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STATISTICAL ANALYSIS OF SERVICE STRESSES IN AIRCRAFT WINGS

By Hans W. Kaul

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STATISTICAL ANALYSIS OF SERVICE STRESSES IN AIRCRAFT WINGS*

By Hans W. Kaul

INTRODUCTION

A statistical analysis of service stresses may be undertaken for a variety of reasons, but it is usually made for one of three purposes:

The first is to establish the number of recurrences at which certain reference values of the stress are reached over a sufficiently long given time period by a certain type or by a group of the same type, on the basis of measurements made on an airplane designed for a specific purpose of use, such as commercial, touring, acrobatics, and so forth.

The second involves the compilation of statistical data based on systematic measurements under certain given conditions as may be applied to any other type of aircraft by means of aeromechanical or other considerations and thus enable the prediction of the service stresses to be expected on a new type with known purpose of use.

Thirdly the statistical analysis can be of use in aeromechanical research problems involving confirmation of theory by flight test under conditions where a single measurement cannot be satisfactorily repeated as, in the recording of airplane stresses due to gusts. In this respect repeated attempts have been made abroad to secure reproducible single measurements by seeking to establish a certain gust caused by the ground contour under certain atmospheric conditions as "standard gust" for the purpose

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*"Statistische Erhebungen über Betriebsbeanspruchungen von Flugzeugflügeln." Jahrbuch 1938 Der Deutschen Luftfahrtforschung Supplement. pp. 307-313.

> of checking aeromechanical arguments. These attempts, however, were unsuccessful, so that here also the statistical analysis alone holds out some promise.

Problems 1 and 2 are therefore concerned with the collection of data for the required strength of a structural component, especially relative to recurrent stresses while problem 3 involves the solution of definite aeromechanical research tasks.

On the wing structures of modern high speed aircraft, in particular, the comparatively high-service stresses and the consistently increasing number of hours of operation during the life of the separate airplane parts make the studies of strength requirement under recurrent stresses appear of major concern. The DVL has therefore within the past few years made exhaustive studies for this structural group of airplanes, some results of which are reported in the following. Because of lack of time available the investigations cannot be recounted in detail; a comprehensive treatment will be found in the Jahrbuch 1938 Der Deutschen Luftfahrtforschung, pp. I 274-288.

TEST VALUES

As a measure of the stress in the wing structure the component of the acceleration in the center of gravity of the airplane at right angles to the plane of the wing, or the deflection of the wing or else the strain of highly stressed wing components, such as the beam flanges, may be chosen. Appropriate investigations have shown that at the present state of development of aircraft the restriction to acceleration measurements in the airplane center of gravity is justified; they are easier to obtain and the findings more readily applied to other aircraft than the data from strain or deflection measurements.

The acceleration record immediately affords the extreme values of the stresses measured during the explored operating period, hence data for the required static strength, that is, resistance against a one-time stress. In studies involving the determination of strength requirement under recurrent stress cycles, a recurrence appraisal is practically effected in the manner that the total scope of the recorded stresses is divided into a number of equal class intervals and the number of stress peak values during the test period counted within each of the individual class intervals. The result is a table of distribution for each individual test flight, the contents of which are plotted as distribution polygon (fig. 1).

MAXIMUM STRESS VALUES AND REQUIRED STATIC STRENGTH AGAINST GUST STRESSES

The static strength requirements of the wing structure against gust stresses are laid down under ciphers 1141 and 1142 of the airplane design specifications. The safe load factor defined in these specifications is compared in figure 2 with the maximum values recorded on seven different types of aircraft during various operating periods. The studied types are very unlike both as regards dimensions, aspect ratio, that is, $dc_a/d\alpha$, design (monoplane, biplane), as to flight characteristics, especially as to static longitudinal stability. The wing loading G/F_{Tr} ranged between 40 and 90 kilograms per square meter, the speeds, during tests, between 140 and 325 kilo~~grams~~ per hour.
ometers

RECURRENT STRESSES IN GUSTS

In as much as the safe-load factor defined by the specifications or its departure, respectively, from value "1" in inaccelerated level flight has proved itself characteristic for the rarely occurring maximum load peaks in gust stress, its use is suggested as reference quantity in frequency studies for any load stages.

However, in a comparison of recorded load frequencies H_i of a specified stress category i, it would be remembered that these absolute recurrences depend, besides the total recording period, upon the flying speed of the experimental airplane, since a fast airplane hits a greater number of gusts per unit time than a slow one. Furthermore to refer the load frequencies to a specified flight distance, is for the present, undesirable for the reason that the gust frequency, that is, the number of gusts registered in the airplane in unit time is of importance also for the planning of strength tests. It is therefore appropriate to extend the comparison between dissimilar test series for the time being to the relative recurrences $h_i = H_i/\Sigma H_i$, by which it is indicated what fraction of all the gusts recorded during operation has produced stresses in the designated category i. The relative recurrences thus define the form of the stress distribution polygon.

That the forms of distributions recorded at various degrees of gustiness over different test periods on totally dissimilar airplanes differ only within moderate limits is seen from figure 3, where the relative recurrences are shown plotted against the stress categories; the gust load factor expressed in hundredths of $(n_{safe}-1)$ serves as a criterion for the stress, where, of course, the safe gust load factor is not calculated conformably to the strength requirements for the maximum level speed v_h of the pertinent aircraft type, but for the average speed $v_{cruising}$ actually maintained in the test flights, since the measurements on the same type included different throttle settings, so the load factor computed for full throttle-level flight was ruled out as practical reference value.

On the basis of these findings a "standard form" of distribution of gust stress, such as indicated in figure 3, can be established. This form is valid for flights at levels below 600 meters, within which all the test flights were made, hence applies to the particularly turbulent layer near ground level.

The formation of strength specifications for recurrent stresses involves, other than the form of distribution, the scope of the statistical data, that is, the total number of gusts to be expected within a specified operating period, as explained in the previous report. The gust frequency per unit time is largely dependent upon the flying speed and the degree of gustiness. The Darmstadt gust scale used by the weather forecasting stations, which proved practical for the purpose concerned, served as indication for the gustiness in the DVL studies.

By ascertaining the number of gusts registered in the aircraft per unit time for the various degrees of gustiness, and then forming averages corresponding to the frequency of recurrence of the individual gustiness degrees in yearly average, a zone of scatter bounded by the straight lines indicated in figure 4 is obtained. The scatter is due in part to the fact that the averaging for the individual degrees of gustiness was made from a moderate number of separate measurements for economical reasons, and in part that extremely gust-susceptible airplanes recorded measurable gust stresses which others, less susceptible, did not register at all. Strength considerations on structural parts should for the present be based on the upper limit of the empirical zone, as was done in the establishing of the standard form of distribution. But in that event the additional safety factor customary otherwise in the strength specifications can be omitted, unless deemed necessary for congruence of experimental scatter of the strength tests.

With figures 3 and 4 the maximum load frequency required for any operating period and flying speed for every stress category is predictable. Since the form of the standard distribution in figure 3 is almost symmetrical to the load in unaccelerated level flight, it is permissible in strength tests to superpose two loads of equal amount with opposite sign in succession on the loading in unaccelerated level flight. This then affords load tests at which an alternating load corresponding to the designated stress category is superposed on a static base load. The fact that great and small loads follow one another at random in flight operation must be suitably reflected in the execution of these tests.

It is true that the foregoing is predicated on the assumption that the acceleration subsequent to each gust shock has sufficient time to die down to 1 g before the next gust arrives. But this is not always so, that is, in a number of cases stress fluctuations center about an average value other than the loading in unaccelerated level flight; this fact has been lost sight of up to now in the evaluation.

Next it is of particular importance to compare strength requirements secured from systematic statistics of problem type 2 with operation measurements on individual airplanes of specified purpose of use, hence, results of problem type 1. Thanks to the friendly cooperation of the Lufthansa the DVL was enabled to use some of their airplanes on established air routes for the study of statistical operating stress measurements. The data from these tests, having been kindly put at our disposal by Mr. Freise (DVL), are compared in figure 5 with the result of the systematic investigations in the 0- to 600-meter-flight level range, and the load cycles per 100 hours of operation. All data have been uniformly reduced to 350 kilometers per hour, flying speed. The evaluation of the long-period-operation measurements in the Lufthansa service which altogether covered more than 700 flying hours* was made according to a kind of sample-taking collection, rather than by the procedure described above. But in spite of this the findings of these two undertakings should be accurately enough comparable. It was found that the test data in commercial flight operation are, as anticipated, lower on an average than the maximum values of the systematic measurements secured for the extremely gusty part of the atmosphere in ground proximity; this holds, at any rate, for the range of stresses exceeding 50 percent of the safe load; in the range of lower stresses, on the other hand, the values obtained for the entrance under adverse conditions are definitely reached.** These stress measurements were made over the following air routes: Berlin to Köln to Paris, Berlin to Dresden to Prague to Vienna, Berlin to Danzig to Königsberg, Berlin to Budapest to Athens and Stuttgart to Senf, Marseilles to Barcelona. Further measurements, particularly on the recently introduced large aircraft units will show whether these initial results obtained on only three in part older commercial types of aircraft are confirmed on newer types also.

RECURRENT STRESSES IN FLIGHT MANEUVERS

While on aircraft of stress categories 2 and 3 intended for long-distance service the stresses due to pilot control operation ordinarily take no decisive part in studies of recurrent stresses, hence are not included as a separate part in the current operation stress measurements, those caused by the pilot in acrobatic maneuvers in aircraft designed for this purpose, must be analyzed separately.

The DVL measurements were made on three types of aircraft. In view of the longer duration of an airplane maneuver compared to a gust reaction and because of the impossibility to execute successive measurements of acrobatic maneuvers as long as in gust stress measurements, the

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*It took scarcely 40 flying hours to accumulate the data of the systematic flight measurements.

**For comparison with strength tests under recurrent stresses, see Nissen's report on p. 158. (1938 DLF Yearbook).

scope of the available test data is obviously considerably smaller and the zone of scatter appreciably greater than for the gust test data. Even so, an averaged stress distribution is afforded which proves correct for the three aircraft types studied to date, although a limiting curve about the test data was no longer possible. Figure 6 illustrates these averaged stress frequencies during acrobatic maneuvers, expressed in load reversals per 100 hours of operation. (Because here also an approximately symmetrical distribution of the additional stresses about the load factor "1" of unaccelerated level flight was involved, load reversal figures instead of individual load peaks can be indicated, the prediction of which proceded from a load frequency of 75 hours,* which merely comes into question as maximum value in acrobatic flight training.)

Besides the stresses in flight maneuvers, acrobatic aircraft is also subject to gust stresses. Assuming that an acrobatic airplane of stress category 4 is never used throughout its life for acrobatic maneuvers but exclusively for long-distance operation the stress distribution polygon can be deduced from the foregoing results, when observing that the safe pull-out load factor prescribed for acrobatic aircraft is higher than the gust load factor. In figure 6 it is presumed that the safe gust load factor is only 5/6 of the safe pull-out load factor - both conformable to the German strength specifications. The result is the plotted distribution polygon for gust stresses, whose ordinates diminish if the assumed 5/6 is not reached by a certain aircraft type.

The extent to which an acrobatic airplane is used during its lifetime for acrobatics in still air and for distance flight in gusty weather, is unknown for the present. But figure 6 indicates that, even under the worst possible assumption, the acrobatic and gust stresses are cumulative, the resultant excessively severe demands are restricted to a comparatively narrow stress range in the neighborhood of $0.5\ (n_{safe}-1)$. Therefore the thick distribution polygon of figure 6 is, for the time, practical. Because of the higher safe-load factors in aircraft of stress category 5 the the portion of the gust stress is even smaller than appraised for category 4 in figure 6, and the attainment of a safe-load factor of 6 to 7 is likely to occur less frequently in acrobatic flight than for stress category 4. Indiviually it should be supplemented by additional measurements of

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*One acrobatic maneuver equals several load alternations (2 to 3).

acrobatic maneuvers permitted solely with fully acrobatic aircraft.

STATISTICAL ANALYSIS AS AN AID TO INVESTIGATIONS INVOLVING FLIGHT MECHANICS

In conclusion two practical examples of statistical stress measurements are cited concerning the effect of given flight performance - or characteristic quantities on the stresses and motions of an airplane due to gust. Such a systematic study of problem type 3 is, for instance, the determination of the effect of the flying speed on the accelerations caused by gusts. Here the problem involves the analysis of various flying speeds within a short total time period successively, in order that the intensity and type of gust along the test flight path has not changed during the measurement. This automatically rules out the restriction of the evaluation to individual, outstanding values, such as the highest, temporarily obtained acceleration peaks, for instance, since they are largely dependent upon chance in short period measurements; whereas a comparison of the distribution polygons plotted at various speeds indicates that at a comparatively short test period of about 1/2 hour the effect of the flying speed on the recorded accelerations is clearly manifested.

Figure 7 gives the result of such measurements in a somewhat different representation than for problems of type 1 or 2. From the latter the designer tries to obtain probable lines of development for the wing design; hence the test data are used by a source other than which recorded and appraised it. Therefore a method of representation of the data dependent upon the class division of recurrence evaluation seems advantageous, which reminds the user that the quality of measurement and appraisal should be observed in the application to another class division.

In the argument of the effect of a certain aeromechanical characteristic, on the other hand, a type of representation independent of the chosen class division is necessary. This is achieved, for instance, by plotting as ordinate the number of acceleration peaks located above the designated threshold value against a certain threshold value of the acceleration as abscissa, when the threshold corresponds to an acceleration greater than 1 g (or below the threshold value if it corresponds to an acceleration less than 1 g). This affords two branches of a curve which ordinarily do not meet at 1 g acceleration.

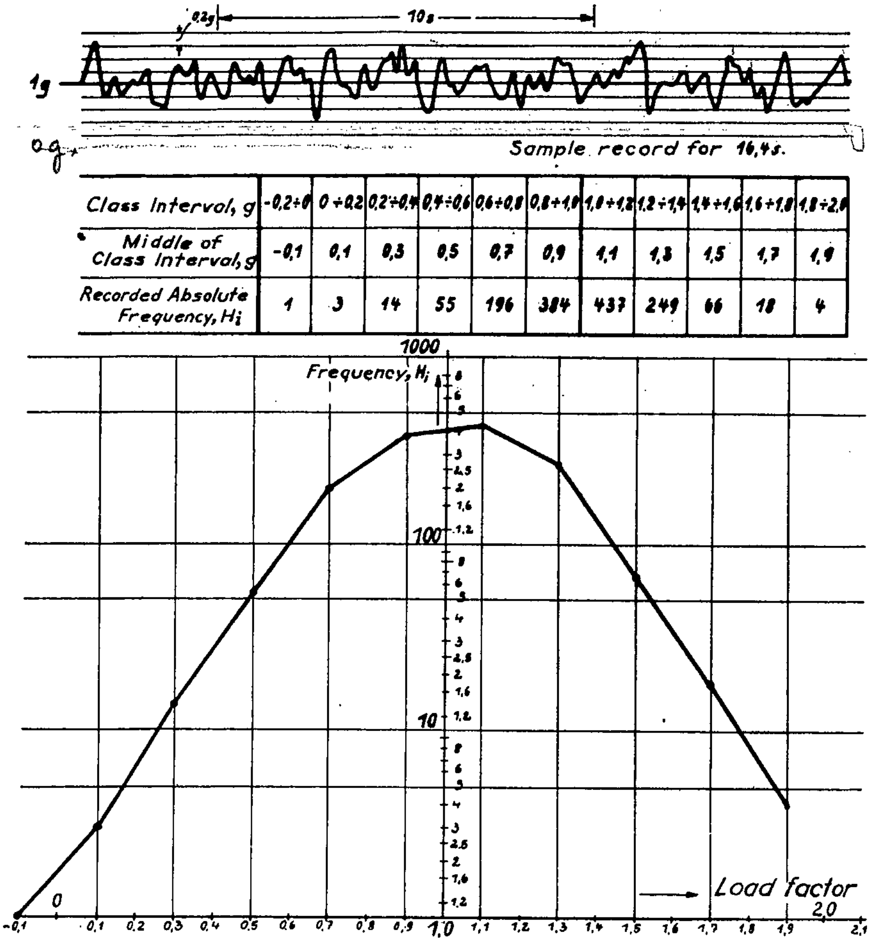
The test data for two successive flights at different flying speeds were plotted in this manner in figure 7. The branch of the curve corresponding to one flying speed can be transferred to that corresponding to the other speed, by correcting the abscissas of the test points in ratio of the speed, as indicated by the points with arrows. The test therefore confirms the mathematical result that throughout the entire stress range the additional accelerations caused by gusts are, under otherwise identical conditions, proportional to the flying speed. ✓ OK

The effect of a center-of-gravity displacement and the ensuing change in longitudinal stability on the acceleration due to a gust can be checked in the same way. Approximate solutions on this subject are found particularly in English literature. Supplementing Küssner's studies where the unstationary effects on the development of the circulation about the wing are allowed for, while rotations of the craft about its lateral axis are ignored, the English reports assume that all aerodynamic forces are linearly dependent on the designated air stream angles as occurs in stationary flow; instead of it, however, the effect of rotations of the aircraft about its lateral axis and hence the effect of the stability and damping characteristics are taken into account.

This same method was used on several German aircraft types to determine the extent to which the additional accelerations effected by three different "standard gust forms" change under the enumerated assumptions as a result of changed center-of-gravity position and hence of the static longitudinal stability. The supplementary load factor $\Delta n = n - 1$ caused by the three standard gusts is shown plotted in figure 8 against the static longitudinal stability factor x_0 ($x_0 = 0$) characterizes the neutral center-of-gravity position $x_0 > 0$ the presence of static longitudinal stability with blocked elevator). The range of the x_0 values corresponding to the permissible operating center-of-gravity positions is given for the two aircraft types. According to it a substantially smaller effect on the gust accelerations should be expected on the Heinkel He 45 D by a center-of-gravity displacement within the permissible range than on the Henschel Hs 122 in its admissible range. A comparison of these two types in flight test is therefore an excellent means of securing some initial information concerning the value of the previously outlined approximate calculation. With this in mind the DVL made some test flights in which two of the named types of aircraft each were simultaneously flown in gusty weather at the same speed over the same course, one airplane being loaded so as to bring the center of gravity far forward, the other far back. The gross weight of both was the same. These flights were supplemented by others in which both airplanes had the same center-of-gravity position. The tests on the He 45 D are finished and have been evaluated. They disclosed on an average a 1.2 time increase of accelerations with the center of gravity shifted back to the amount given in figure 8. The calculation gives 1.07 to 1.18 time increases, depending upon the assumed gust form. Of the test flights with the Hs 122 only the first three have been evaluated. They show a 1.17 to 1.28 fold rise in gust accelerations with the center of gravity shifted back, as against 1.20 and 1.62 by calculation for the three gust forms. Upon completion of further test flights it should be possible to tell whether or not the effect of the center-of-gravity position on the gust stresses is correctly described by the approximate solution.

The last two sketched examples indicate that the statistical analysis of operating stresses is not only suitable for obtaining data on the strength required against recurrent stresses, but can also be used with good advantage in the treatment of certain aeromechanical research problems in flight testing.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.



Class Interval, g	-0,2÷0	0÷0,2	0,2÷0,4	0,4÷0,6	0,6÷0,8	0,8÷1,0	1,0÷1,2	1,2÷1,4	1,4÷1,6	1,6÷1,8	1,8÷2,0
Middle of Class Interval, g	-0,1	0,1	0,3	0,5	0,7	0,9	1,1	1,3	1,5	1,7	1,9
Recorded Absolute Frequency, H_i	1	3	14	55	196	384	437	249	66	18	4

Figure 1.- Record of a flight test (He 70, D-UKOL - 10 min. flight from Adlershof - Brandenburg, speed v = 310 km/hr .

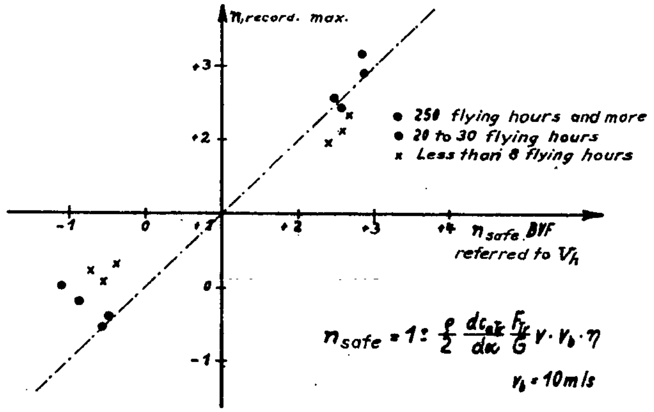
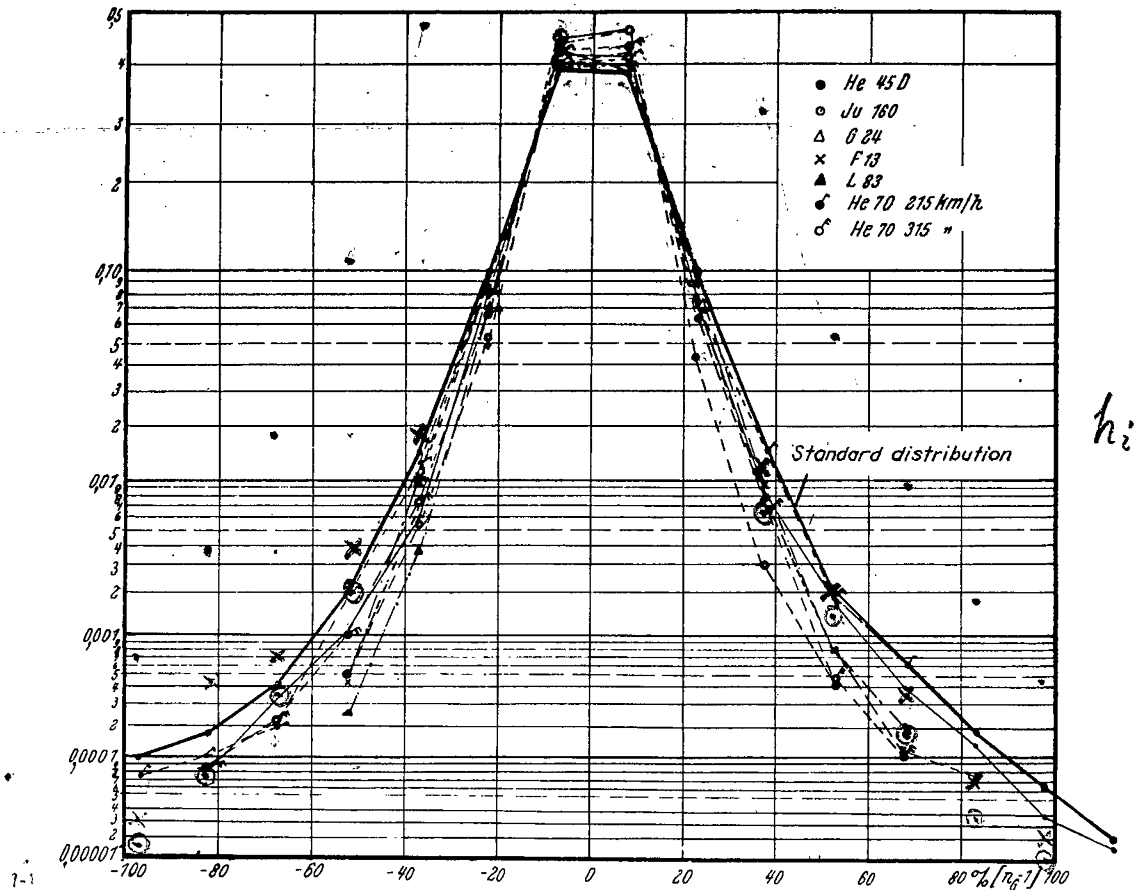


Figure 2.- Comparison of maximum accelerations recorded in gusty weather with the BVF specifications.



$h_i = \frac{H_i}{\Sigma H_i}$

Figure 3.- Form of distribution polygons for 6 different types of airplanes.

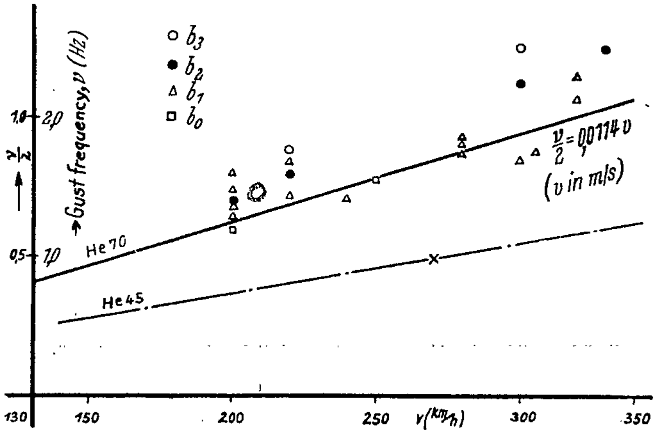


Figure 4.- Gust recurrence against flying speed.

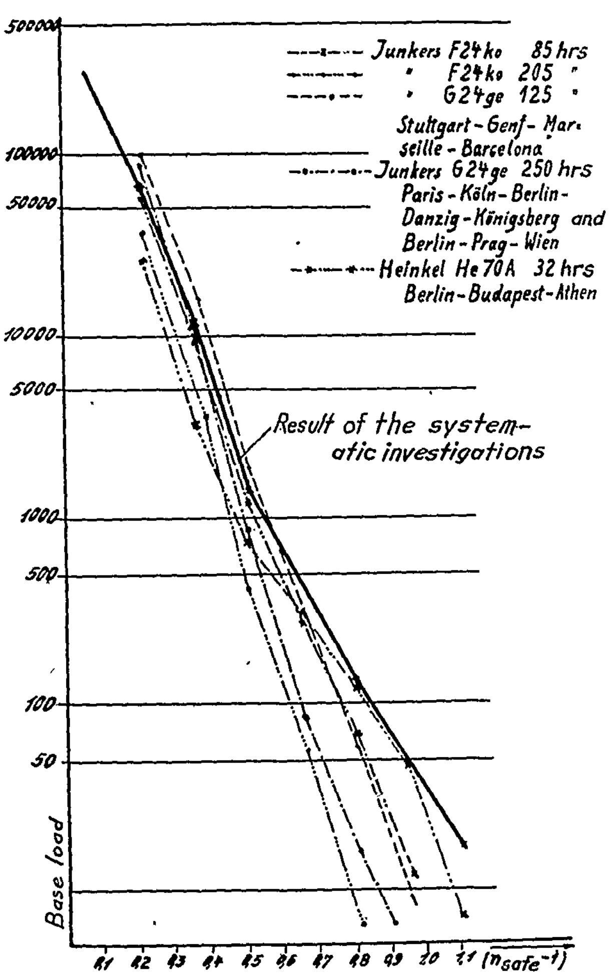


Figure 5.- Comparison of Lufthansa data with the systematic flight tests (load cycles shown plotted per 100 hrs of operation).

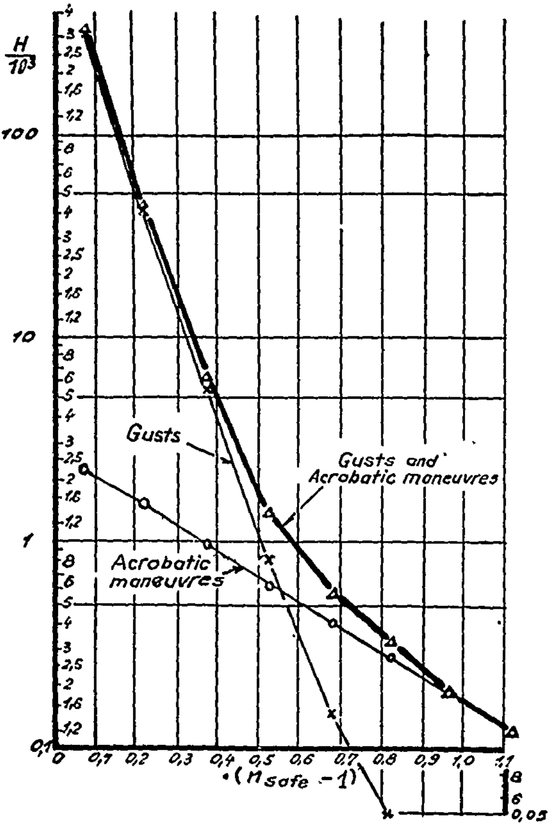


Figure 6.- Load reversals per 100 operating hrs for acrobatic aircraft of stress category 4.

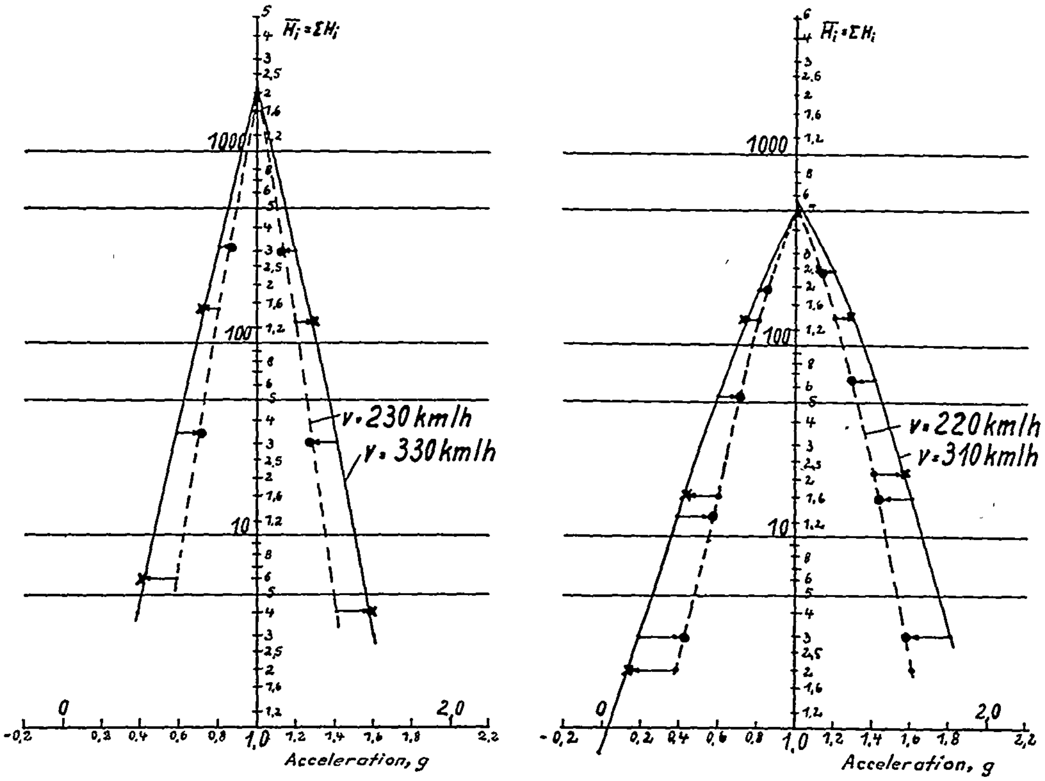


Figure 7.- Effect of flying speed on gust accelerations (examples for He 70).

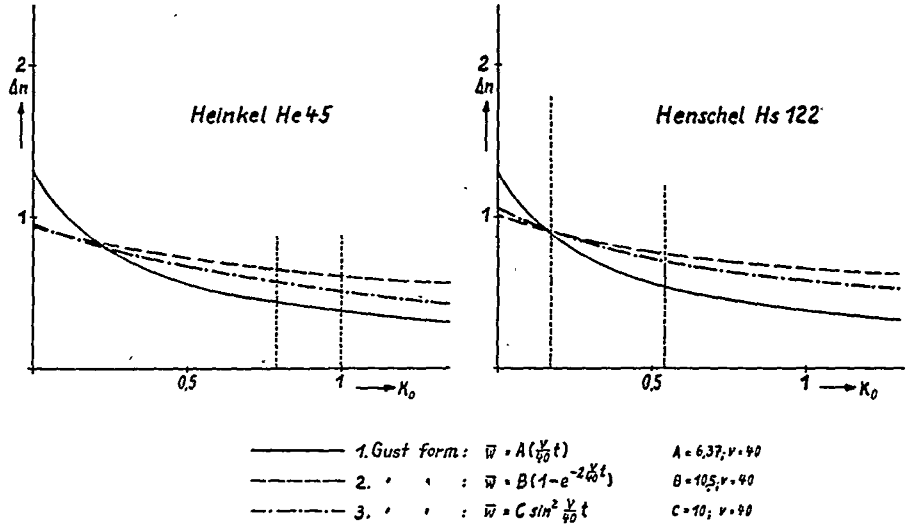


Figure 8.- Effect of changes in static longitudinal stability factor due to changes in rearward shift of the c. g., on the gust accelerations for three forms of gusts.

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