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A SUMMARY OF GROUND-LOADS STATISTICS

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SUMMARY

This paper briefly summarizes the more important statistical data obtained by the NACA on the subject of ground loads. The information presented relates primarily to landing-impact and taxiing loads; however, some limited data are also presented on one phase of ground-handling loads, namely, braking friction. A number of experimental and theoretical papers dealing with various aspects of the subject are listed in the bibliography.

INTRODUCTION

The NACA has for some time been concerned with the study of ground loads on aircraft; these include landing-impact loads, taxiing loads, and loads due to ground handling. A number of experimental and theoretical reports that have been published on various aspects of the subject are listed in the bibliography. The present paper summarizes the more important statistical data on ground loads obtained by the NACA, which may serve as a basis for predicting the ground-loads experience of aircraft.

The two major phases of the ground-loads problem considered herein are landing impact and taxiing loads; however, some limited data are also presented on one phase of ground-handling loads, namely, braking friction.

The section on landing impact considers first the initial contact conditions, then landing-gear reactions and airplane response. The contact conditions are in the form of statistical data on five parameters: vertical velocity, horizontal velocity, bank angle, rolling velocity, and wing lift. Although there are other parameters, the ones considered appear to be the most important. The discussion of ground reactions and airplane response is primarily concerned with the analytical prediction of vertical and drag loads from the known initial conditions.

On the subject of taxiing loads, data are available in the form of runway profiles and acceleration measurements from VGH records in taxiing; the latter are presented in statistical form. Some considerations on airplane structural response in taxiing are also given.

With regard to ground handling, some limited data are presented on the coefficient of friction as measured in braking tests with an airplane and with a specially designed tow cart.

SYMBOLS

F_v	vertical ground force, lb
f	frequency, cps
g	acceleration due to gravity, ft/sec^2
Δn	incremental center-of-gravity acceleration, g units
p_{tire}	tire pressure, lb/sq in.
V_v	vertical velocity at contact, fps
W	airplane weight, lb
μ	coefficient of friction

Subscript:

max	maximum

RESULTS AND DISCUSSION

Landing Impact

Statistics.- The available statistics on the initial contact conditions are summarized in figures 1 to 4. Figure 1 shows probability curves for the vertical velocity at contact. The ordinate is the probability of equaling or exceeding a given value of vertical velocity; the abscissa is the vertical velocity. Because there appeared to be definite differences in the statistics for civil and military (land-based) airplanes, the probability curves for these two categories are shown separately. Although the reasons for the differences between the two categories are not completely understood, it is probably significant that, on the whole, two different generations of airplanes are involved - the civil airplanes were all piston powered, whereas the military airplanes were mostly jets. Furthermore, some of the military landings were transitional-training flights. The more severe character of the military landings is indicated by the generally higher values of vertical velocity at a given probability level. For example, 1 in 10,000 landings of military airplanes would be expected to equal or exceed a vertical velocity of about $8\frac{1}{2}$ feet per second; the corresponding value for the civil airplanes is about 5 feet per second.

Figure 2 shows similar probability curves for the airspeed at contact. The ordinate is the probability of equaling or exceeding a given value of airspeed; the abscissa is the airspeed at contact, expressed as percent above the stalling speed. Again, the military operations appear to give higher velocities at a given probability level.

With regard to bank angle and rolling velocity at contact, which are of concern for unsymmetrical landings, wing span appeared to be a better criterion for separating the data than types of operations. Accordingly, with the number of engines taken as a crude measure of wing span, the airplanes with four and more engines were put into one category and the single- and twin-engine airplanes into another. Figure 3 presents the probability curves for bank angle. As might be expected from geometric considerations, the larger span airplanes have somewhat smaller angles of bank. The probability curves for rolling velocity are shown in figure 4; here the differences are more pronounced than for bank angle. It may be that these differences reflect not only the geometrical span effect, but also the greater moments of inertia and damping in roll of the larger airplanes.

A study was made to determine whether there was any statistical correlation between bank angle and rolling velocity, on the one hand, and vertical velocity or horizontal velocity, on the other hand. It was found that no such correlation existed. There was also no correlation between bank angle and rolling velocity. It therefore appears that all of these parameters may be treated as independent quantities in calculating unsymmetrical landing loads.

With regard to the wing lift at contact, both past and more recent studies have shown that, for civil transport airplanes, the most probable value of wing lift at contact is 1g and that in 95 percent of the landings the wing lift was between 0.9g and 1.1g.

The statistical analysis indicated no significant correlations between wing lift and vertical velocity.

Although a fairly substantial amount of statistical data has been obtained on these initial contact conditions, the sizes of the samples are still insufficient to permit the final resolution of the effects of such variables as airplane type, size, wing loading, and so forth.

Reactions and response.- On the subject of landing-gear reactions and airplane response, the first problem to be discussed is the determination of the vertical loads when the initial contact conditions are given.

In recent years analytical methods have been developed for predicting the behavior of the landing gear during impact and the loads applied to the airplane. Good agreement has been obtained between the theoretical results and data from landing-gear drop tests. The analytical method also appears to be reasonably satisfactory when compared with flight-test data.

Figure 5 shows a comparison of the maximum vertical loads obtained from flight tests of the SNJ airplane and calculated maximum loads based on the assumption that the airplane is a rigid body. The ordinate is the maximum center-of-gravity acceleration obtained for each impact, and the abscissa is the vertical velocity at contact. There is considerable scatter in the flight data, about 30 percent above 4 feet per second, reflecting the effects of such factors as shock-strut binding due to drag loads, unsymmetrical landings, side force due to yawed landings, and so forth, all of which can modify the vertical loads developed. At the lower values of vertical velocity the experimental data are somewhat higher than the calculated curve, largely because of the effects of shock-strut preloading and breakout friction which were not considered in these calculations. Above a vertical velocity of about 4 feet per second, the calculated curve seems to lie fairly close to the mean of the experimental data.

Figure 6 shows a similar comparison of measured and calculated maximum vertical loads for the larger and more flexible B-29 airplane. The ordinate is the maximum landing-gear vertical-load factor and the abscissa is the vertical velocity. The dashed line represents the calculated values. The break in the curve results from the effects of shock-strut breakout, which were included in these calculations. Although there is a scarcity of test points at the higher values of vertical velocity, it does appear that the calculated results are in fairly good agreement with the flight-test data.

With regard to the prediction of spin-up drag loads, the most important unknowns have been the magnitude and variation of the coefficient of friction between the tire and runway during the impact. Figure 7 summarizes the available experimental information on the variation of coefficient of friction during the wheel spin-up process. The ordinate is the coefficient of friction, and the abscissa is the skidding velocity, which is defined as the instantaneous difference between the forward speed of the airplane and the peripheral speed of the tire. The shaded bands are envelopes of the data obtained in several different test programs. The two relatively narrow bands represent tests with an SNJ landing gear in the Langley impact basin. The shorter of these two bands is for true forward-speed impacts; the longer one represents impacts with forward speed in combination with reverse wheel prerotation (to simulate higher horizontal velocities beyond the range of the impact-basin equipment). The wider dotted band shows results obtained with the B-29 airplane in flight tests. The lowest band represents data recently obtained with a B-57 landing gear at the new landing loads track.

All these bands illustrate the fairly well-known fact that the coefficient of friction decreases with increasing skidding velocity. The width of the bands represents the effects of other factors which influence the coefficient of friction, such as the slip ratio, the vertical load, variable-heating and contamination effects, and variations in the runway surface conditions, plus, of course, experimental errors. It will be noted that the SNJ and B-29 data, which are for relatively low tire pressures, are generally in good agreement with one another, whereas the results for the B-57 landing gear, which has a much higher tire pressure, indicate appreciably lower coefficients of friction. These results appear to verify a previously suspected trend, namely, that the coefficient of friction decreases at higher tire pressures.

Although the shapes of the bands are fairly consistent for the various tests, it is not as yet possible to take into account quantitatively all the factors that contribute to the spread of the values of the coefficient of friction. Therefore, it seems that the most practical approach at present is to select a shape for the curve, and then normalize it on the basis of the maximum value. From inspection of the data it appears that a reasonable range of the maximums might be from about 0.4 to 0.9, the value to be used depending on the conditions involved.

Taxiing Loads

On the subject of taxiing loads, essentially two types of data are available at present; that is, measurements of runway profiles and center-of-gravity acceleration data from the impact portion of VGH records.

Two possible ways of utilizing runway profile data are: (1) as specific displacement inputs in analog computations, or (2) as statistical power spectra in generalized harmonic analysis. Both of these approaches present certain practical difficulties. In the case of the analog method, one of the major problems is to define a representative runway. As to the use of generalized harmonic analysis, the main stumbling blocks are as yet unsolved problems of nonlinear landing-gear response and the determination of a unique transfer function.

With regard to the VGH acceleration data, several general relationships have been found which appear to be applicable to a number of different types of airplanes and which provide a common basis for estimating the loads experience in taxiing. These are shown in the following table:

		AIRPLANE TYPES
TAXIING TIME	APPROX. 5 MIN	3
C.G. RESPONSE	1 TO 2 CPS	5
SPEED AT Δn_{MAX}	< 20 MPH	4
SCATTER AT CUM. FREQ. $= 10^4$	1.5 : 1	4

First, an analysis of the time spent in taxiing, for three transport airplane types, showed that this time was remarkably constant, averaging within a few seconds of 5 minutes.

Second, it was found that the predominant frequency in the center-of-gravity accelerations - that is, the frequency at which the airplanes respond most to the runway roughness inputs - is also remarkably constant for five different types of airplanes ranging from the B-36 bomber to a small jet fighter. This predominant frequency varied only from about 1 to 2 cps, with an average value of about 1.75 cps, despite a very wide range of wing bending frequencies for the airplanes involved. This frequency of about 1.75 cps appears to be associated with the natural vibration of the airplane on its tires.

Third, it was found that, for four transport types in several hundred taxi runs, the maximum taxiing loads occurred at speeds usually below 20 mph.

Fourth, detailed analysis of all the loads experienced in taxiing for four airplane types showed that the probability distributions were very similar, and the scatter in the load level at a given probability was small, being about 1.5 to 1, or less than the scatter for such parameters as vertical velocity or horizontal velocity. Consequently, it may be assumed that a combined distribution of taxiing loads can be used to represent all taxiing operations.

Figure 8 shows distributions of center-of-gravity accelerations in taxiing, per 1,000 flights. The ordinate is the number of times a given value of center-of-gravity acceleration is equaled or exceeded in 1,000 flights; the abscissa is the center-of-gravity incremental acceleration. The ordinate scale can be ratioed in direct proportion to the number of flights considered. In calculating these curves, the approach used was first to construct a cumulative frequency distribution of all the individual incremental load peaks, both positive and negative, based on a very detailed analysis of a relatively few VGH records; these results were ratioed up to represent 1,000 flights, and are shown by the upper curve. Then, on the basis of data for 7,000 flights, a cumulative frequency distribution was obtained for the maximum taxiing load in each flight. This distribution of maximum loads was also ratioed to represent 1,000 flights and is shown by the lower curve. In the limit, the two curves should coincide at a cumulative frequency of 1. In view of the nature of the assumptions involved and the fact that the two distributions were obtained independently, the convergence appears to be quite good.

If the predominant frequency of the input to the airplane is assumed to be 1.75 cps, one can make a straightforward response calculation for steady-state forced vibration and, thus, determine the variation of the acceleration along the span, which can then be compared with the acceleration at the center of gravity. The ratios resulting from such a comparison would permit converting the abscissa scale in figure 8 from center-of-gravity acceleration to acceleration at any point along the span.

As an example, such a response calculation has been made for the B-29 airplane; two flexible symmetrical bending modes were considered and a steady-state sinusoidal input force at 1.75 cps was assumed to act at the landing-gear attachment point. Figure 9 shows a plot of the acceleration response of the B-29 as a function of position along the span. The dashed line is the rigid-body response; the solid line is the total dynamic response. For the input frequency of 1.75 cps, the ratio of incremental wing-tip acceleration to incremental center-of-gravity acceleration is about 7.9. It is of interest to note that data obtained in taxiing tests of a B-29 at the Wright Air Development Center showed acceleration ratios of the same order. However, there are still some aspects of the problem which are not fully understood; for example, even though the B-29 records showed frequencies of about 1.5 to 2.0 cps at the center of gravity, the frequencies at the wing tip were, in some cases, considerably higher.

Braking Loads

The last topic to be discussed is the subject of braking friction. Recent NACA tests with a special tow cart and with a C-123B airplane have provided the data shown in figure 10. Here the maximum coefficient of friction in braking on dry concrete is plotted against the horizontal velocity. The circles are data obtained with the C-123B airplane; the squares are results obtained with the tow cart at lower speeds. Although this type of information can be useful in the calculation of maximum braking loads, no statistical data are as yet available regarding pilot operating practice in applying the brakes, that is, the magnitude and frequency distributions of braking loads.

CONCLUDING REMARKS

The foregoing material summarizes the more important NACA data applicable to the calculation of repeated ground loads. Additional work will be necessary to extend the size and scope of the statistical samples and to fill in the several analytical gaps which still exist.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 5, 1957.

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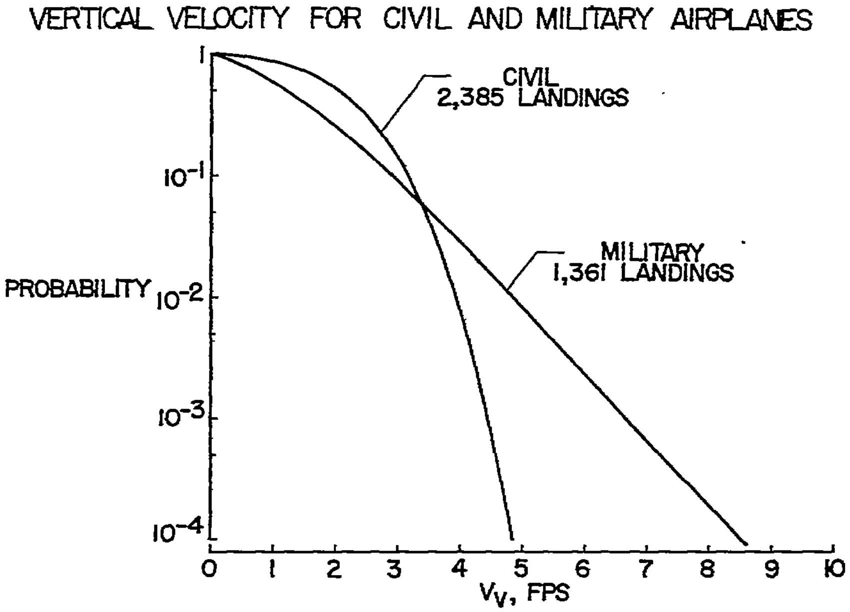

Figure 1

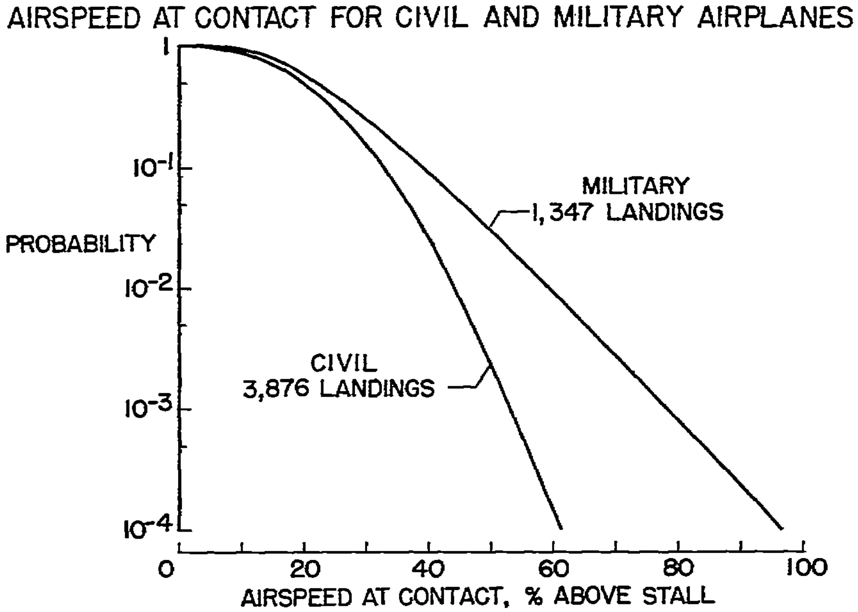

Figure 2

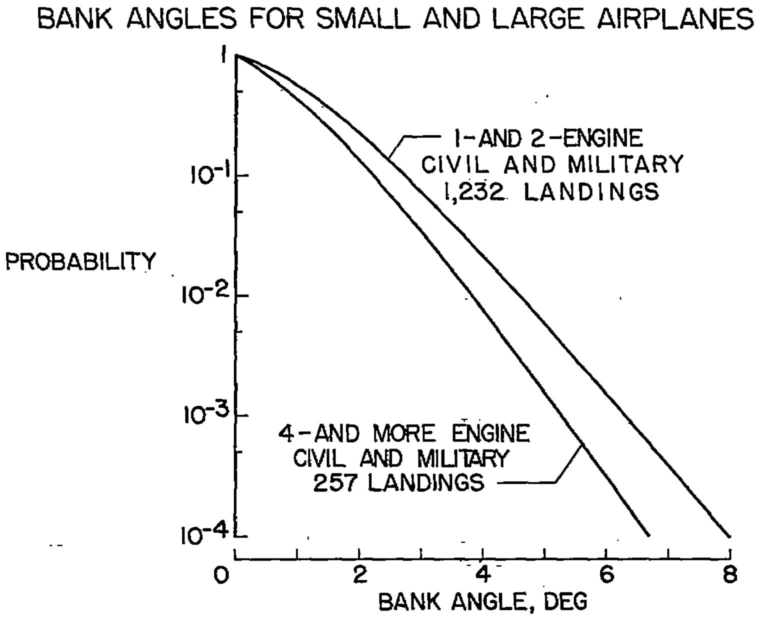

Figure 3

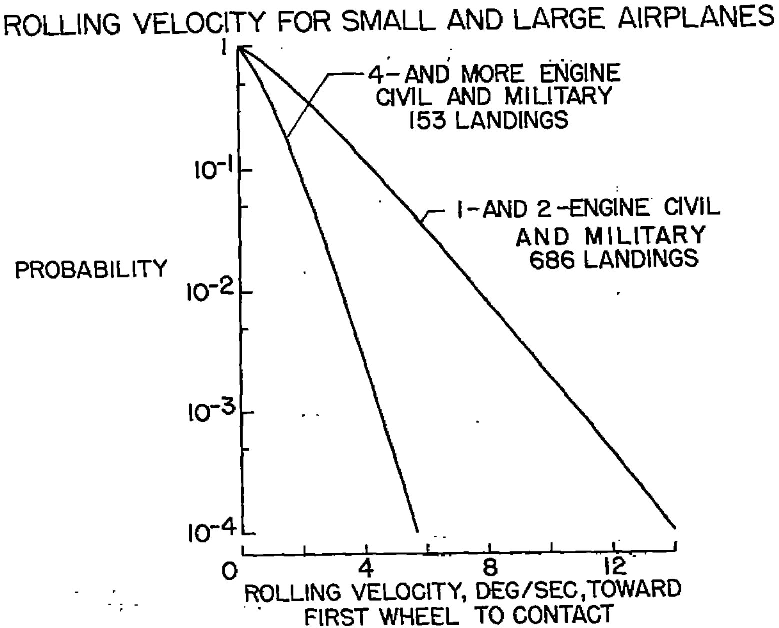

Figure 4

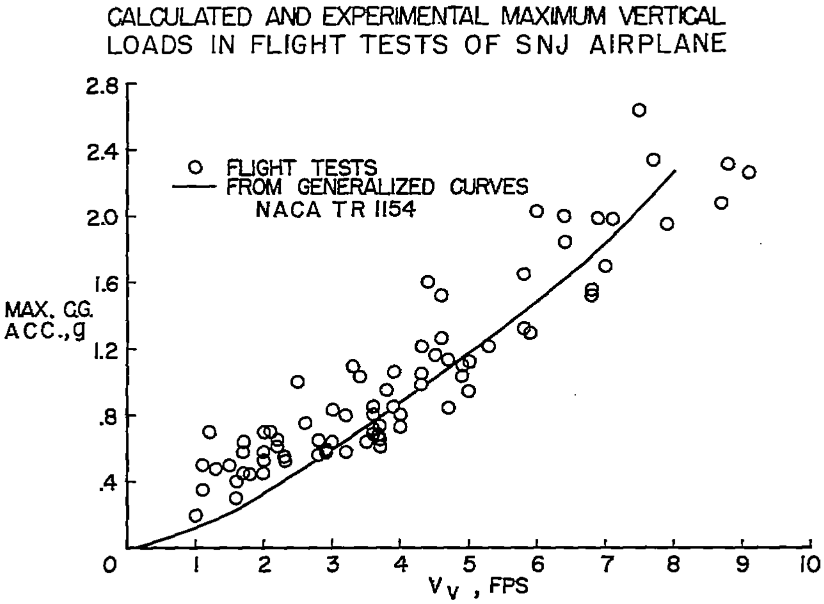

Figure 5

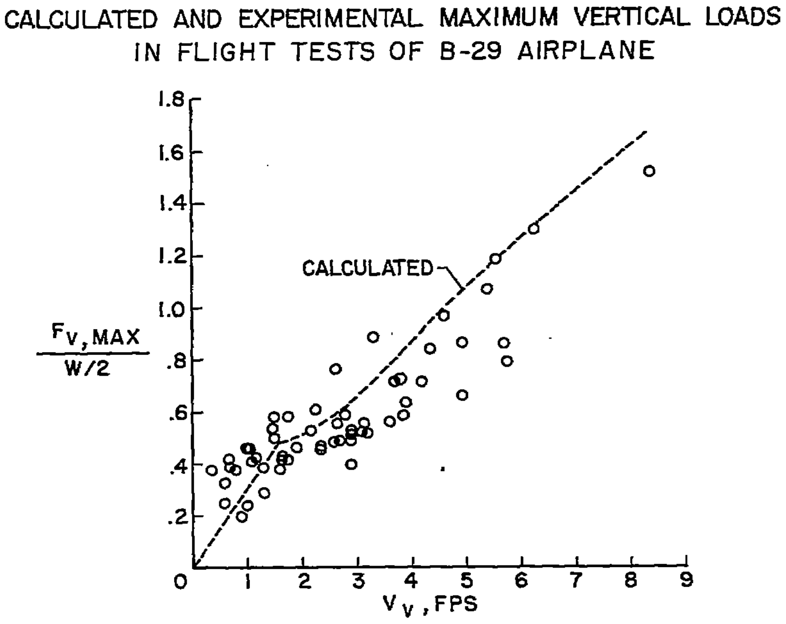

Figure 6

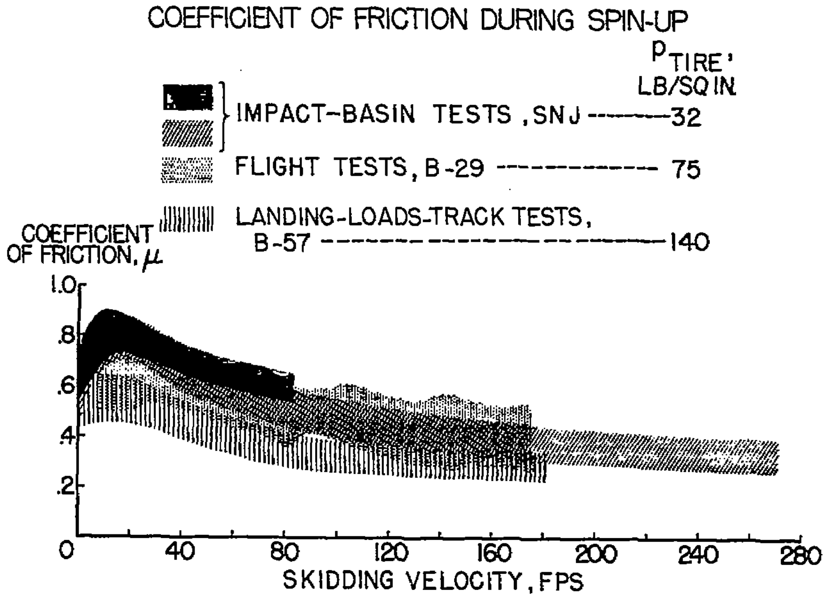

Figure 7

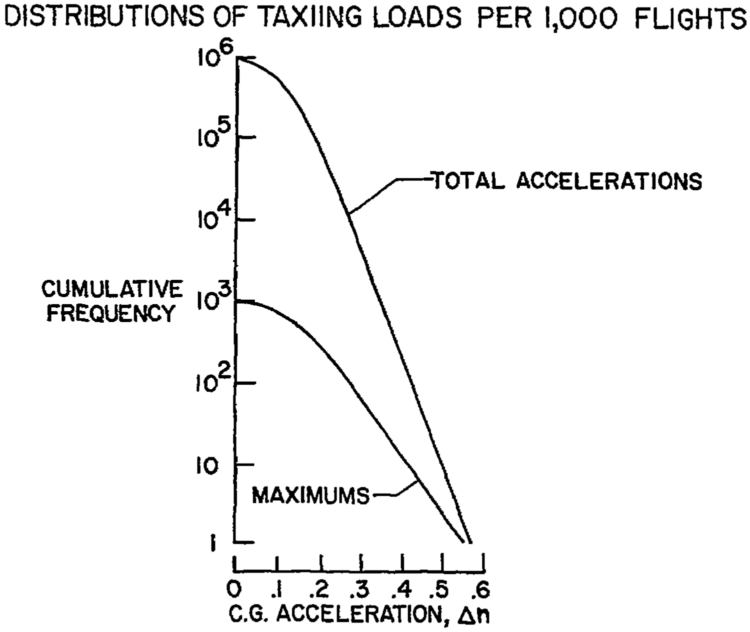

Figure 8

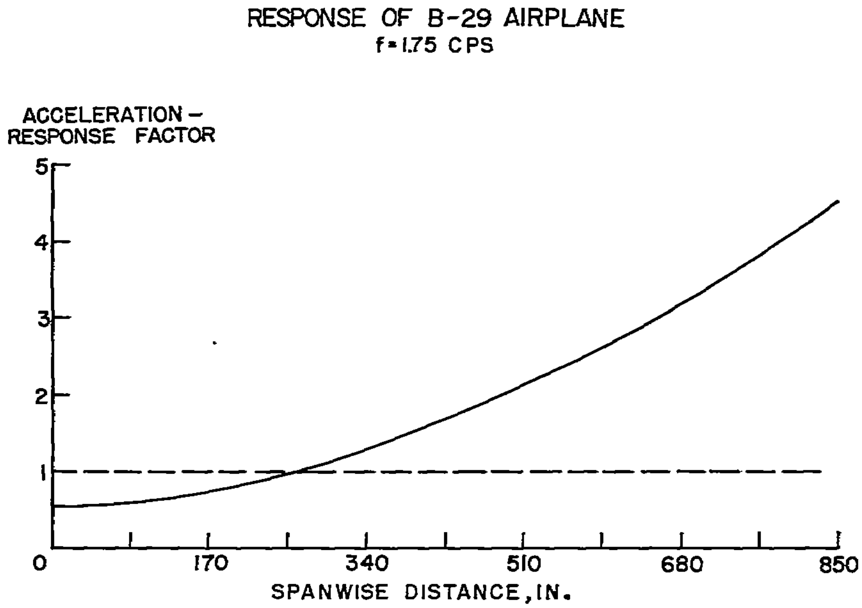

Figure 9

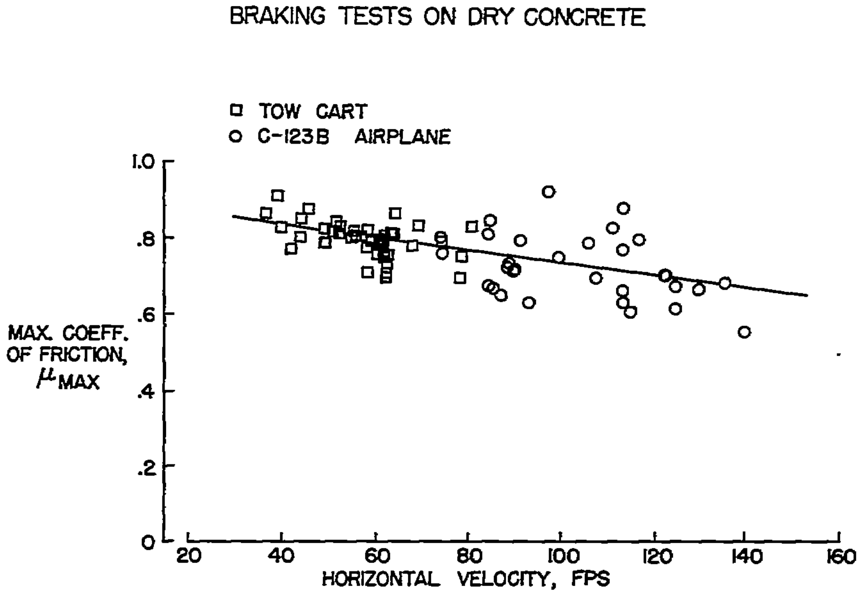

Figure 10

NACA - Langley Field, Va.