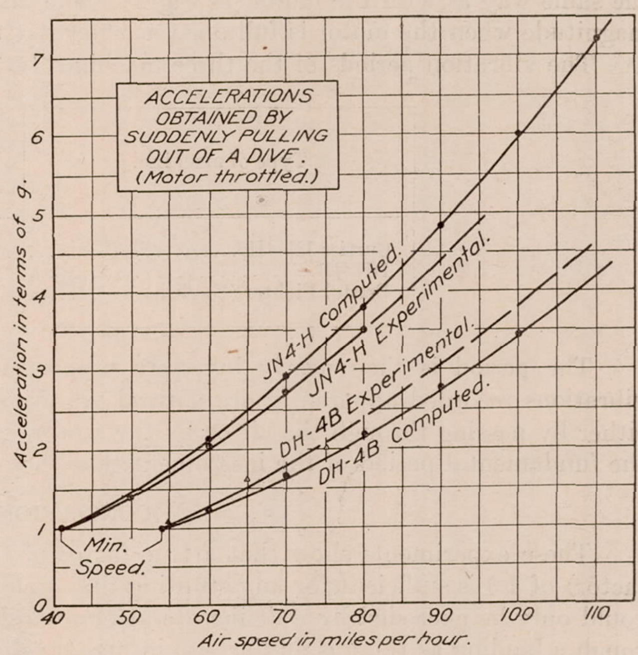

FIG. 34.—Accelerations obtained by suddenly pulling out of a dive (motor throttled).

A similar set of readings was taken in a DH–4B and one record is shown in Fig. 14, but as it was necessary to place the instrument at a considerable distance behind the center of gravity there was a considerable negative acceleration at the instant of pulling back the stick due to the angular acceleration of the whole machine. For this reason it is probable that the maximum acceleration obtained is not correct. The points, however, are plotted in Fig. 34 along with the theoretically determined curve, and the points lie slightly above the theoretical curve instead of below it as they should. This may be due to a wrong estimate of the minimum speed of the plane, as no careful performance tests have been made with this plane as they have with the JN–4H, or it may be due to an error caused by the angular acceleration of the machine. At any rate these tests seem to show conclusively that the loads determined in pulling out of a dive at any speed, from the assumption that the machine is instantly turned up to its maximum angle before losing any forward speed, will give the loads very closely to those actually experienced in flight.

Assuming that the limiting velocity of the JN–4H is 150 M. P. H., the theoretical maximum load in pulling out suddenly would be 14 g., but from the exterpolated experimental curve it would be only 12.5 g., and even this figure would be too high, as the pilot would relax his pressure on the stick to a considerable extent before reaching this acceleration.

If the designer could be assured that a machine would never experience an acceleration above a certain fixed limit, he could design his machine so that it would not carry any excess weight in the structure, thus greatly increasing the machine's efficiency. It would seem possible to make a device consisting principally of a weight on a spring that would nose the machine over whenever it underwent more than a certain acceleration. In other words, it would act as a safety valve for the airplane structure.

MACHINE VIBRATIONS.

It is noticeable from the records that whenever the wheels are free from the ground the machine has a certain vibration. It would naturally be supposed that this vibration is wholly due to the motor, and would vary in period as the motor speed is changed. A careful examination of the records shows, however, that the vibration for a given machine is nearly constant in period no matter what the motor speed. In fact, on one occasion the machine was glided for a considerable time with a dead stick and the vibrations persisted in exactly the same way as with the motor on Fig. 6. The vibrations are, however, of somewhat greater magnitude when the motor is full open as shown at the end of Fig. 11.

The vibration periods of the three machines tested are approximately as follows:

Type of machine.	Approximate weight (pounds).	Frequency of vibration.
Curtiss JN-4H	2,000	17.0
DH-4B	3,600	8.6
Bristol Fighter (English)	3,000	10.2

The period is then nearly inversely proportional to the weight of the machine. The vibrations recorded apparently are natural vibrations of the airplane structure, being excited either by passing through the air or by the motor. These vibrations are so much slower than the fundamental period of the instrument that they can not be accounted for in that way.

CONCLUSIONS.

These experiments show that a true factor of safety in the air (exclusive of the material factor) of 4.5 is sufficient for any stunting that would ordinarily occur in flight, and this value could only be exceeded by a deliberate attempt to break the machine. The load factor in as rough a landing as there is any excuse in making should not exceed 5, but no definite rule can be laid down, the landing loads being dependent on the condition under which the machine ia used. The accelerometer record is an excellent indication of the pilot's skill and should find extensive use in examining fliers. Smaller and lighter instruments are now being built, and accelerations will be recorded along all three axes of the airplane, as well as the angular accelerations about the center of gravity. The theory of the accelerometer will be taken up in a subsequent report.

○