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RESEARCH MEMORANDUM

VERTICAL AND DRAG GROUND-REACTION FORCES DEVELOPED IN LANDING IMPACTS OF A LARGE AIRPLANE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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VERTICAL AND DRAG GROUND-REACTION FORCES DEVELOPED IN LANDING IMPACTS OF A LARGE AIRPLANE

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SUMMARY

Tests were conducted on a large bomber-type airplane to determine the ground reactions imposed on the landing gear under actual landing conditions. The program covered landings made at vertical velocities up to 8.5 feet per second and forward speeds at contact from 95 to 120 miles per hour. Landings were made on both wet and dry concrete runways. Results are presented of the effects of vertical velocity at contact and the effects of runway surface condition (wet and dry) on the vertical and drag ground reactions obtained during the landing impact.

INTRODUCTION

In recent years, considerable interest has arisen in the problem of obtaining a more rational understanding of the ground-reaction forces applied to the airplane in landing and taxiing because of structural failures that have arisen from these forces. Prediction of the dynamic structural forces causing these failures is possible by use of existing dynamic-analysis methods, but the methods require knowledge of the forcing functions, that is, of the ground-reaction forces. At present, only a limited amount of reliable experimental results defining the ground-reaction forces under actual flight conditions or under conditions duplicating flight conditions is available.

An experimental investigation has therefore recently been conducted on a large bomber-type airplane to obtain information, applicable to large airplanes, on the ground reactions imposed on the landing gear under actual landing conditions. The investigation included study of the interrelations of the ground reactions, as well as the relationship of the ground reactions to landing-approach conditions and to landing-gear and airplane characteristics.

The results presented in the phase of the investigation reported herein are limited to the effects of vertical velocity and the effects of surface condition (wet and dry) on the vertical and drag ground reactions obtained during the landing impact.

TESTS AND INSTRUMENTATION

The test program covered landings of a large bomber at vertical velocities ranging up to 8.5 feet per second and forward speeds at contact from 95 to 120 miles per hour with various drift and roll attitudes at contact at two airplane weights. Most of the landings were made on dry concrete, but in one flight six landings were made on a runway wetted down by fire hoses to simulate a heavy rain.

A complete list of the quantities measured for the purpose of defining both the landing-approach conditions and the impact and spin-up phenomena is tabulated, as follows:

Approach

Center-of-gravity acceleration
Airspeed
Pitch attitude
Pitching velocity
Roll attitude
Rolling velocity
Yaw angle
Yawing velocity
Drift angle
Pilot's control motions

Impact

Wheel vertical reaction
Wheel drag reaction
Truck side reaction
Truck yawing moment
Truck vertical velocity
Tire deflection
Wheel rotational velocity
Oleo displacement
Nose-gear trail angle

The present paper is limited to the vertical and drag ground-reaction results obtained on the main wheels of the landing gear.

Figure 1 illustrates the general arrangement of one of the dual-wheel main landing-gear trucks of the airplane with one of the wheels removed. The weight of the airplane for these tests was approximately 100,000 pounds, necessitating a tire pressure of about 75 pounds per square inch in the 56-inch-diameter tires. The shock strut shown has an overall telescoping action of 12 inches. Also illustrated is the instrumentation pertinent to the results given in this paper. The dynamic vertical and drag reactions imposed on each wheel during the landing impact and wheel spin-up were obtained from measurements made with the strain gages and linear accelerometers shown. As a check, the drag reaction was also obtained on one wheel (from consideration of the torque applied to the wheel by the drag reaction) by means of measurements of wheel rotational acceleration and measurements of tire deflection with the trailing arm shown. The trailing arm included instrumentation to give the vertical velocity of the truck at instant of contact. The rotational speed of each wheel was determined by a tachometer fastened to the outer brake shoe and geared to the wheel.

RESULTS AND DISCUSSION

Vertical and Drag-Reaction Time Histories

Figure 2 illustrates a time history of the vertical and drag reactions on one wheel experienced in a landing at a vertical velocity of 5.5 feet per second on dry concrete. The upper curve shows the buildup of the vertical reaction during the impact and its decay as the wheel starts to rebound. The two lower curves show the buildup of the drag reaction as the wheel is spinning up, the sudden decay of the reaction to about zero as the wheel fully spins up and the oscillatory nature of the reaction as the wheel springs forward and rearward after spin-up. The good agreement throughout the spin-up of the results from the two methods of measuring the drag reaction is shown. Following spin-up, the drag reaction from the strain-gage linear accelerometer measurements is not believed to be as reliable as that from the angular accelerometer tire-deflection measurements because of nonlinearities and hysteresis effects due to the axle arrangement which were amplified by the rapid changes in the drag reaction. It is interesting to note that spin-up of this relatively large wheel for the impact shown was completed in a little over 0.1 second corresponding to about one-third of a revolution of the wheel.

Wet and Dry Surface Conditions

Figure 3 shows a comparison of time histories (similar to the one shown in figure 2) for landings on both wet concrete and dry concrete at vertical velocities V_V of 2.5 and 5.5 feet per second. Several basic effects can be observed from this figure. An increase in the maximum vertical load with increase in vertical velocity for both wet and dry conditions is evident. For the lower vertical velocity, the maximum vertical load is about the same for the wet-runway condition as for the dry-runway condition. At the higher vertical velocity, the maximum vertical reaction is slightly higher for the dry condition than for the wet condition; however, this result was not consistently obtained, as will be shown later. For the wet-runway condition, it is evident that the coefficient of friction between the tire and runway (the instantaneous ratio of the drag reaction to the vertical reaction) is less than that for the dry condition. As would be expected from impulse-momentum considerations, the time to reach maximum drag reaction is greater and the value of the maximum drag reaction is less for the wet condition than for the dry condition. The maximum drag load for the wet condition is decreased both by the lower coefficient of friction and by the delay of the maximum drag load to a time where the vertical load has decreased.

Maximum Vertical Reactions

In figures 4 and 5, the effect of vertical velocity on the maximum vertical reactions measured for a number of landings is shown. Figure 4 shows the maximum vertical reactions measured on a truck (the sum of the loads on both wheels of a truck). Results are given for both left and right trucks for landings on dry and wet concrete. Examination of the results showed no apparent effect of the sequence of impact; that is, for a given vertical velocity of a truck the resulting vertical reaction was about the same whether the truck was the first or second to make contact. Inspection of the results obtained from the landings on wet concrete shows no consistent effect of the greatly reduced friction coefficient present in these tests on the maximum vertical reactions. This last result is in contrast to results reported in reference 1 which showed, for the bomber airplane used in those tests, an appreciable reduction in the maximum structural vertical load when the structural drag force was reduced by prerotation of the wheels, apparently because of reduced friction in the shock strut. The rather high values of the maximum vertical reaction shown at low vertical velocities apparently result from the fact that a vertical reaction averaging about 24,000 pounds had to be developed, because of the air pressure in the strut and the strut static friction, before the telescoping action of the shock strut started. Thus, up to this "breakout" force, the variation of the maximum vertical reaction with vertical velocity apparently had a rather steep slope determined by the load-deflection characteristics of the tires. The breakout force was about the same for both wet and dry conditions; consequently, this force was apparently unaffected by the lower drag reaction in the wet condition.

For correlation with the experimental results, values of the maximum vertical reactions for several vertical velocities were calculated by means of a numerical integration procedure similar to that described in reference 2. In the calculations, a rigid airplane in a symmetrical landing with the wing lift equal to the weight was assumed. The average breakout force mentioned previously was used, and thus the calculations were divided into two parts, one part being prior to and the other subsequent to the beginning of shock-strut telescoping. The effect of the unsprung mass was neglected and the pneumatic force was assumed to remain constant at its initial value. The actual static deflection-load characteristics of the tires and the actual hydraulic-force characteristics of the shock strut including metering-pin effects were used in the calculations. As can be seen in figure 4, the calculated values of the maximum vertical reaction subsequent to beginning of shock-strut telescoping show the same trend with vertical velocity as the experimental results, but the calculated values are from about 10 percent to 15 percent higher than the faired experimental values, possibly because of the effect of airplane flexibility.

The relatively large scatter of the results shown in figure 4 is believed to be caused primarily by variations in such factors as the airplane lift and the unsymmetrical and rolling conditions at contact as well as small errors in vertical velocity. As an indication of the accuracy of the values of vertical velocity obtained from the trailing arm, some vertical-velocity values were computed by integration of the center-of-gravity accelerometer to which corrections were made for the effects of airplane rolling velocity. The results indicated that the probability of agreement of values of vertical velocity by the two methods was within 0.5 foot per second 95 percent of the time.

For comparative purposes, design limits of the test airplane based on the weight used in these tests are shown. The upper limit represents the maximum vertical load for the case of zero drag load while the lower limit is for the case of drag load equal to the vertical load.

In figure 5 the maximum vertical reaction measured on the first wheel of a truck to make contact is shown - for example, in a landing in which the left truck contacts first, the results shown are for the left outboard wheel and the right inboard wheel. The dashed curve shown is one-half the value of the faired truck reaction (fig. 4). It can be seen that, if an average is considered, the maximum vertical reaction on the first wheel of a truck to contact is somewhat greater than one-half the value for the truck, and therefore the average maximum vertical reaction on the other wheel of a truck is less by the same amount. Although all factors which cause the differences in reactions on the two wheels of a truck are not yet understood, it is believed that the differences for the most part arise from factors which affect the roll angle of the truck with respect to the ground, so that one wheel makes contact first and has a greater tire deflection and consequently a greater reaction than the other throughout the impact. Examination of the airplane roll attitude at contact indicated that, if an average is taken, a roll attitude of about 1° existed in such a direction as to cause this effect. This roll attitude used with the known force-deflection characteristics of the tires gave computed differences in the reactions of the wheels of about 2,500 pounds at low vertical velocities and about 4,500 pounds at the higher vertical velocities. These computed values account for all the difference in the reactions on the two wheels at the higher vertical velocities, but about only one-half the difference at the lower vertical velocities.

Variation of Coefficient of Friction

The variation of the coefficient of friction with the instantaneous skidding velocity of the wheel during the spin-up period is shown in figure 6. The spin-up occurs from right to left, the highest skidding velocity occurring at the instant of impact and zero skidding velocity occurring when the wheel attains the fully rolling condition. Results are shown for a typical landing on dry concrete and for a typical landing on wet concrete. In each case the highest skidding velocity shown by the data is about 3 percent less than the horizontal velocity at initial contact because the measured loads for a small interval after contact are so small that errors in the measurements are significant in computing the friction coefficient. At skidding velocities near zero, data are not presented because the sudden decay of the drag load at this time prevented accurate determination of the coefficient of friction. In figure 7, the variation of the same quantities for both wet and dry conditions are shown for a number of landings as shaded regions. These regions represent the overall variation of the faired values of the individual landings. The variations in the results among landings is believed to be caused primarily by differences in the condition of the runway surface - for example, in the dry condition the presence of skid marks, oil, dirt, etc., and in the wet condition by these same effects and the amount of water present on the runway. The friction coefficient for the dry condition is seen to increase from values of 0.36 to 0.50 at nearly full sliding to 0.68 to 0.85 at incipient skidding. For the wet condition, the values of friction coefficient range from 0.10 to 0.20 at nearly full sliding to 0.28 to 0.47 at incipient skidding. Results are also shown from impacts with forward speed and from impacts with both forward speed and reverse rotation of a small wheel on dry concrete in the Langley Impact Basin (ref. 3). The results agree well with the present results near spin-up, but the trends with skidding velocity appear to be in disagreement, probably as a result of the effects of different impact conditions, especially different slip ratios, where the slip ratio is defined as the ratio of the skidding velocity to the forward speed of the wheel. The ratio of the maximum structural drag load to the structural vertical load obtained in the bomber landing tests of reference 1 attained values as high as 0.8, although the majority of the results were considerably lower, probably because the runways used in these tests were still partly covered with a camouflage material consisting of sawdust spread on an asphalt binder.

The present results indicate that, for landings on dry concrete, the maximum drag reaction will be of the order of 80 percent of the vertical reaction at spin-up. It also appears that, for estimation of the variation of the drag reaction during spin-up for use in dynamic-analysis methods, consideration should be given to the variation of the coefficient of friction from the full-sliding value to the incipient-skidding value. The considerably lower values of the coefficient of friction on the wet concrete surface suggest the possibility of reducing drag loads in the landing impact by artificial lubrication of the tire or runway during the wheel spin-up period.

SUMMARY OF RESULTS

The principal results presented are summarized as follows:

1. The maximum vertical reaction on a landing-gear truck appeared to be primarily a function of the truck vertical velocity and to be unaffected by whether the truck was the first or second to make contact.

2. The maximum vertical reaction was apparently unaffected by the greatly reduced friction coefficient present in the landings on wet concrete.

3. When an average was considered, the first wheel of a truck to make contact was found to have a maximum vertical reaction somewhat greater than that of the other wheel of the truck. The difference in the reactions on the two wheels of a truck is believed to arise primarily from factors which affect the roll angle of the truck, which causes one wheel to have a greater tire deflection and, consequently, a greater reaction than the other throughout the impact.

4. Calculations by means of a numerical integration procedure of the maximum vertical reaction agreed well with the experimental results, particularly in the variations of the maximum vertical reaction with vertical velocity.

5. The coefficient of friction between the tire and the runway was found to increase during wheel spin-up for the dry-surface conditions from values at nearly full sliding between 0.36 and 0.50 to values at incipient skidding between 0.68 and 0.85. For the wet-surface condition, the values increased from a range of 0.10 to 0.20 at nearly full sliding to a range of 0.28 to 0.47 at incipient skidding.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 26, 1955.

REFERENCES

1. Westfall, John R.: Measurements of Landing-Gear Forces and Horizontal-Tail Loads in Landing Tests of a Large Bomber-Type Airplane. NACA TN 1140, 1946.

2. Milwitzky, Benjamin, and Cook, Francis E.: Analysis of Landing-Gear Behavior. NACA Rep. 1154, 1953. (Supersedes NACA TN 2755.)

3. Milwitzky, Benjamin, Lindquist, Dean C., and Potter, Dexter M.: An Experimental Investigation of Wheel Spin-Up Drag Loads. NACA TN 3246, 1954.

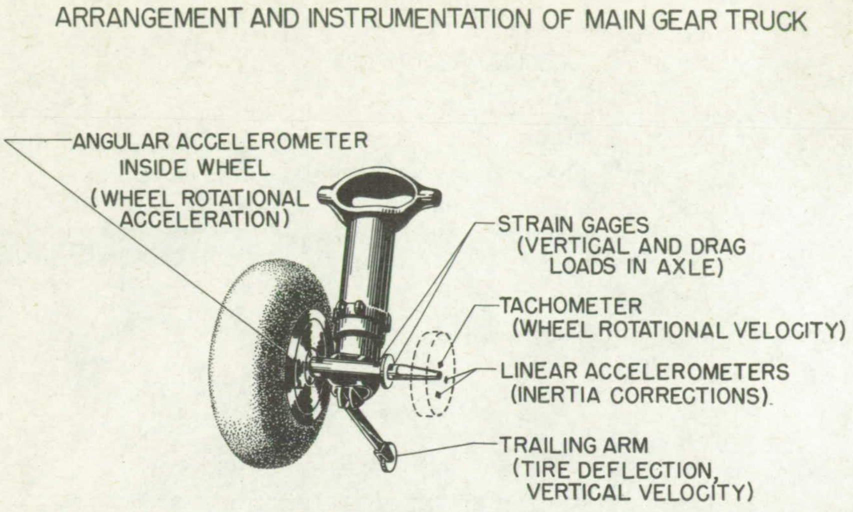
ARRANGEMENT AND INSTRUMENTATION OF MAIN GEAR TRUCK

Figure 1

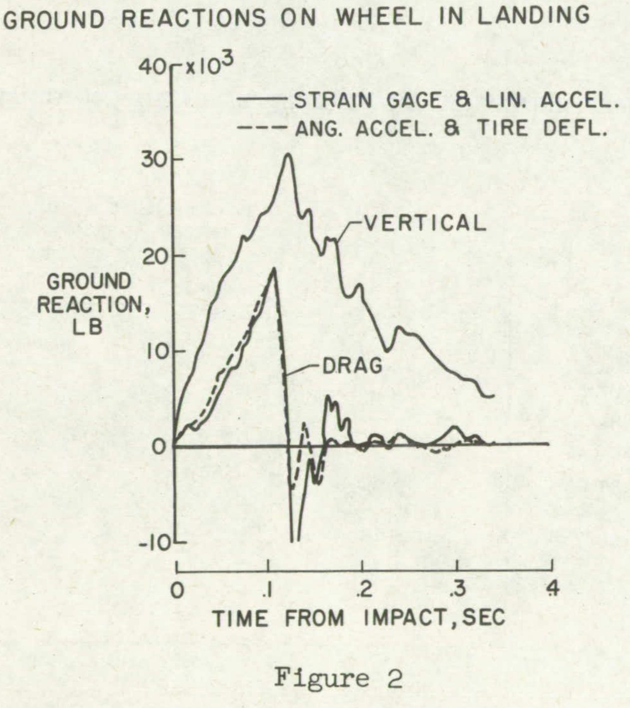
GROUND REACTIONS ON WHEEL IN LANDING

Figure 2

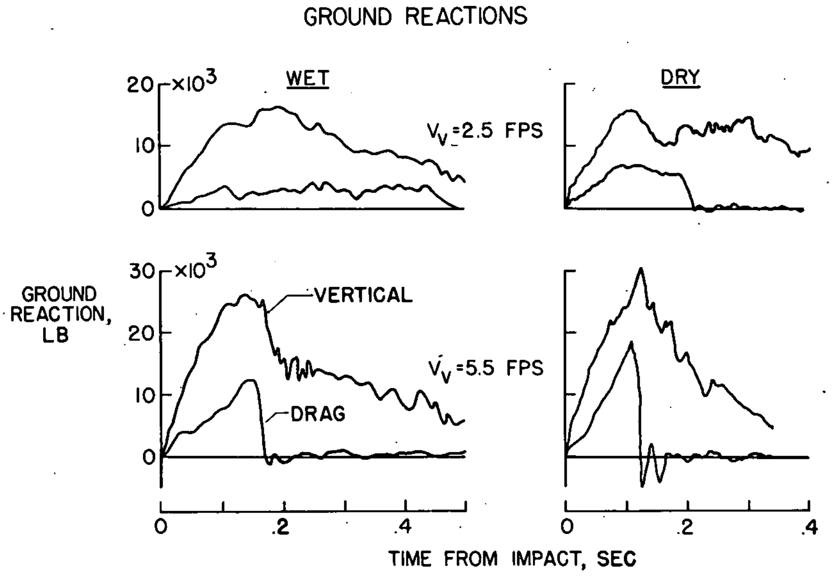
GROUND REACTIONS

Figure 3

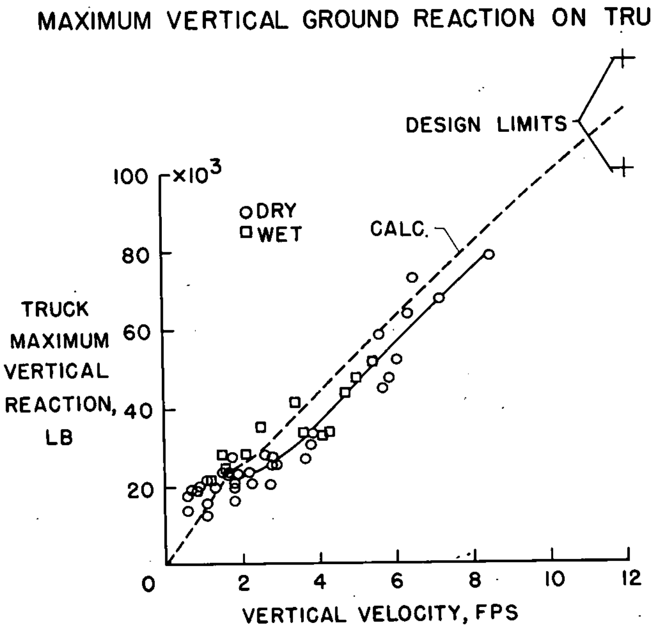
MAXIMUM VERTICAL GROUND REACTION ON TRUCK

Figure 4

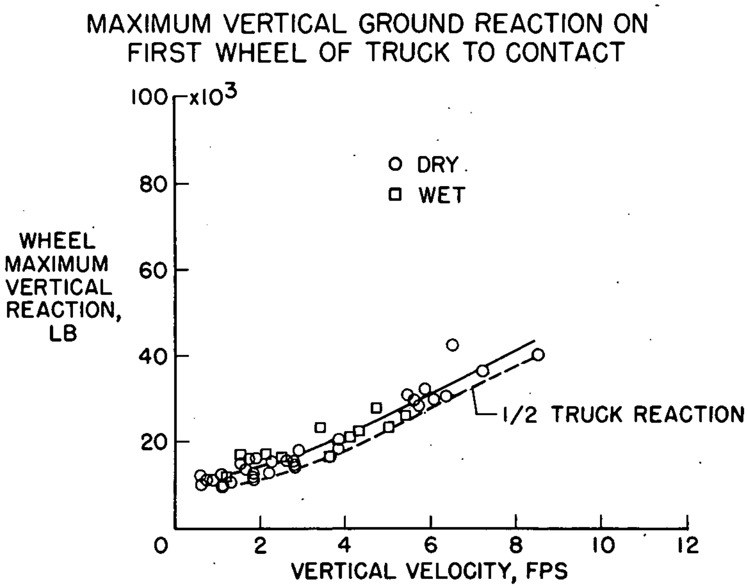

Figure 5

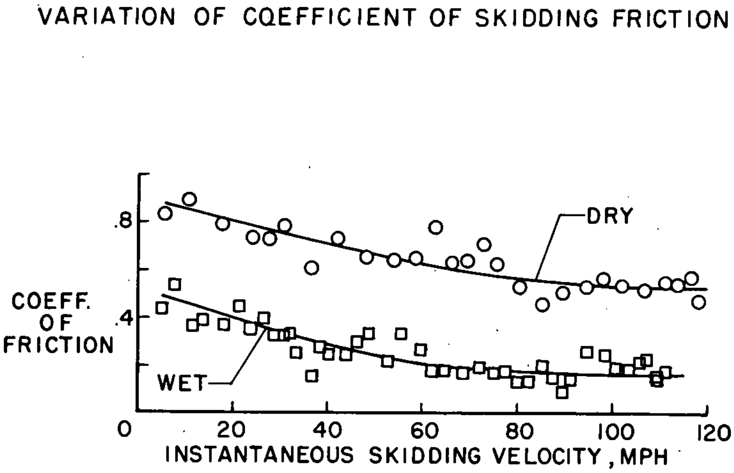

Figure 6

VARIATION OF COEFFICIENT OF SKIDDING FRICTION

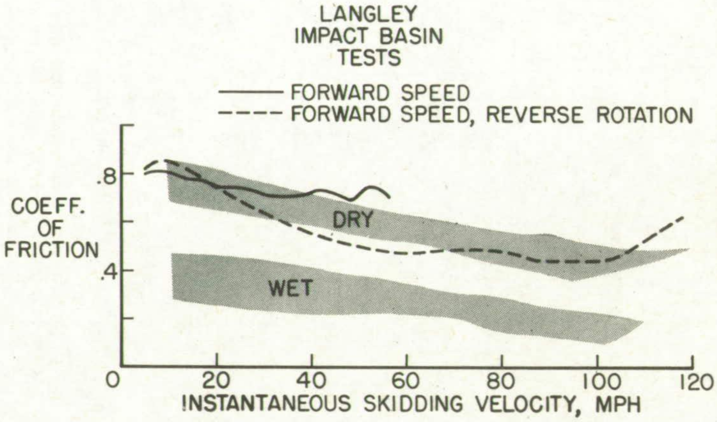

Figure 7

NACA-Langley