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MODERN LANDING IMPACT LOAD CALCULATIONS AND OLD-FASHIONED REQUIREMENTS

by
J. Yff, Head
Department of Dynamics and Computation
Fokker-VFW N. V., Schiphol, the Netherlands

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MODERN LANDING IMPACT LOAD CALCULATIONS AND OLD FASHIONED REQUIREMENTS

J. Yff
Fokker-VFW
The Netherlands

Abstract

In this paper it will be shown that more modern airworthiness requirements for design loads due to landing impacts, are badly needed.

Present requirements are based on an obsolete state of art in which dynamic effects were not yet known. Nowadays very refined calculations can be performed in which all dynamic effects are fully taken into account.

Modern requirements based upon the possibility of performing an accurate dynamic analysis, considering the most general landing, i.e. an asymmetric, one-wheel first landing with a lateral velocity component between wheel and runway, are formulated.

For such requirements combinations of initial conditions have to be prescribed, defining design load conditions. Combinations which can be derived from statistical considerations of measured landing parameters.

Finally a comparison is presented between results obtained with such a set of proposed rational requirements and with calculations based upon the existing requirements.

I. Introduction

The definition of design limit loads for aircraft structures is stated in the FAA requirements as being "maximum loads anticipated in normal conditions of operation", i.e. loads with a certain small probability of occurrence.

These loads, however, are a result of certain operating conditions. The prediction of design loads therefore always involves two steps, viz :

- .the definition of certain operating conditions
- .the calculation of loads for given operating conditions.

These two steps are always coupled in airworthiness requirements, although this is not always clearly recognized. When very accurate load predictions are possible the operating conditions can be defined in such a way that they occur with the certain small probability of occurrence as mentioned above. But when it is possible that the load prediction will be performed in a rather primitive way so that too low values can be predicted, it is necessary to include in the definition of the operating conditions such a conservatism that the combination of operating condition and load prediction, which can be on the unsafe side, still predicts in any case loads with the certain small probability of occurrence mentioned earlier.

However, load prediction capabilities have developed tremendously in the last decennia due to the availability of digital and analog-computers. And when better calculation schemes become available and are prescribed, also the prescribed operating conditions should be adjusted, as otherwise the predicted design loads can become too conservative.

Such a situation exists nowadays in particular with respect to the requirements for landing loads. As a result of the landing impact the structure is exposed to loads which increase in very short time from zero to their maximum values. The landing impact therefore has a dynamic character, which means that inertia forces due to the elastic deformation of the structure are becoming more and more important. The existing requirements however are based on an obsolete state of the art in which no dynamic effects were taken into account by the stress analyst. Consequently the values of the initial conditions - the sinking speed in particular - in the existing requirements had to be specified rather conservatively, as a safeguard against the shortcomings in the state of the art.

But later there is formulated a general requirement stating that when any rate of load application likely to occur in the operating conditions might produce transient stresses appreciably higher than those corresponding to static loads, the effect of this rate of application must be considered. This brings about that a full dynamic analysis is required, whereas the old conservative operating conditions still remain valid. As will be shown later on, this combination of requirements also poses interpretation problems.

Therefore a new formulation of landing impact load requirements is badly needed in which both the landing conditions and the level of sophistication of landing impact load calculation are defined. It is the aim of the present study to investigate whether it is possible to formulate more up to date, yet simple requirements for the landing impact load cases.

First of all it will be illustrated how sophisticated and accurate landing load calculations can be performed already, and how refined the structural schematisation of the aircraft has to be in order to predict sufficiently accurate the dynamic loads due to landing impacts. Then it will be illustrated how large the relative importance can become of the asymmetric aspects of a landing, i.e. one wheel touching down before the other and/or lateral friction forces due to initial lateral skidding velocity between wheel and runway.

Modern requirements will be proposed based upon the availability of accurate calculation methods and considering the general landing with the asymmetric effects mentioned above. Combinations of initial conditions have to be prescribed for defining design load cases. These combinations are to be derived from the statistical material available. Finally a comparison will be made between landing impact load calculations based on the existing requirements and on the proposed requirements.

II. Accuracy of landing load prediction

As an example of how accurate nowadays landing gear load time histories can be predicted analytically, a comparison between experiment and analysis will be presented for nose gear drop tests on a wedge.

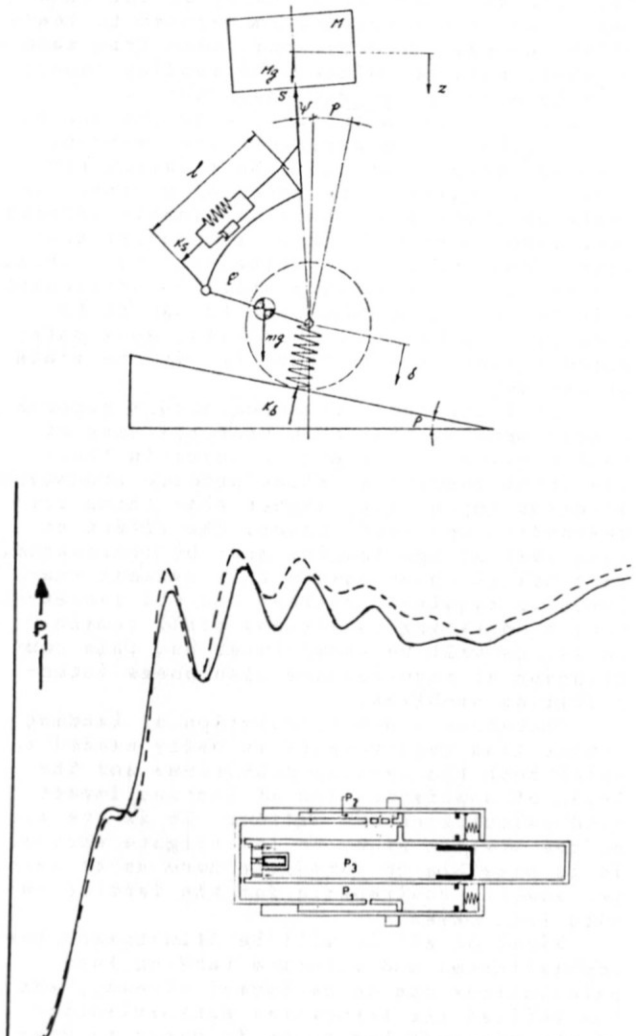


Fig. 1

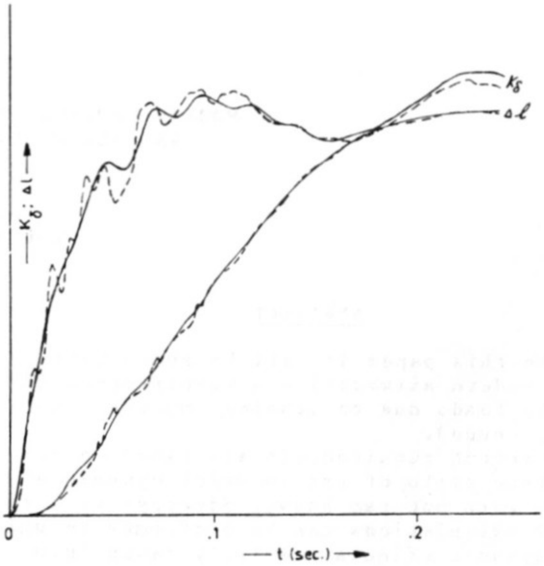


Fig. 2

Fig. 1 gives a scheme of the nose gear and shock absorber, while fig. 2 gives the comparison between drop test and analysis for a number of important parameters. At first the high frequency oscillation could not be reproduced. Then it was discovered that introduction in the analysis of oil compressibility also explained this phenomenon. The simulation of the shock absorber required also in other aspects more sophistication than just the hydraulic damping force and pneumatic spring force. In addition, shock absorber bearing friction, break out friction and constant friction of the seals had to be taken into account. The numerical values of these friction properties could be determined by first comparing a simple vertical drop test with the analytic results for the determination of break out friction and seal friction. Then a drop test on a wedge was used for the determination of the bearing friction. The so obtained analytic model then was checked against some other drop tests.

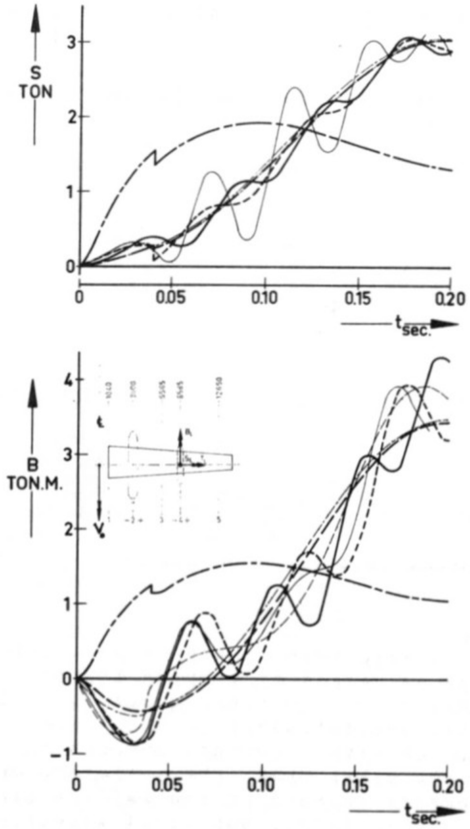
Fig. 2 is valid for a 10ft/sec drop test on a wedge. Due to the excellent agreement obtained in this way, the airworthiness authorities allowed the extrapolation of these results to a descent velocity of 12 ft/sec. By this procedure the ultimate drop test could be omitted and the landing gear saved.

The other aspect of accuracy in load prediction due to landing impacts, deals with the required sophistication of the dynamic schematisation of the aircraft structure. Due to the fact that the tire friction forces reduce to very small values in a few hundredths of a second after touch down, when the wheel attains the rolling condition, rather high frequencies are excited. Therefore it can be expected that the dynamic schematisation has to be rather refined. How refined, has been investigated by comparing results of landing impact load calculations of the Fokker F-27 Friendship for various degrees of sophistication in the dynamic schematisation.

Fig. 3 Fokker F-27 Friendship

The schematisation consisted of a rigid fuselage and tail to which a slender elastic wing without sweep is connected. The rigid landing gear is rigidly connected to the wing in the same wing station as the engine. Wing elasticity is adequately described by both the first two bending and torsion modes, as well as by a single in-plane bending (η_h) mode. It is moreover assumed that the engine pod can pitch with respect to the wing, and that the pylontank is connected elastically to the wing with a horizontal spring in the wing plane(Λ).

This dynamical system, valid for a landing weight of 35,700 lbs, filled wing fuel tanks and 50% filled pylontanks, has been subjected to a 10 ft/sec symmetrical 10° tail down landing impact with a forward speed of 40 m/sec (friction coefficient is $\mu_x = 0,8$). In fig. 4 some wing loads are compared in a single wing station, for various degrees of sophistication. It will be immediately obvious from these results that the rigid body concept is inadequate. Taking into account only fundamental wing bending improves considerably the results for shear forces and bending moments. Wing torsional moments however are still reproduced very poorly. These quantities can only be predicted with a reasonable accuracy when also wing torsion and engine pitch are introduced in the schematisation.



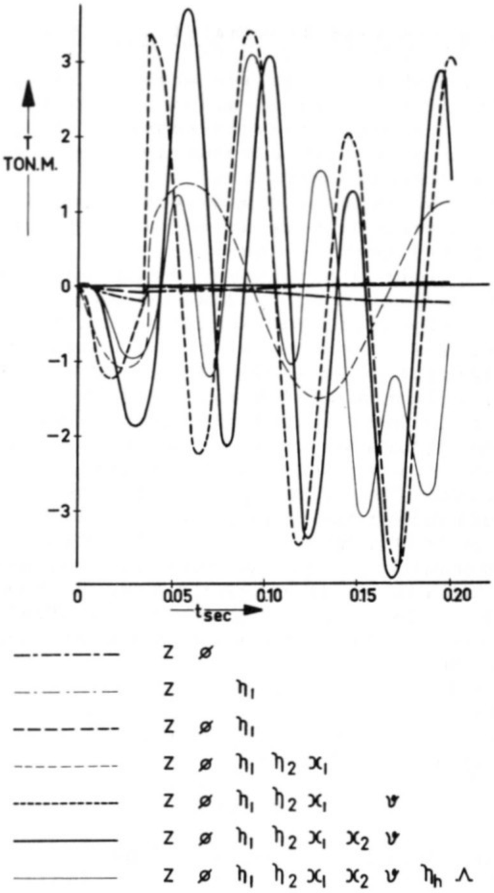


Fig. 4

The general conclusion is that the dynamic schematisation has to be fairly sophisticated in order to predict reliably landing loads for given initial conditions. As a yardstick it can be said that normal modes and frequencies up to at least 20 cps have to be represented fairly accurately.

However, different types of aircraft have to be schematised differently, in accordance with their individual features. For this example, wing elasticity is especially important. For rear engined jet aircraft also the dynamic representation of the rear fuselage, engine-tail combination deserves attention. Fuselage elasticity may also become important in the case of very long, slender fuselages.

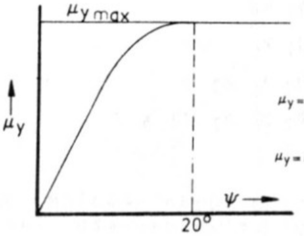
Hence, both landing gear loads and structural loads due to the landing gear loads can be predicted very accurately nowadays, provided a sufficiently accurate analytical model is defined.

III. The asymmetric aspects of normal landings

All actual landings are asymmetric landings. Always one wheel touches down after the other. In many cases moreover a lateral velocity between tire and runway is present, generating lateral tire forces.

Therefore it is worthwhile to consider the importance of these asymmetric aspects for the total landing loads in the aircraft structure. This will involve an investigation into the variation of landing loads with the initial roll angle, and a comparison of the max. values so obtained with the loads found for an initial roll angle of zero.

The influence of lateral tire forces on loads due to landing impacts depends mainly on the magnitude of these tire forces. Being frictional forces, they are proportional to the vertical tire force. However, the friction coefficient μ_y is not a constant but depends on the tire yaw angle ψ. The relation between μ_y and ψ follows from empirical relations as given in ref. 2. For the present calculation example, the Fokker F-27, this relation takes the form as sketched in fig. 5.



$$\mu_y = \mu_{y_{max}} \times 0{,}075\,\psi^\circ \left\{1 - \frac{4}{27}(0{,}075\,\psi^\circ)^2\right\} \quad \text{for } \psi < 20^\circ$$

$$\mu_y = \mu_{y_{max}} = 0{,}7 \quad \text{for } \psi > 20^\circ$$

Fig. 5

The question can be put however, whether this dependence need to be taken into account at all. The tire yaw angle can reach much larger values than 20° as soon as the wheel rotates, at the moment of complete spin-up, so that during most of the impact, $\mu_{y\,max}$ is valid. This has been investigated by comparing landing impact calculations with $\mu_y(\psi)$ and with μ_y is constant.

A third case has been investigated as well, viz one with a constant μ_y and moreover the rigid body degree of freedom of lateral translation being frozen. This has been done in order to know which further simplifications are possible in a rational asymmetric analysis without losing too much accuracy in the results. Some results are presented in figs. 6 and 7.

It follows indeed that the dependence of μ_y on ψ only influences the initial part of the lateral tire force K_y, while maximal values are hardly affected, Yet, the influence on wing loads is certainly not negligible as is shown by fig. 7, although it must be mentioned that this load station has been chosen because it shows the largest differences between the three cases.

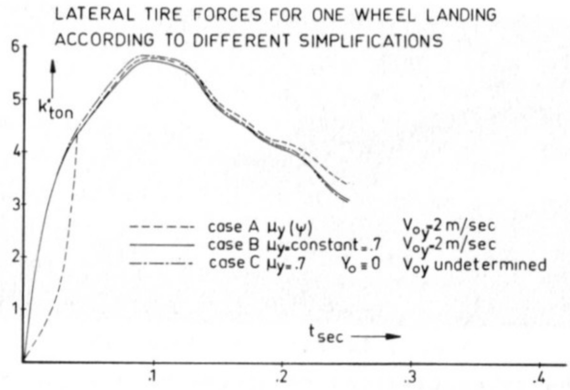


Fig. 6

It should be taken into account however that for low wing aircraft, the influence of lateral friction forces on wing loads is much smaller than in the present example.

There is another reason why this refinement of $\mu_y(\psi)$ need perhaps not to be introduced in an analysis aimed at predicting design loads. Therefore it has to be considered that heavy landings very often occur just due to large crosswind components, so that a certain correlation between these two initial conditions is present. Then the initial value of ψ becomes already so large that during nearly the whole impact $\mu_{y\,max}$ has to be used.

Therefore it is justified, in particular for design load conditions, to consider a combination of maximum values of descent velocity and μ_y and to neglect the rigid body degree of freedom of lateral displacement.

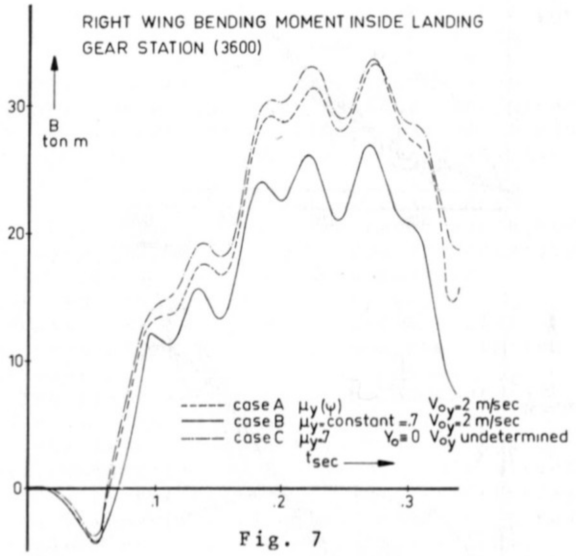


Fig. 7

When the magnitude of the lateral friction forces is varied by varying the constant values of μ_y between 0 and 0,7 , it follows that the influence of the lateral tire forces on wing torsional moments is small. On the other hand, the influence on bending moments inboard of the landing gear is large. Not so large, but still significant is the influence on wing shear forces and outboard wing bending moments.

The influence of initial roll angle on wing loads has been studied for a 10° tail-down landing with a descent velocity of 6 ft/sec. It is furthermore assumed that the full elastic aircraft is drifting to the right with respect to the runway, thereby creating lateral friction forces which are 0,7 times the vertical tire force. The longitudinal friction coefficient is assumed to be 0,8 during the whole spin-up phase and zero after the moment of spin-up. By varying the roll angle between 0 and 3°, it is found that the maximum values of most wing loads vary quite irregularly with the roll angle, while others do not show too much variation. It is moreover observed that no definite preference for either wing half exists when maximum loads in left and right wing halves are compared. But as compared with zero initial roll angle, the maximum values of some quantities increase considerably. Differences ranging from 10 - 50% are found in the present investigation.

As not a single roll angle produces maximum loads in general, and because it depends on the load concerned which roll angle produces maximum loads, the only sensible thing to do is to take into account the initial roll angle as a variable in an analysis aimed at predicting design loads.

Now that the contributions of the two asymmetric aspects of the landing impact have been analysed quantitatively separately, the relative importance of both these aspects can be compared. With respect to torsional moments it is clear that the increases as compared with an impact with zero initial roll angle, are mainly due to the initial roll angle. For the other quantities considered, wing shear forces and bending moments, it follows that in general the effect of the lateral friction forces is more important than the initial roll angle.

Hence both lateral friction forces and initial roll angle are important. Any analysis aimed at predicting design loads and which want to be called a rational analysis, therefore has to represent an asymmetric landing with one wheel touching down before the other and drifting with respect to the runway.

IV. Formulation of rational requirements

When more rational requirements for design landing loads have to be formulated and when the analytical and computational capabilities of todays aircraft design offices can form the basis of such requirements, then the most logical approach is to consider the general asymmetric landing as treated in the previous paragraph as the aircraft condition for which the design conditions have to be specified.

The consequence of such an approach is however that a large number of initial conditions have to be specified. The values of these initial conditions can be derived from measurements during landings with various aircraft types. The statistical properties of all these initial conditions separately then can be determined. The question remains however which combination of initial conditions has to be specified in order to define critical design loading cases. This problem becomes still more complicated by the fact that for different sections of the structure, different combinations of initial conditions can become critical.

In principle this problem can be approached in a statistical way. Some of the more recent literature (ref. 2) follow this line of attack. From the statistical properties of the individual initial conditions, random combinations of these initial conditions can be formed by means of certain statistical techniques. When such random combinations are applied to the dynamical system describing the aircraft- and landing gear behaviour of a specific aircraft, resulting loads, stresses and accelerations are obtained in the form of probability distributions. From an abstract physical point of view such an approach would be the only correct one.

Unfortunately, however, in practice this approach does not work in providing design loads (i.e. limit loads and/or ultimate loads). This is due to several reasons. The most important one is that the initial condition defining limit and ultimate loads have to be extrapolated from the available statistical information, since for these extreme conditions statistical information is not available.

Moreover, due to the limited amount of available statistical data, only a few measured values are available for severe landings. Hence, the statistical accuracy of the extreme (extrapolated) values is even more doubtful. This is still more valid for a combination of the values which raise extreme landing impact loads.

A further reason is that the great amount of statistical information needed is not yet available for all relevant initial conditions. It is even doubtful whether this information ever will become available, as a constant updating will be required for each succeeding generation of aircraft.

Therefore it has been studied in ref. 3 whether another approach is possible. By studying the relative importance of the various initial conditions, it has been determined that some of them exert only a minor influence on the loads, so that fixed values can be specified without too much loss of accuracy, that others, such as the initial roll angle, can be varied in order to detect maximum loads, and that reliable statistical information is only required for the main initial condition (i.e. the descent velocity). Then the statistical task is surmountable.

It must be emphasized that such a procedure is conservative because only for the descent velocity statistical considerations are proposed while for all the other initial conditions, which also have a certain probability of occurrence, it is proposed to specify values resulting in maximum loads. The combination of these proposed values certainly has a very small probability of occurrence.

From the analysis with respect to the influence of lateral tire friction forces as presented in the previous paragraph, it follows that initial lateral velocity with respect to the runway, initial yaw angle and initial yaw velocity all can be set zero when these forces are assumed to be a fixed proportion of the vertical tire force. These are the three initial conditions which determine the tire yaw angle with respect to the runway. By prescribing that the lateral tire forces have to be determined in this way, these three initial conditions can be left undetermined, i.e. they can be set to zero.

It also follows from the previous paragraph that the initial roll angle is a quantity which has to be varied for detecting maximum loads. Initial roll velocity will be treated together with descent velocity.

It is well known that the aircraft pitch degree of freedom can be safely ignored in a landing impact analysis. The consequence of this is that the initial pitch velocity can also be neglected, i.e. set to zero. However, the initial pitch angle itself is certainly of such an importance, especially for the landing gear loads proper, that all values possible in a landing have to be considered. Hence, besides the roll angle, also the pitch angle has to be varied in order to detect all possible maximal loads.

The horizontal forward speed V_{0_x} enters the analysis of dynamic landing impacts only in the expression for the spin-up time t_s . A larger spin-up time due to larger landing speeds involves a spin-up coinciding with a larger vertical force and hence with a larger spin-up force. From calculations with different values of V_{0_x} , it is found that some wing loads increase with V_{0_x} while others decrease. For most loads, however, V_{0_x} is of secondary importance. A variation of V_{0_x} therefore seems to be appropriate. According to ref. 4 a variation between V_S and 1,6 V_S is found in practice (V_S is stalling speed), although nearly all landings for modern aircraft are performed between 1,2 V_S and 1,4 V_S. As moreover the probability that a high descent velocity combines with an unfavorable forward speed for a particular design load is very small indeed, and because V_{0_x} is of secondary importance for most loads, it seems justifiable to prescribe only a single value for the forward speed, viz 1,3 V_S.

In order to get design loads, a rational maximum value of the initial vertical velocity, or descent velocity, $\dot{Z}_0$, has to be defined. Fig. 8 presents probability distributions of measured vertical velocities, as presented in ref. 5.

It follows that the large turbojets experience larger descent velocities. Most probably this is not due to the class of aircraft, viz the large turbojet aircraft, but due to the aircraft weight, wing loading, distance of the pilot forward of the landing gear, mean horizontal touch down speed, and the elevator effectiveness. As is shown in ref. 5, these are the important parameters controlling the probability of a certain descent velocity.

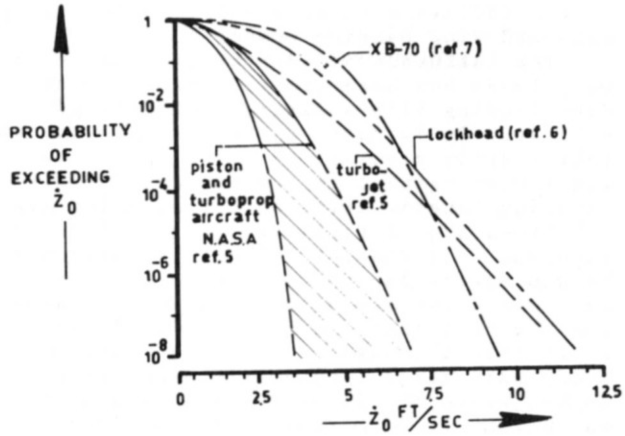


Fig. 8

There is, however, a strong interdependence between these parameters. A larger and thus heavier aircraft nearly always has a larger distance between pilot and c. of g., very often a higher horizontal speed, and in many cases a smaller elevator effectiveness. One can argue therefore that descent velocity statistics are primarily dependent on aircraft weight, with the heavier aircraft experiencing larger descent velocities.

Deriving limit vertical descent velocities from these probability curves has to start from the definition of limit loads, viz. loads occurring not more than once in a lifetime of the aircraft. For transport aircraft life generally is assumed to be 30-40,000 hrs. The number of landings, however, is very much dependent on the class of aircraft considered. For short haul aircraft a typical flight is of the order of half an hour. For long distance airliners the typical flight is at least of 3 hours duration. However, very often long distance aircraft are downgraded later on to shorter routes. Therefore it can be stated that the number of landings per aircraft lifetime can vary from about 30,000 for long distance aircraft to a maximum of 100,000 for typical short haul aircraft. This latter class is included in the turboprop category of fig. 8, the outer band of which then indicates a limit descent velocity of 5 - 5,5 ft/sec.

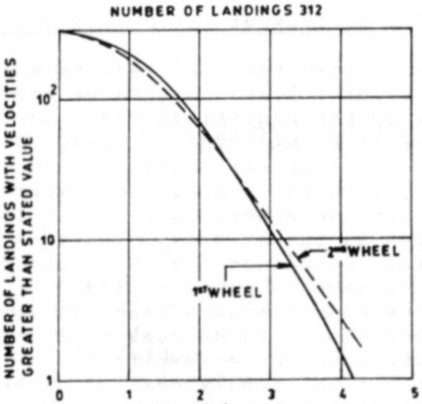


Fig. 9

As these descent velocities are not determined at the wheels (except the XB-70), but at the aircraft c. of g., the influence of initial roll velocity can increase, as well as decrease the wheel descent velocity. An indication of how important this effect can be is given in fig. 9, derived from ref. 4, indicating that for the larger descent velocities the statistical difference in descent velocity for both gears is rather small indeed. Extrapolating, however, to small probabilities of exceedence still an extra 0,5 ft/sec descent velocity should be taken into account for the combination of initial aircraft c. of g. descent velocity and initial roll velocity. It is thought therefore that a limit descent velocity of 6 ft/sec (5,5 + 0,5), is a rational value for smaller turboprop aircraft and older piston engined aircraft up to a landing weight of about 50.000 lbs.

According to fig. 8 a rational value for the turbojet aircraft then should be about 8 - 8,5 ft/sec. For the new generation of jumbojets the distance of the pilot forward of the landing gear again is much larger and therefore it is more difficult to judge and control the descent velocity at impact. It may be expected therefore that the descent velocity statistics will be still more unfavorable for this class of aircraft. Proposing for this class of aircraft the presently required limit descent velocity of 10 ft/sec seems to be appropriate. A lower landing weight limit of about 300.000 lbs will cover this type of aircraft. By lack of more refined statistical data about the relation between aircraft weight and limit descent velocity, it is proposed here to prescribe a linear relationship between these two quantities, in the landing weight range between 50.000 lbs and 300.000 lbs. This can be expressed in the following formula :

$$6 < \dot{z}_{0}(\text{ft/sec}) = 6 + \frac{W_L - 50.000}{50.000} \times 0,80 < 10$$

(W_L= landingweight in lbs)

With the set of initial conditions as defined above, and assuming that initial accelerations are all zero, a rational analysis can be performed rather easily. For all initial conditions, except for roll angle and pitch angle, fixed values are prescribed. Roll- and pitch angle have to be varied in order to look for most conservative limit loads.

Hence, it is thought that a much improved, yet relative simple set of requirements can be formulated on the basis of the philosophy presented above. The properties of the required analysis for such an approach can be summarized as :

- A dynamic analysis of the asymmetric, one wheel first landing impact is required.
- Lateral tire forces which are a fixed ratio of vertical tire forces have to be included in the analysis.
- The dynamic schematisation of the aircraft structure has to be so sophisticated that the normal modes and -frequencies of the structure up to at least $\sim$20 cps are accurately represented.
- Shock absorber schematisation has to be rather sophisticated, and at least involves hydraulic damping forces proportional to shock absorber velocity squared, and a correct representation of the pneumatic shock absorber spring characteristics.
- Horizontal friction forces determined by a friction coefficient of 0,8 and an adequate description of spin-up phenomena, have to be included in the analysis.

The only parameter for which a quantitative value is still required, is the lateral tire friction coefficient μ_y . In principal, values of μ_x and μ_y should be identical. However, the present FAR requirements define lateral tire forces of 0,6 and 0,8 times the vertical tire force and therefore a mean value of 0,7 can also be chosen. Still lower values of 0.25 are specified by the British requirements. This point needs further study, as there are also indications that the true tire yaw angle can be much smaller than the geometric one. As a result of the relation between tire yaw angle and lateral tire friction coefficients as given in fig. 5 , this can result in a much smaller effective value of the lateral friction coefficient.

V. Comparison of existing and proposed requirements

The consequences of the proposed rational requirements for aircraft structural design, in relation to the application of the existing requirements, can only be determined by comparing loads calculated with both sets of requirements.

The existing requirements define some combinations of constant, time independent, vertical and horizontal landing gear forces, which have to be applied to the structure. Fig. 10 illustrates the five loading cases of the present FAR requirements which are based on the availability of landing gear load time histories.

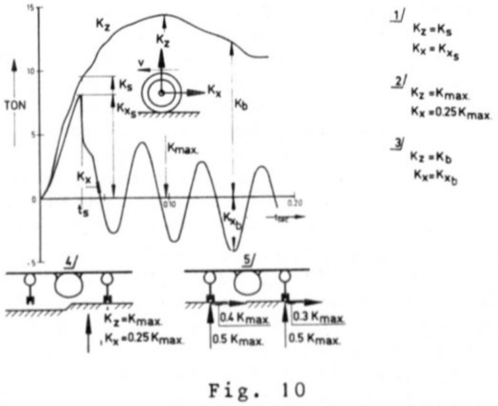


Fig. 10

The British requirements are built up along similar lines, although only three loading cases are defined.

However, real interpretation problems arise when it is attempted to meet both these old-fashioned requirements and the more recent general requirement stating that dynamic loads due to transient deformation have to be properly taken into account. When complete time histories of landing gear loads are available, and are acting on the elastic aircraft structure, it is found that resulting structural loads are at their maxima at quite different moments.

The problem then is whether we have to read the resulting forces and moments at the instants at which the loading cases are specified (e.g. time of maximum drag force or maximum vertical force), knowing that at that time structural loads have not yet achieved, or have already surpassed their maximum values.

The only alternative is to interprete the existing requirements quite liberally and look for absolute maximum values. In that case, however, a discussion is possible about the value of the friction coefficient. Has this value to be 0,8 as specified for the maximum drag case in both the American and British requirements ?

Another possibility is to take the values of μ_x specified for the maximum vertical force case (0,25 for the FAR and 0,40 for the BCAR). One may expect that this would result in lower loads. Because for the proposed requirements a value of 0,8 is defined, the more conservative value of 0,8 has been applied also for the existing requirements.

With this value complete time histories of landing gear and structural loads have been calculated in order to cover the objectives of the general requirement with respect to the transient deformation, as closely as possible.

As the FAR requirements have been chosen for the comparison, three specified landing conditions are dealt with (i.e. symmetric landing, one wheel landing and lateral drift landing without longitudinal drag forces) and the maximal values of the individual structural load time histories are used as the basis for comparison.

In these requirements the max. vertical force for the symmetric- and for the one wheel landing case are equal, whereas for the lateral drift landing 50% of this value is specified. As it is the descent velocity which forms the starting point for the calculation of the load time histories, this again poses problems. For the one wheel landing case the same descent velocity of 10 ft/sec as is specified for the symmetric case proves to result in nearly identical vertical forces. For the calculation example of the F-27 turboprop aircraft these values are 14506 and 14773 kg respectively.

For the lateral drift landing a descent velocity of 5,5 ft/sec resulted in a mean vertical force which is very close to 50% of the vertical force of the symmetric case. For the present example with the aircraft drifting to the right, the values for right and left landing gear are 7,70 and 6,81 ton respectively, as compared with 14,77 ton for the symmetric landing. These unequal values of left and right landing gear illustrate another difference between the formal requirements and the interpretation followed in order to take into account the transient effects. In the requirements (see fig. 10) for the lateral drift landing, both vertical forces are equal, whereas only the horizontal forces are differently specified.

The maximum positive and negative values of the calculated wing- and landing gear loads, as well as of vertical engine acceleration n_m and horizontal pylontank acceleration n_p are compared in table 1 for both the FAR requirements and the proposed requirements. For the calculation example with a landing weight less than 50,000 lbs (35,700 lbs), the descent velocity then had to be 6 ft/sec, whereas initial roll and pitch angle have been varied in such a way as to produce highest loads.

In general the rational analysis results in lower loads, although there are many exceptions. For the landing gear loads the differences are significant too. These differences are directly related to the difference in descent velocity.

As it has been shown already that with the rational approach certainly conservative loads are calculated, it must be concluded in general that if the above given conservative interpretation of the existing requirements is followed, in many cases too high loads are calculated.

For heavier aircraft than the F-27 these differences will be smaller, since the proposed descent velocity values increase with landing weight. This implies that for aircraft with landing weights over about 200,000 lbs the proposed requirements can easily lead to higher loads than will be found with the FAR requirements.

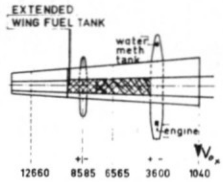
In order to investigate in a more general way the implications of the proposed requirements, especially for larger aircraft, it will be worthwhile to apply these requirements to a number of existing modern aircraft.

The author is convinced however, that application of the proposed rational requirements will improve considerably the accuracy of the load predictions. It is thought therefore that replacing the old-fashioned existing requirements by the proposed rational ones will bring the objective of designing light and economic aircraft structures for a given standard of strength and stiffness a step nearer to its ultimate goal.

VI. Conclusions

- With present analytical and computational facilities an accurate prediction of loads due to landing impacts is possible.
- Taking into account properly structural elasticity requires a dynamic schematisation which predicts properly normal modes and frequencies up to at least 20 cps.
- Present landing load requirements, based on a set of constant, time independent forces applied to the structure, pose severe interpretation problems when they are confronted with the general require-

	wing station	1040	− 3600	+ 3600	6565	− 8585	+ 8585	12660	acc. g.		ton
S_{ton}	A	4,1 -7,1	3,9 -7,4	6,4 -2,4	3,6 -1,9	2,1 -1,7	1,7 -1,5	0,7 -0,6	6,0 -7,5	K_z	-8,8
	B	2,3 -8,1	1,8 -8,5	7,8 -1,0	5,2 -1,3	3,2 -0,9	2,1 -0,9	0,4 -0,4	7,3 -10,9		-14,5
B_{tonm}	A	22,1 -18,7	23,8 -18,5	2,7 -3,0	3,8 -3,5	3,4 -3,1	0,6 -0,6	0,1 -0,1	n_m ↕	K_y	- 6,3
	B	29,8 -21,3	29,4 -18,1	2,2 -2,8	4,0 -4,2	3,6 -3,9	0,7 -0,8	0,1 -0,1	n_p ↔		- 5,6
T_{tonm}	A	28,0 -17,2	33,8 -11,1	21,4 -11,3	9,5 -7,7	5,1 -4,6	4,9 -4,1	0,7 -0,6	6,5 -5,7	K_x	- 4,0
	B	29,1 -11,6	31,8 -8,1	31,4 -6,3	11,6 -4,6	4,3 -3,0	4,1 -2,9	0,4 -0,3	6,0 -0,1		-6,4



A = Rational analysis
B = FAR analysis

filled wing fuel tank
50% filled pylon tank

table 1

ment stating that dynamic effects should be taken into account.

- As a starting point for more modern requirements for design load predictions, based on statistical data with respect to the descent velocity, the most general asymmetric landing impact with one wheel touching down before the other, and with lateral tire forces present, can be used.
- Such an approach can be kept simple because only the initial roll- and pitch angle have to be varied in order to detect maximal possible loads, whereas for all other initial conditions, fixed values can be derived. It is proposed that limit descent velocity will be a function of aircraft landing weight.
- Comparing landing impact load calculations according to the existing and to the proposed requirements, indicates that for small aircraft the proposed requirements can predict somewhat lower loads, whereas for larger aircraft it may be expected that the proposed requirements will be more severe.

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