8th PLANTEMA MEMORIAL LECTURE

LANDING GEAR LOADS OF CIVIL TRANSPORT AIRPLANES

by

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FOREWORD

When Frederic J.Plantema joined the Nationaal Luchtvaartlaboratorium in 1934, I was not yet born, and when he founded the International Committee on Aeronautical Fatigue in 1951, I visited classical high school dreaming of a career as musician.

My late father's anxious advice for more serious profession, my studies of mechanical engineering, chosen more by curiosity than affection, and my first steps as engineer in the stress office of an airplane company were the junctions which led my path of life into the mental neighbourhood of Dr.Plantema. I admired first his carefully written publications. Then, after I had joined LBF, I had now and then a chance to listen eagerly to Dr.Plantema's presentations. Dr.Gassner has introduced me to him in 1963 in Rome on occasion of the ICAF meeting. I was impressed by the personality of Dr. Plantema, especially by his silent, almost hidden dignity and his gentle politeness originating from a deep humanity.

I met Dr.Plantema for the last time on October 6, 1966 in Paris. Since the public transport was on strike, I walked in the morning from my hotel to Denfert-Rocherau, where a bus was supposed to collect the attendees of a Structures and Materials Panel Meeting of AGARD. When I had arrived at the square, I saw Dr.Plantema sitting by himself outside of a cafe smoking deliberately and reflectively a cigarillo. As soon as he recognized me, he invited me to his table. During our conversation he spoke also about his book "Sandwich Construction" and gave me the well-intentioned advice never to write a book because of the enormous amount of work involved. When we said goodbye at the end of that day I didn't know that it was for the last time, because he passed away unexpectedly for all his friends and colleagues a few weeks later.

When I have been asked to present the eigth Plantema Memorial Lecture and that in his native country, I do not only regard this as an outstanding honour and a scientifique challenge, I came also in the honour of Dr.Plantema, a great man and scientist.

1. INTRODUCTION

Statistics of airworthiness authorities and research institutes show that airplane landing gears fail very often in service, if compared with other structural assemblies (Refs. 1 and 2). Analyses reveal that relatively many failures result from unknown operational loadings. There are many reasons for this situation, the three major ones of which shall be mentioned here:

1. Most parts of landing gears had to be designed so far according to the safe-life philosophy. Hence, the safety reserves as included in a fail-safe design are not available in case of a crack due to an unexpected loading condition. (Possibly this will change along with the introduction of landing gear structures as designed according to damage tolerance principles).

2. Information about flight loads was about 25 years earlier available than comparable data about ground loads. McBrearty was probably the first who has critically valued landing gear failures in a paper published in 1948 (Ref.3). He compiled in 1957 (Ref.4) a report about main landing gear load spectra, which however, did not contain all load cases to be considered for an adequate fatigue life assessment. A first attempt to accomplish this was made in 1969 (Ref.5).

3. The loading conditions at a landing gear are complicated because of the interaction of loads acting in three or even four degrees of freedom, if torsion about the vertical axis is included. Hence, it is difficult to develop mathematical models for the description of the load components itself and their correlations, and it is a very cost and time consuming task to measure loads at landing gears under operational conditions.

Beyond that it has to be taken into account that the landing environment of landing gears has changed during the last decade, e.g.:

- The new generation of wide-body airplanes have forced designers to increase both the number of wheels per airplane and the static load per wheel.
- The boundary conditions at runway contact during landing are different for wide-body airplanes from those of the other (smaller) types of airplanes due to ground effect and higher moments of inertia.
- Automatic landing procedures will possibly result in other cumulative frequency distributions of sinking speeds than those observed for pilot-performed landings.
- Modern airports have usually larger taxiways than the older, and they may have finger-type ramps which require special ground manoeuvering of the airplanes.

In order to provide reliable information about loads as necessary for a safe and economic usage of landing gear structures, three general problems have to be solved by means of measurements performed at landing gears under operational conditions during representative periods of observation:

- New loading conditions must be described which so far didn't exist or haven't been considered, e.g. towing of an airplane,
- known loading conditions must be adjusted to changed ground handling of airplanes with regard to magnitude, number of occurrences per landing, and/or sequence of loads, or must be corrected according to new relevant information, e.g. landing impact loading of nose gears,
- relations between load components have to be derived, e.g.for the loads occurring during taxiing.

Measurements of loads at landing gears during normal operational usage were carried out by the Fraunhofer-Institut für Betriebsfestigkeit (LBF) in the last two decades at two types of military transport airplanes (Refs. 6 and 7), a fighter type airplane (Refs. 8 and 9), and a wide body transport airplane of type Airbus A300-B2 (Ref.20). Results from these measurements will be presented and compared with other results published in the literature in order to establish basic loading information for the design of main and nose landing gears of civil transport airplanes.

2. COORDINATES AND GROUND REACTION FACTORS

The operational loads acting at the wheel of a landing gear correspond to a vector which changes its magnitude and direction versus time. If a landing gear has more than one wheel, it is usually sufficient for design purpose, to know the resulting load components at the complete gear. For an appropriate description a coordinate system may be assumed, the origin of which is located e.g. at the point of intersection between the centerline of the main strut of the landing gear with the ground plane. For the case of steerable landing gears it is usually assumed that the coordinate system will rotate together with the steering angle about the vertical axis of the coordinate system.

The signs of the loads F acting in x-(drag), y-(side), and z-(vertical) direction and of the torsion moment M_t about the z-axis are chosen as it is shown in Fig. 1. It should be noted, that the positive sign for the side load components F_y at a main gear is assigned always to loads which are directed outboard. This definition doesn't agree with standards, however, it allows to compare directly the results obtained from right and left gears. Attention has to be paid to the fact that for deriving loads from measured outputs of calibrated strain gage bridges the deflection of the shock absorbers has to be taken into account. Therefore, when establishing load sequences for an experimental or theoretical fatigue life assessment from such results of measurements, the position of the shock absorber has to be defined adequately.

In order to be able to transfer loads as measured at a landing gear to other types of gears, so-called ground reaction factors have to be derived by relating the load F to the instantaneous vertical static gear load $F_{z,stat}$. Thus one obtaines

$$e_x = \frac{F_x}{F_{z,stat}} ,$$

$$e_y = \frac{F_y}{F_{z,stat}} ,$$

$$e_z = \frac{F_z}{F_{z,stat}} ,$$

and for the torsion moment at twin axle (bogie) landing gears

$$e_t = \frac{M_t}{F_{z,stat} \cdot a} ,$$

where a is the distance between the two axles. [1] Similarly, for load increments ΔF ground reaction factor increments Δe are obtained.

3. LANDING GEAR LOADS TO BE CONSIDERED FOR FATIGUE LIFE ASSESSMENT

The loading cases to be considered for fatigue life assessment of aircraft landing gear structures may be arranged in five groups, see Table 1. In each landing case combinations of vertical, side, and drag loads, and in addition even torsion moments may occur as it will be described in the following chapters.

3.1 Landing and Take-off

3.1.1 Landing impact

The maximum vertical load acting at a main landing gear during first ground contact at the end of a flight can be estimated with sufficient reliability from the respective sinking speed of the airplane (Ref. 11). Cumulative frequency distributions of sinking speeds or of normal vertical accelerations are available from the literature (Refs. 12 to 15) or from specifications (Ref. 16). This procedure is well known and will thus here not be discussed further.

As long as no comparable information about landing impact loads was available for nose landing gears, it was used to assume that they would encounter the same sinking speed as the main landing gears. The results of the measurements performed at F-104 G landing gears have caused already doubts whether this assumption could be supported, because it has been found that the cumulative frequency distribution of nose landing gear impact loads was about 2.2 times higher than observed for the main gear (Refs. 8 and 9).

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1) The ground reaction factor e is a real load factor. The latter expression, however, is traditionally used for the ratio of accelerations n. It should be noted that normally a well-defined relation between e and n doesn't exist.

However, one could have objected that a small fighter airplane might have other landing characteristics than e.g. a wide-body transport airplane. Nevertheless, the measurements obtained from the Airbus showed, that a similar relation (1:2.5) exists between vertical ground reaction factors at main and nose gears, see Fig. 2, although the absolute intensity between landing impact loads differs between the two types of airplanes as it would have been anticipated from experiences as contained in specifications and other documents.

It is rather difficult to study the reasons for that unexpected behaviour of nose gears and it is tried here to give some background information without aiming at presenting already a proof. Investigations of NACA demonstrated that no correlations between wing lift and sinking speed, between roll angle and roll rate, as well as between horizontal and vertical speed were found during landings (Ref. 17), and further, that the vertical acceleration in the C.G. of the airplane due to landing impact seems to be independent from forward speed, the C.G. acceleration prior to ground contact, the airplane gross weight, and the normal-force coefficient immediately prior to impact (Ref. 18). Hence follows that in general the boundary conditions to be introduced into a mathematical model for the calculation of vertical forces during landing impact cannot be defined adequately. In addition, most landings of turbine-powered airplanes on normal airfields seem to be so-called two-point landings on the main gears and are made with positive angle of attack taking advantage of the ground effect during the gliding approach of the airplane. A plot of angles of attack at landing impact versus the time difference elapsed between first control of main and nose gears results in a wide scatter band and is, therefore, not very informative, see Fig. 3. The observed time differences varied between 0.8 and 18 seconds, see the statistical analysis presented in Fig. 4.

Consequently, the kinetic energy of the downward movement of the aircraft during landing must have been absorbed by the main gears only, while the nose gear impact is caused mainly by the rotation of the airplane due to elevator movement induced by the pilot, a process with which always lift at the wing is reduced. It can't be answered yet why the ratios of intensities between the cumulative frequency distributions of vertical loads during landing at main and nose gears are so close together for the two different types of airplanes. Unless other information is available, it is recommended, to multiply the intensities of vertical ground reaction factors as described for the main gear by a factor of at least 2, if from the latter vertical landing impact loads at the nose gears are derived.

Further, it has to be considered that at nose gears sometimes several impacts will occur per landing, as it is shown in the example of load time histories as recorded at a main and the nose gear of an Airbus, see Fig. 5. The (average) cumulative number of landing impacts per flight at the nose gears was observed to be 1.5 for the Airbus and 5 for the F-104 G.[2)]

An analysis of the variation of vertical static gear loading shows, that not only the scatter is almost twice but also the absolut values differ more from the respective maximum allowables for the nose gear than it is the case for the main gear, see Fig. 6, where the cumulative frequency distributions of vertical static loads are plotted in a probability paper and approximated by straight lines (log. normal distributions). Changes in payload and fuel will effect the nose gear much more than the main gear because of its sensitivity against variations in the C.G. position of the airplane. Therefore, it may happen, that the spring of the nose gear will be too hard for the actual loading and it then tends to "jump". This will be favoured, if the thrust of the engines is reversed or if the pilot doesn't keep the elevator down.

Another result of the analysis of measurements is the distribution of time differences between the first ground contacts of right and left hand main landing gears, see Fig. 7, which shows about 10 percent more left gear contacts. The maximum of the distribution, however, appears at zero, i.e. contact with both gears at the same time. A similar distribution has been found for the F-104 G (Ref.8).

3.1.2 Spin - up

The prediction of wheel spin-up loads acting in x-direction at a landing gear is very difficult even if the coefficient of friction between the tires and the runway would be known because many other parameters seem to have an influence (Refs. 17 and 19).

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2) It should be noted that drag loads due to spin-up and spring-back will normally only come with the first impact.

A plot of the maximum drag loads due to spin-up versus the maximum vertical landing impact load which have occurred at the same landing, but not necessarely at the same time, show a range of scatter, according to which the (negative) drag load lies between 6 and 85 percent of the corresponding vertical load, see Fig. 8.

The cumulative frequency distributions of ground reaction factors which were caused by spin-up peak loads have not only similar shapes as those obtained for the landing impact, see Figs. 9 and 2, also the differences in intensity between the distributions for corresponding main and nose gears are the same.

This suggests to compare those values of the ground reaction factors e_z and $-e_x$, which have occurred with the same cumulative frequency per flight as it has been suggested earlier (Ref. 20). If this is done, one obtaines that the ground reaction factors due to spin-up (S.U.) are in a narrow relation with the factors due to landing impact (L.I.):

$$-e_{x,S.U.} \quad = \quad (0.4 \ldots 0.6) \cdot e_{z,L.I.}$$

and that for main and nose landing gears of both types of airplanes.

3.1.3 Spring-Back

The energy which was built up in a landing gear structure against the direction of flight (-x) by acceleration the wheels from zero to horizontal speed of the aircraft during first ground contact will result normally in a spring-back which will die away with four low damped oszillations (average) per landing. The corresponding cumulative frequency distribution is almost linear exponentially distributed.

The maximum ground reaction factor due to spring-back (S.B.) has been found from the measurements performed at main and nose gears of both types of airplanes to be 0.5 up to 0.7 times the maximum value of the spin-up wich occur with the same relative cumulative frequency:

$$e_{x,S.B.} \quad = \quad -(0.5 \ldots 0.7) \cdot e_{x,S.U.} \quad ,$$

see Fig. 9 .

3.1.4 Side Loads

Side loads during landing may be caused not only by skidding or yawing movements of the airplane but also by elastic deformations of the landing gear and the wing or fusalage structure to which it is attached (Ref.21). This may be the reason why from the measured side loads not such a simple empirical relation can be derived as it has been found between landing impact and spin-up or between spin-up and spring-back loadings.

There was no landing observed during which not some side loads have occurred. Further, during almost all landings the side loads changed the sign, although the individual side-load histories per landing can be very different.

If analogous to the graph in Fig. 8, the maximum positive and negative side loads $\pm F_y$ are plotted versus the maximum vertical landing impact load F_z, which have occurred at the same landing but must not have happened at the same time, a range of scatter is observed, the boundaries of which are given for nose and main landing gears of both types of airplanes by the relation

$$F_y = \pm (0.40 \ldots 0.55) \cdot F_z \quad ,$$

see Fig. 10.

If the maximum positive and negative ground reaction factors due to lateral loads which have occurred at each landing are plotted as cumulative frequency distributions, see Fig. 11, it is evident that the nose wheel of the Airbus has encountered about three times higher ground reaction factors in comparison to the main gear. Presumably this is caused amongst some other reasons by the actuation of rudder subsequent to first ground contact of the nose gear and fuselage flexibility.

3.1.5 Torsion Moments

Except of only very small samples (Ref. 22) up today no information about torsional loadings of landing gears is available from the literature which can be regarded to be representative for the usage of an airplane.

The maximum positive and negative ground reaction factors, e_t, as observed during landing at the main gear of an airplane of type Airbus are shown in Fig. 12. The differences at low number of occurrences between right and left hand main landing gear torsion loadings are not significant.

3.1.6 Recommendations for Fatigue Life Assessment

Although the maximum values of the load components and the torsion moment during landing will often not occur at the same time, it is recommended to assume for a theoretical or experimentell fatigue life assessment, that the maximum vertical load due to landing impact is kept constant, while corresponding spin-up and spring-back drag loads are combined with a positive-negative for odd and a negative-positive side load cycle for even numbers of flights, where the magnitude of the side loads might be taken from the cumulative frequency distribution of Fig. 11 at random. In order to simulate the torsion moments, the side loads acting at the two axles of a bogie type landing gear should be distributed unequally.

3.1.7 Landing and Take-Off Runs

The cumulative frequency distributions of ground reaction factors during landing and take-off runs as obtained from counting level crossings are shown in Figs. 13 and 14 for nose and main landing gears of an airplane of type Airbus. It should be noted that the magnitude of ground reaction factors of the nose gear is about twice that having been recorded for the main gear, where the accelerations in the cockpit were about 3.8 times higher than those in the C.G. (Ref.10). As the loads acting during these two phases can be regarded as unbraked taxiing with high speed, it is referred here to paragraph 3.2 for details of combinations of load components etc.

3.2 Taxiing

3.2.1 Unbraked Taxiing

Up to now only vertical loads have been taken into account for most fatigue life assessments of a landing gear in the landing condition unbraked taxiing, as it has been proposed by McBrearty (Ref.40) and others (Refs. 12 and 13). Reasons for this are based upon the opinion that side and drag loads during taxiing are small not only if compared with vertical loads but also with other loading conditions. In automotive engineering contradictory experiences have been gained.

However, the dimensiones of landing gears of a wide-body airplane, see Figs. 15 and 16, are such that these loads will cause large bending moments. Moreover, the number of occurrences for each of the three load components is very high relative to all other loading conditions, see Figs. 17, 18 and 19, where the cumulative frequency distribution of level crossings is plotted per minute of taxiing of main and nose landing gears of the Airbus. A statistical analysis of taxi times has shown that for this type of airplane 7 minutes before and 4 minutes after flight will be reached or exceeded with a probability of 50 percent, see Fig. 20[3]. As it has been mentioned already for take-off and landing run loadings, the intensity of ground reaction factors of the nose gear is also during unbraked taxiing significantly higher than that of the main gear. A possible explanation for that behaviour, which has been also observed for the F-104 G (Refs. 8 and 9), may again be found from the significantly greater difference between actual to allowable static vertical loads at the nose gear, see Fig. 6. As far as lateral loads are concerned, also small steering movements may be involved. In addition, the airplane flexibility may be important also for the higher loading intensity at the nose gear (Ref. 21).

3.2.2 About the Combination of Load Components Occurring During Taxiing

The correlation of drag, side, and vertical loads is difficult, because the elastic properties of a landing gear and its tires are different in the three coordinate axes, see Fig. 21, where the power spectral densities of loads during unbraked taxiing have been plotted for nose and main landing gears of the Airbus. Consequently, no determined relation of simultaneously occurring load components can be expected, see Fig. 22.

Investigations of NASA about the relation between drag and vertical loads which result from rolling over defined obstacles, allow to derive an almost proportional behaviour

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3) If as an average a period of 11 minutes taxiing is assumed to happen per flight, the total number of level crossing countings is about $2 \cdot 10^3$ for e_x, $7 \cdot 10^2$ for e_y, and 10^3 for e_z.

(Ref.23). Although this has not been found under normal operational conditions, it is suggested to assume that from three possible reasons for the existence of drag loads during unbraked taxiing which are inertia forces, rolling friction, and loads due to the horizontal component if a wheel is passing an obstacle, only the latter will cause the resulting drag loads.

Therefore, a positive vertical load increment should be combined with that negative drag load which has occurred with the same relative cumulative frequency, and vice versa. The differences in total number of occurrences about the mean values of load will not be taken into account by that procedure.

The lateral loads during unbraked taxi are caused by two different reasons which are forces due to lateral guidance properties of the tires and due to movements of the airplane about its longitudinal axis (rolling). For fatigue life assessment the following procedure is proposed: It may be assumed that one third of all load variations consisting of a combination of vertical and drag loads as described above, will happen without side loads. The following third of load variations beginning with a positive vertical load increment will be combined with the same number of cycles which start with a positive lateral load ($\pm F_y$). The remaining third will be combined with cycles starting with a negative lateral load ($\mp F_y$). The side loads may be assumed to be constant, i.e. the steady distribution as having been measured will be replaced by a rectangular one which should possibly produce the same damage.

The similar procedure is, of course, also suggested for the loads resulting from take-off and landing runs.

3.2.3 Turning, Pivoting and Steering

The analxsis of the measurements as performed at an airplane of type Airbus A-300 B2 resulted after low pass filtering of the lateral load signal as recorded at the main gears at 0.35 Hz in two cumulative frequency distributions of level crossings for the ground reaction factors e_y which are almost identical for turns before and after flight, see Fig. 23. Accordingly, three right hand and left hand turns will occur, and that as well before as after flight. The plot of the cumulative frequency distribution of ground reaction factors due to torsion at the main gears is similar, see Fig. 24 except of the peak values which have occurred with low relative cumulative frequency and which may result from pivoting a significant lateral loading.

The lateral loads obtained for the nose gear due to steering lead to cumulative frequency distributions of similar shape and number of occurrences per flight, see Fig. 25, but to an about 2.5 times higher intensity than for the main gear.

3.3 Braking

From the measurements performed at the Airbus cumulative frequency distributions of ground reaction factors e_x due to braking were obtained with a total number of 3 brakings before and 3 after each flight, see Fig. 26. This is well in agreement with the assumption made so far for most fatigue life assessments of landing gears. However, the intensity of braking loads as observed at the airbus is less than that of the mentioned assumptions (Ref.4). Completely symmetrical brakings at both main gears are very seldom, see Fig. 27, where braking drag loads at right and left main gears have been plotted which have occurred simultaneously. The nose gear encounters due to a pitching movement of the airplane as induced by the brake application at the main gear an increase in vertical static load, see Fig. 28, which in case of extremely unsymmetrical brakings seems to follow another empirical relationship than for the normal, i.e. almost symmetrical brake application. However, the lateral loads induced at the nose gear by unsymmetrical brakings have to be taken into account. This loading condition will happen, if e.g. a pilot aims at taking the nearest possible taxi-way leading off the runway after landing, because he may then actuate the brake of one main landing gear not only in order to reduce speed but also to support the effect of steering with the nose wheel.

Engine run-ups with braked landing gears before flight are no longer usual for civil transport jet airplanes. Engine run-ups after overhaul or inspection periods have to be taken into account seperately, also if the airplane is hold during this procedure with ropes being attached to special lugs at the gear structure. In the latter case the changed points of load introduction have to be noted.

3.4. Towing and Pushing from Ramp

Many conjectures have been made in the past about the magnitude of the loads occurring at the nose gear during towing and pushing-back from finger-type ramps of modern airports.

The measurements have demonstrated that the ground reaction factors at the nose gear due to drag loads amount to magnitudes which will exceed even the (only negative) spin-up loadings and will occur as well in positive direction as with a much higher number of occurrences, see Figs. 29 and 30. This means that the fatigue life of nose gear parts which are critical against drag loads will be determined to a large extend by these loading conditions. A similar conclusion was drawn in a recently published report having been prepared for the FAA (Ref.24), and the results of another study demonstrated, that a relatively simple model could be used to predict the towing load response (Ref.25).

The considerations of several airlines to tow airplanes in future to the run-ways instead of having them taxiing by own power in order to safe fuel and to reduce noise are under these aspects unrealistic, because nose landing gears have not been designed against that loadings. Two recommendations can be given in this context:

a) The rigid bars as used today for towing or pushing-back airplanes having just one predetermined breaking point should be replaced as soon as possible by such bars having a proper spring and damping system in order to avoid load peaks caused by sudden starts or stops of the towing vehicle. In addition, pilots should be advised not to use the brakes if the airplane is being towed or pushed.

b) The information as obtained from the measurements as presented here may be used for designing new nose gears against this loading condition or even to strengthen older types. However, it should be tried in designing the landing gear structure such that the towing point is as close to the fuselage as possible in order to reduce the bending moments.

3.5 Misellaneous Loading Conditions

Beside the loading conditions as mentioned before additional loadings have to be included in a fatigue life assessment for a landing gear or have at least to be checked whether they are important with respect to possible fatigue damage.

- Of course, the <u>ground-air-ground transition</u> has to be taken into account, which occurs once per flight.

- Also during rectraction or extension of the gear dynamic loadings may occur caused by the speed of the hydraulic actuation or if the gears have to be rotated in direction of flight so that air loads may originate.
- Tire imbalance is a loading condition which can hardly be described by other methods than experiments, because it doesn't obey to determined laws rather than to unequal wear of originally well balanced wheels and tires, Therefore, it is made reference here to the relevant literature.
- Self-excited Oscillations may result from the interaction of a friction surface with the compliance of two -or more- degrees of freedom systems. Especially wear may cause "brake linings" and exhibit unstable torque velocity slopes, as do the tire to runway friction characteristics. A brakes-locked-phenomenon encountered on a wet surface of a Lockheed Constellation (Ref.3) was later treated analytically (Ref. 26). Also modern type airplanes are reported to have been found in self-excited oscillations including nose and main gears, and antiskid systems (Ref.27).
- Nose Gear Shimmy has been investigated extensively including nonlinear theories (Refs. 28 and 29) and it should be avoided by suitable design methods. In 1975 a study was performed for developing an active shimmy control system (Ref.30).

4. CONCLUSION

The most astonishing result is obviously the high loading intensity of the nose landing gear in general, and especially in the loading conditions towing and pushing-back from ramp. This result must not directly lead to the danger of early fatigue failures, because the vertical static load of the nose gear which the ground reaction factors are related to is significantly lower than of the main gear. However, fatigue is not only a result of (positive) peak loading but amongst others also of the variation of loading. Therefore, it will be necessary to look in more detail into the loading environment of nose landing gears. Some possible areas of research are beside the investigation of the effect of structural flexibility which seems to be very important, the study of rudder and elevator usage during landing, and the redesign of tow-bars.

It is hoped that the results presented may contribute in a time where already active landing gear controls are planned (Refs. 31 and 32) to the goals of ICAF in the sense of F.J.Plantema, i.e. to make aircraft landing gear structures safer, more reliable and more economical.

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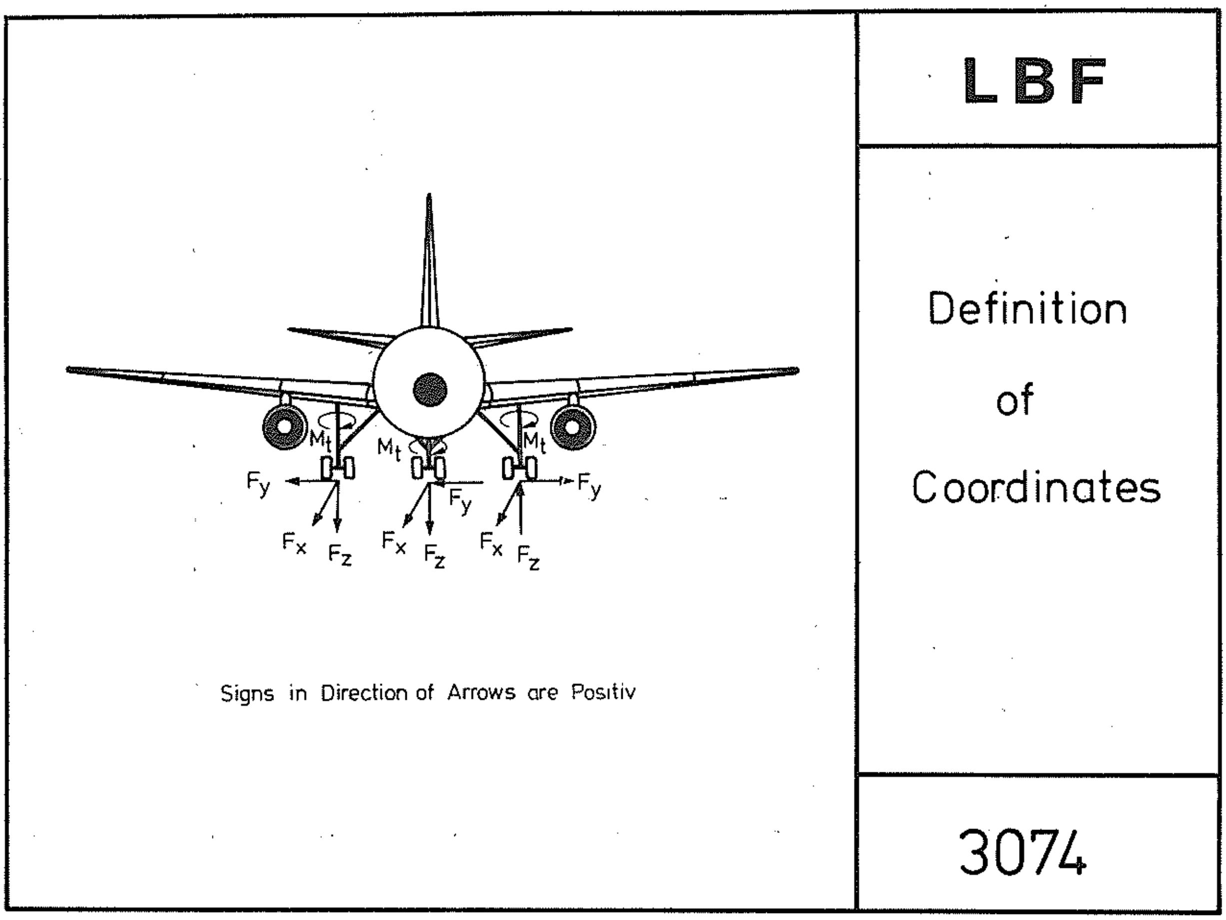
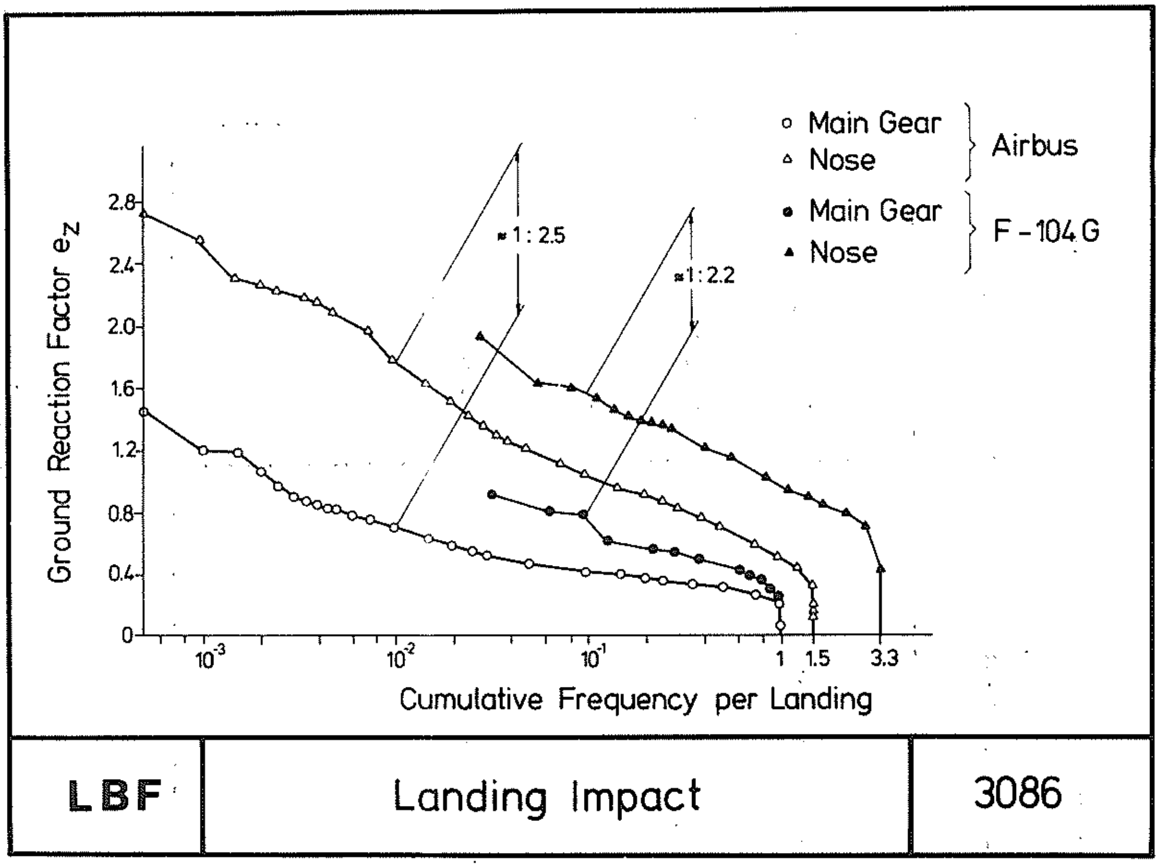
Landing and Take - off	Taxiing	Braking	Towing	Miscellaneous
Landing Impact and Spin - up	Unbraked Taxiing	Symmetrical Braking	Normal Towing	Ground Air - Ground Transition
Spring - Back	Steering	Unsymmetrical Braking (plus Steering)	Pushing from Ramp	Tire Imbalance
Landing Run	Turning	Engine Run - up		Self - Excited Oscillations
Take - off Run	Pivoting			Shimmy
				Extending and Retracting

Table 1 : Loading Cases to be Considered for Fatigue Life Assessment of Aircraft Landing Gears



LBF
Definition of Coordinates
3074
Mt
Fy
Fx
Fz
Signs in Direction of Arrows are Positiv

Fig. 1



Main Gear
Nose
Airbus
Main Gear
Nose
F-104G
≈1:2.5
≈1:2.2
Ground Reaction Factor e_Z
Cumulative Frequency per Landing
LBF
Landing Impact
3086

Fig. 2

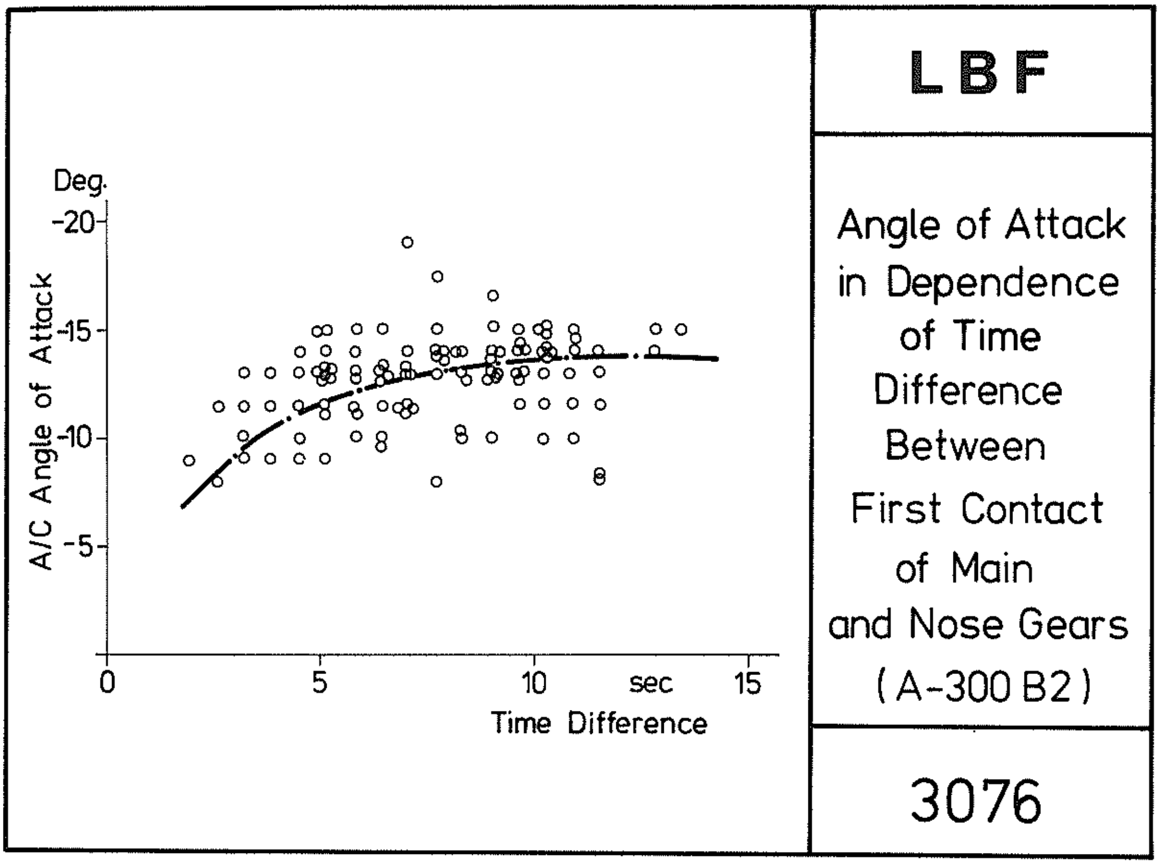

LBF
Angle of Attack in Dependence of Time Difference Between First Contact of Main and Nose Gears (A-300 B2)
3076
Deg.
-20
-15
-10
-5
A/C Angle of Attack
0
5
10
sec
15
Time Difference

Fig. 3

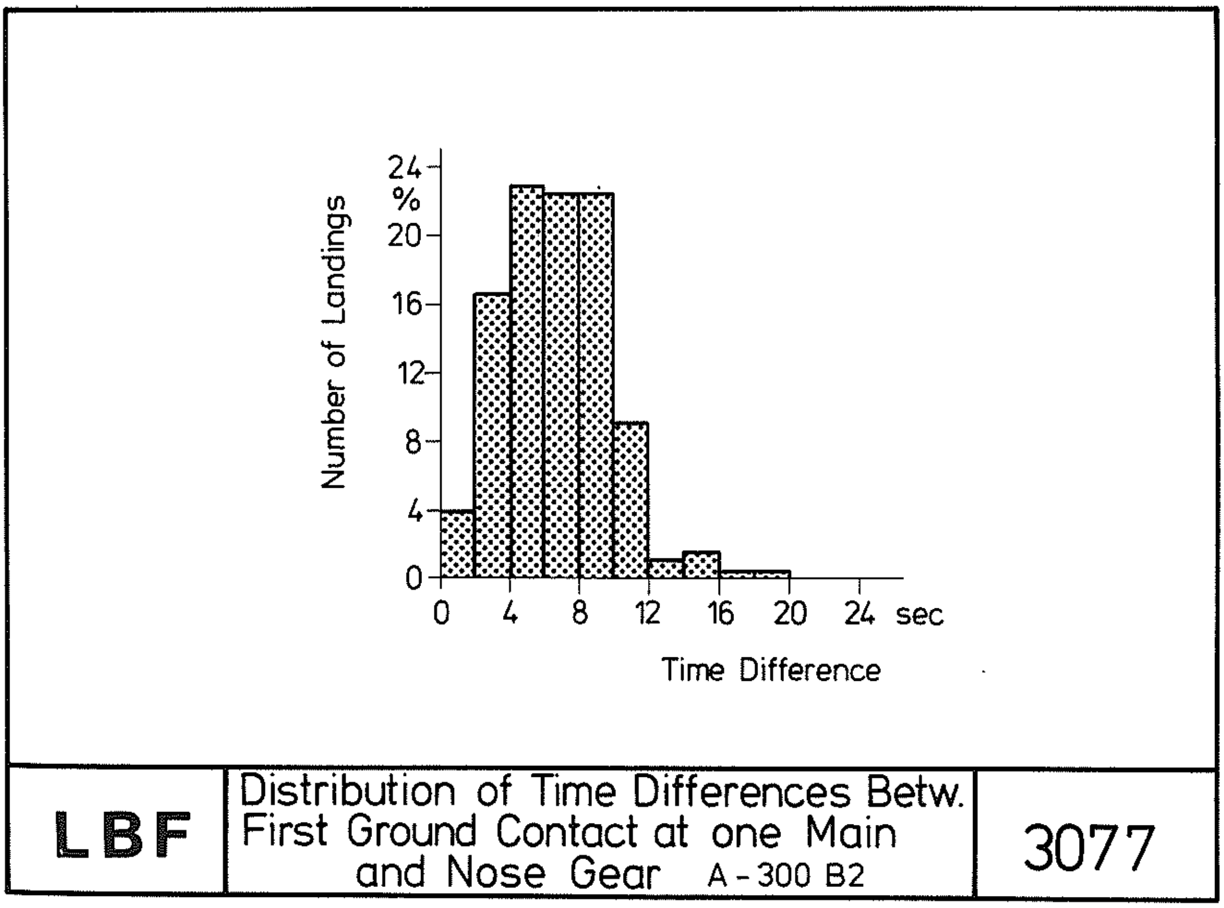
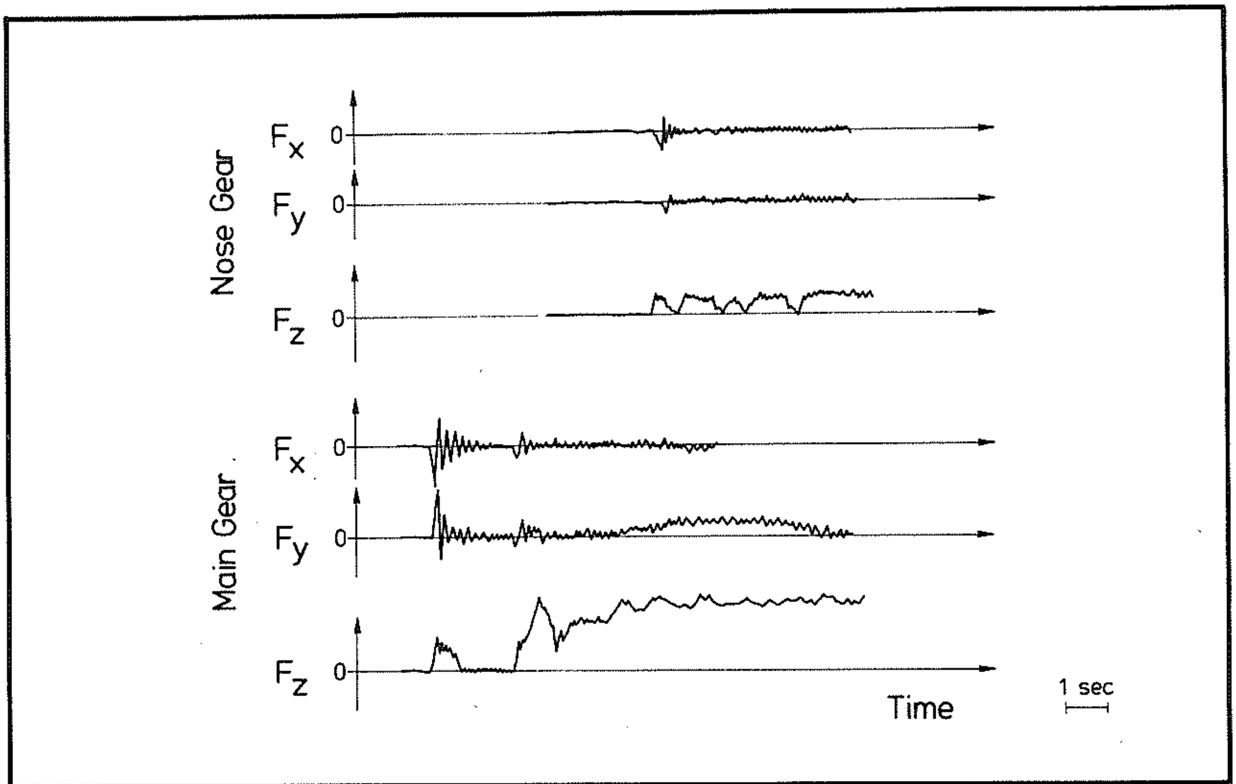
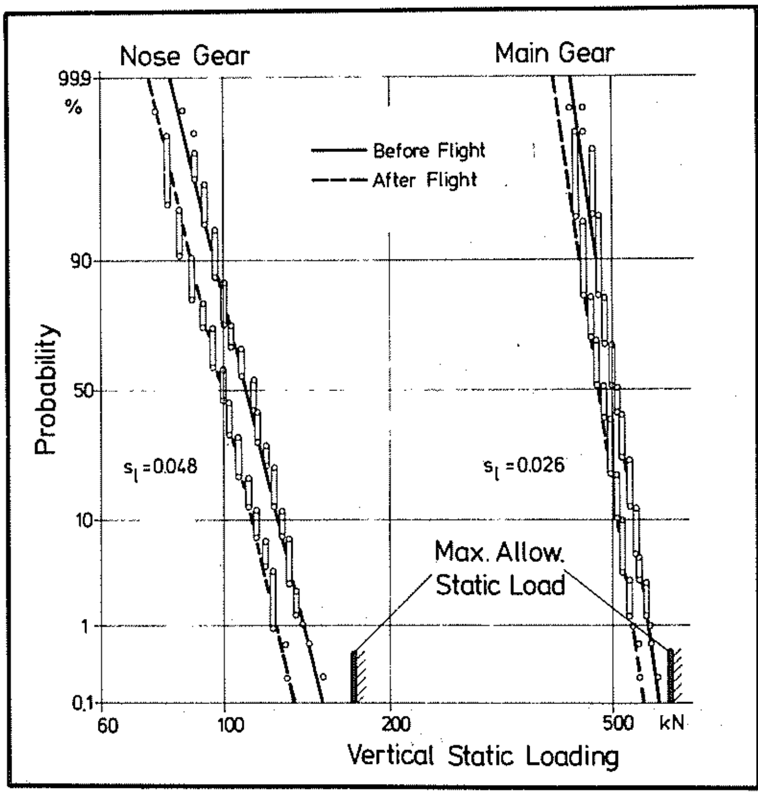

24
%
20
16
12
8
4
0
Number of Landings
0
4
8
12
16
20
24
sec
Time Difference
LBF
Distribution of Time Differences Betw. First Ground Contact at one Main and Nose Gear A-300 B2
3077

Fig. 4



LBF | Load-Time Histories During Typical Landing (A-300 B2) | 3085

Fig. 5

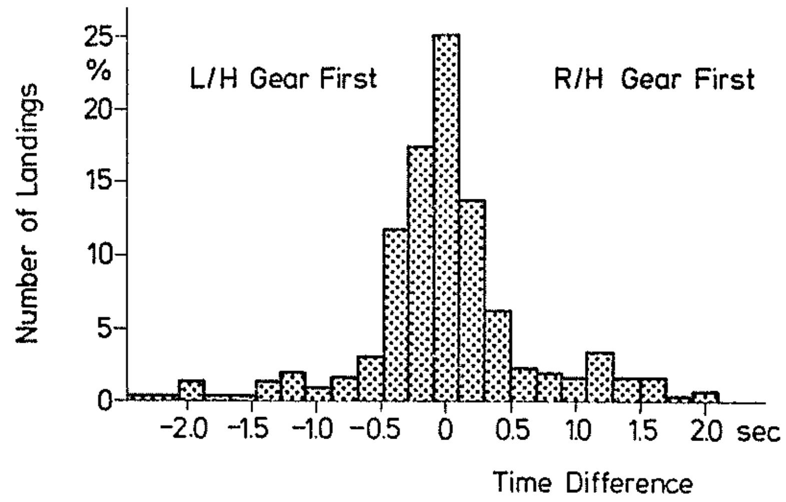


LBF

Cumulative Frequency of Vertical Static Loading at Nose and Main Landing Gears (A-300 B2)

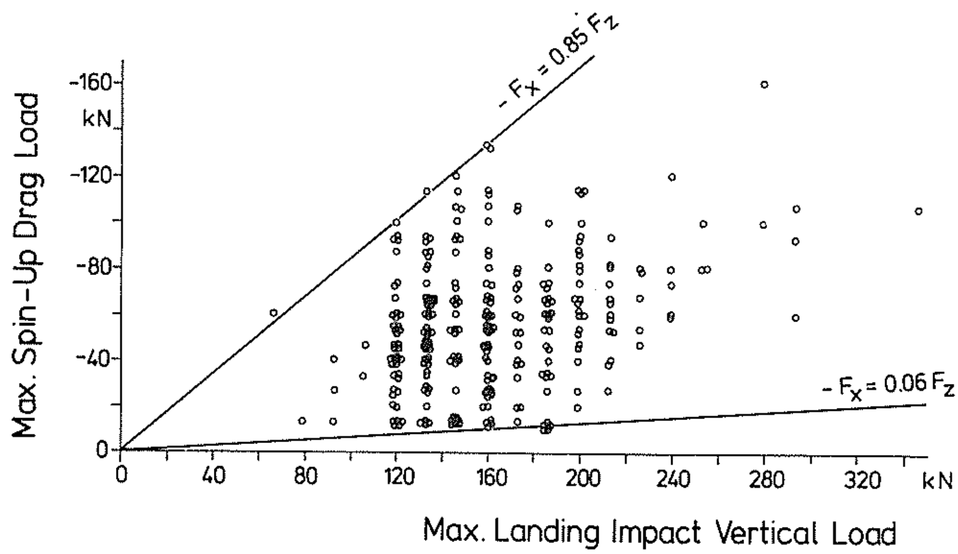
3087

Fig. 6



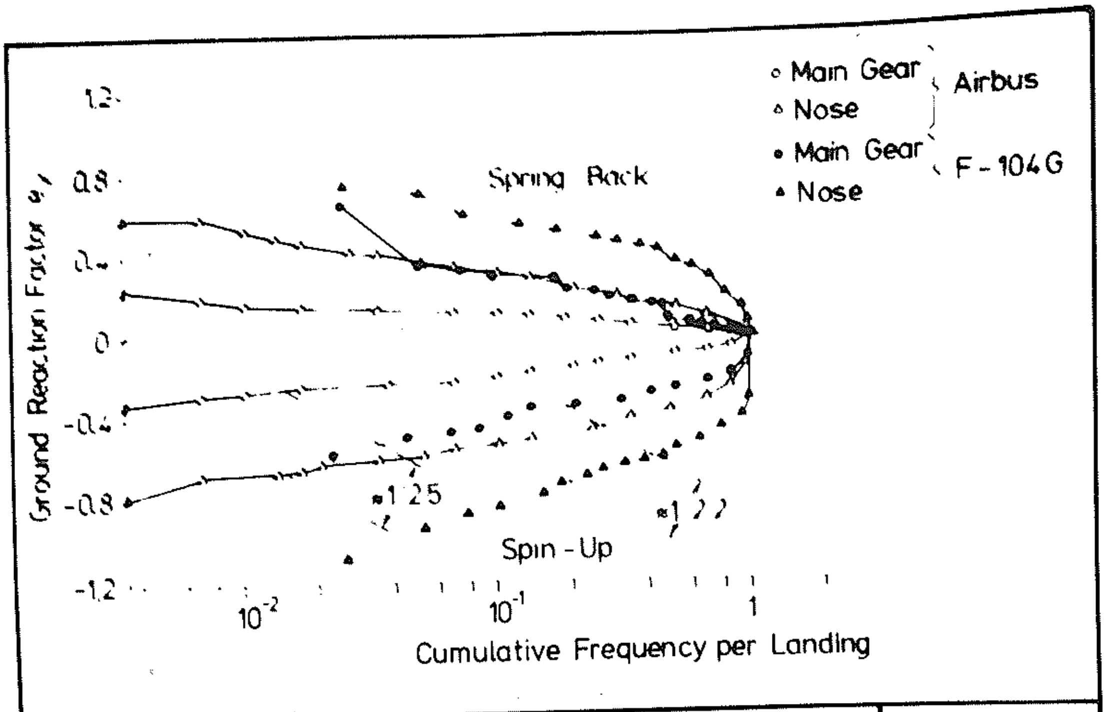
LBF	Distribution of Time Differences Betw. First Ground Contact of R/H and L/H Main Landing Gear A-300 B2	3080

Fig. 7



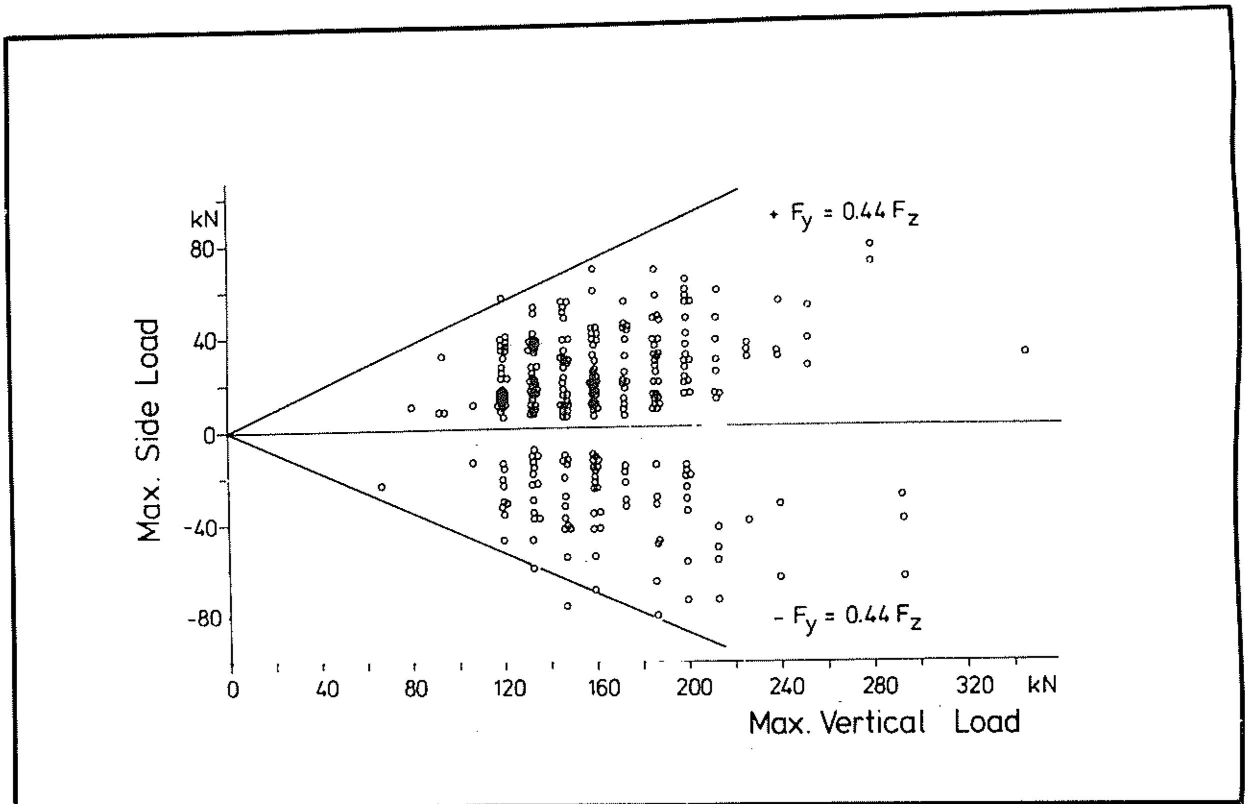
LBF	Correlation of Max. Drag and Vertical Loads During Landing Impact (A-300 B2, Main Landing Gear)	3084

Fig. 8



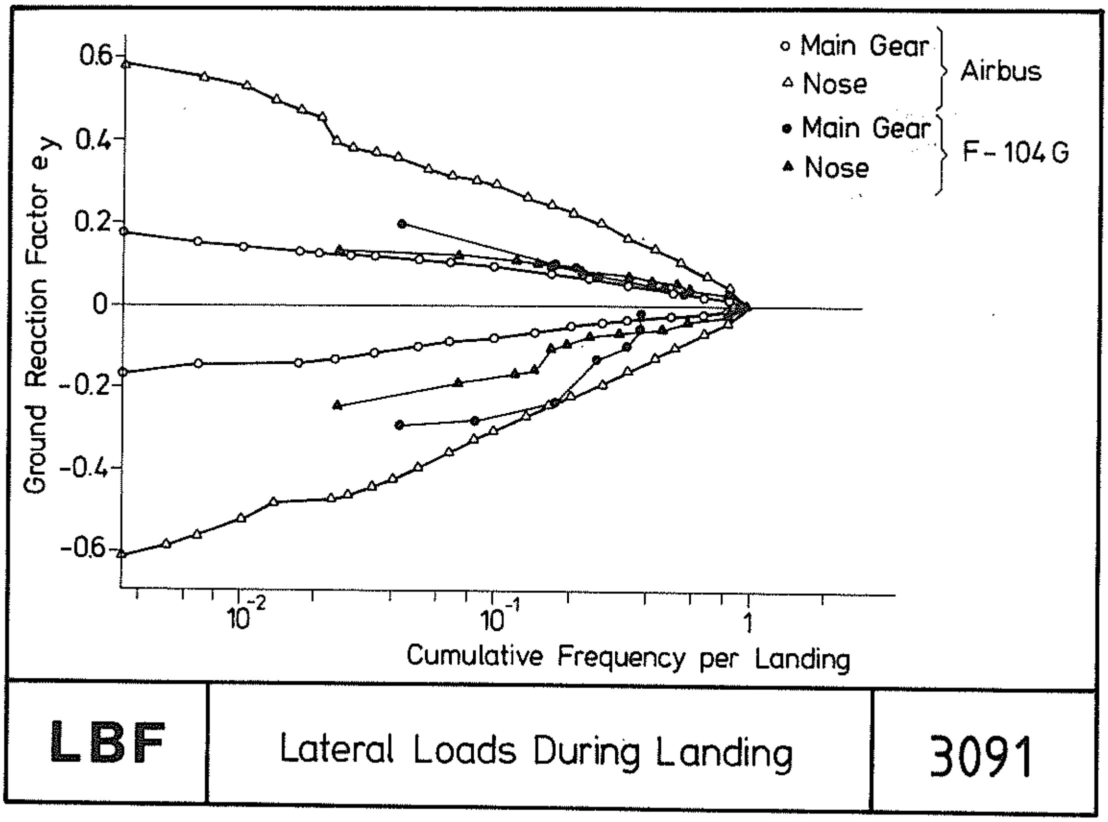
LBF	Spin-Up and Spring-Back	3081

Fig. 9



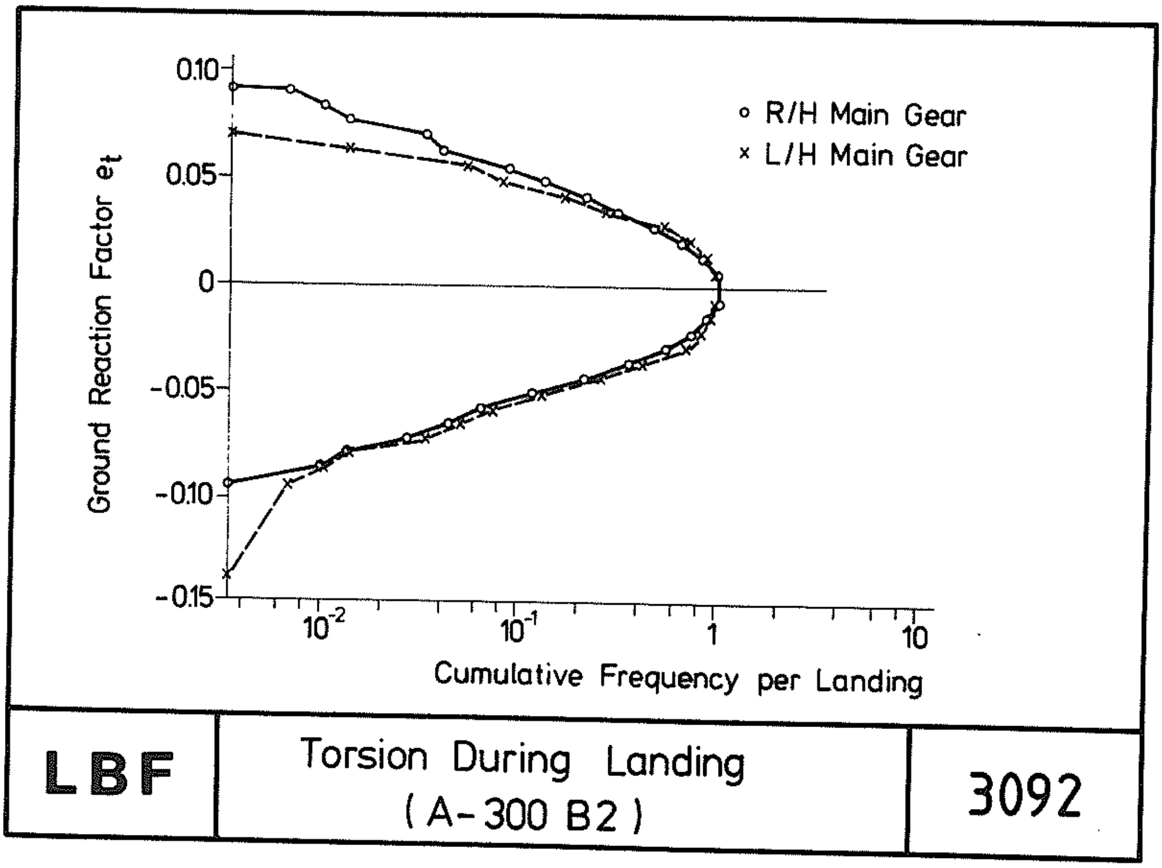
LBF	Correlation of Max. Side and Vertical Loads During Landing Impact (A - 300 B2 , Main Landing Gear)	3083

Fig. 10



Ground Reaction Factor e_y
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
10^{-2}
10^{-1}
1
Cumulative Frequency per Landing
Main Gear
Nose
Airbus
Main Gear
Nose
F-104 G
LBF
Lateral Loads During Landing
3091

Fig. 11



Ground Reaction Factor e_t
0.10
0.05
0
-0.05
-0.10
-0.15
10^{-2}
10^{-1}
1
10
Cumulative Frequency per Landing
R/H Main Gear
L/H Main Gear
LBF
Torsion During Landing
(A-300 B2)
3092

Fig. 12

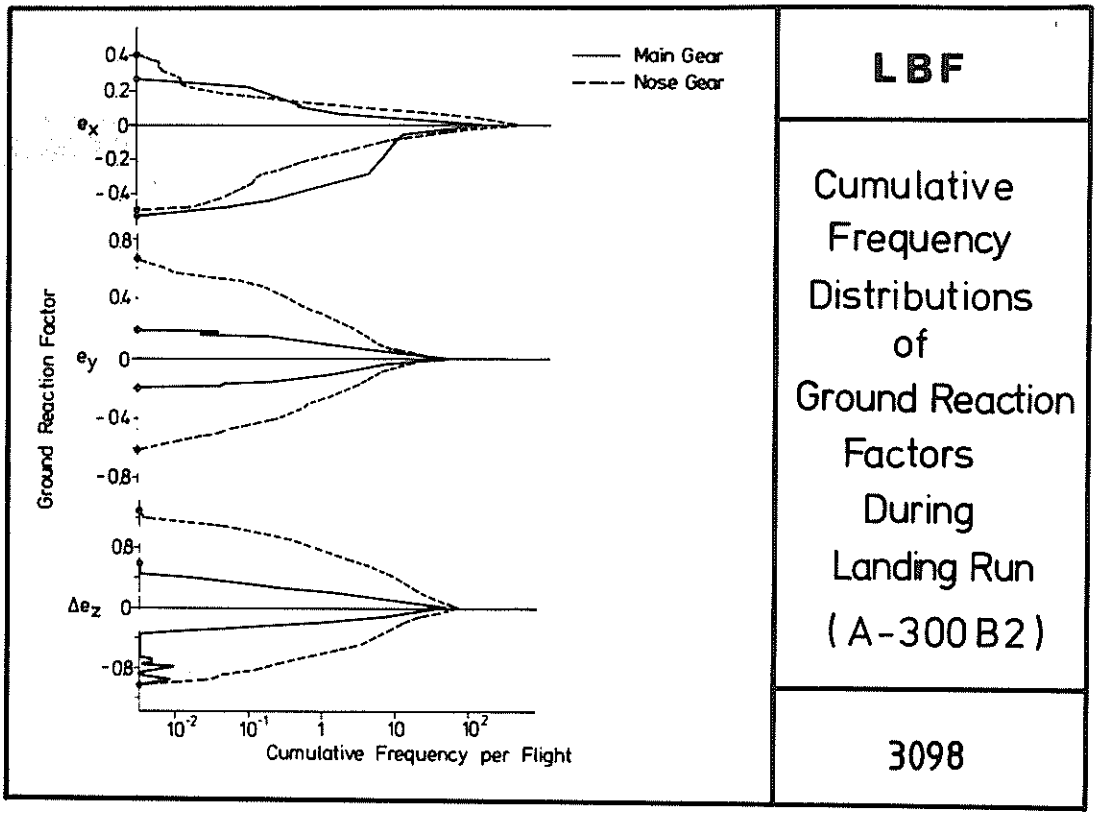

Main Gear
Nose Gear
Ground Reaction Factor
e_x
e_y
Δe_z
0.4
0.2
0
-0.2
-0.4
0.8
0.4
0
-0.4
-0.8
0.8
0
-0.8
10^{-2} 10^{-1} 1 10 10^{2}
Cumulative Frequency per Flight
LBF
Cumulative Frequency Distributions of Ground Reaction Factors During Landing Run (A-300 B2)
3098

Fig. 13

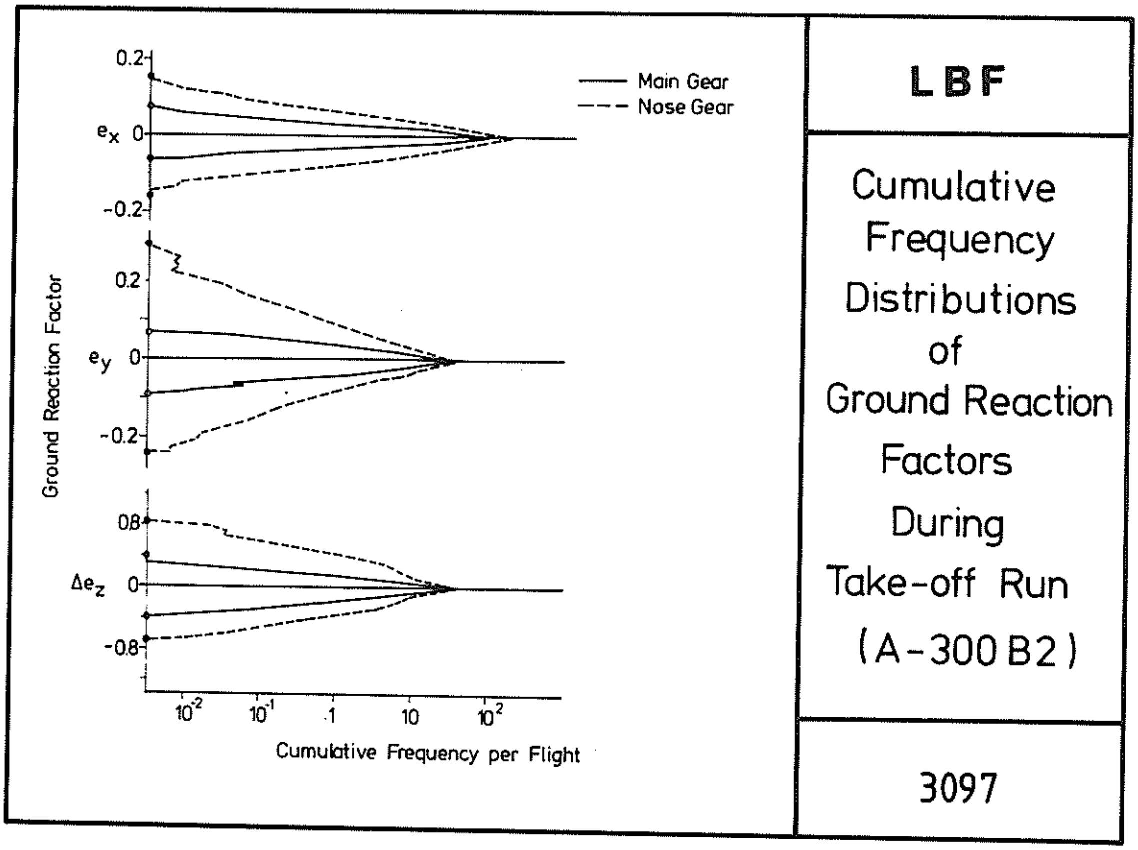
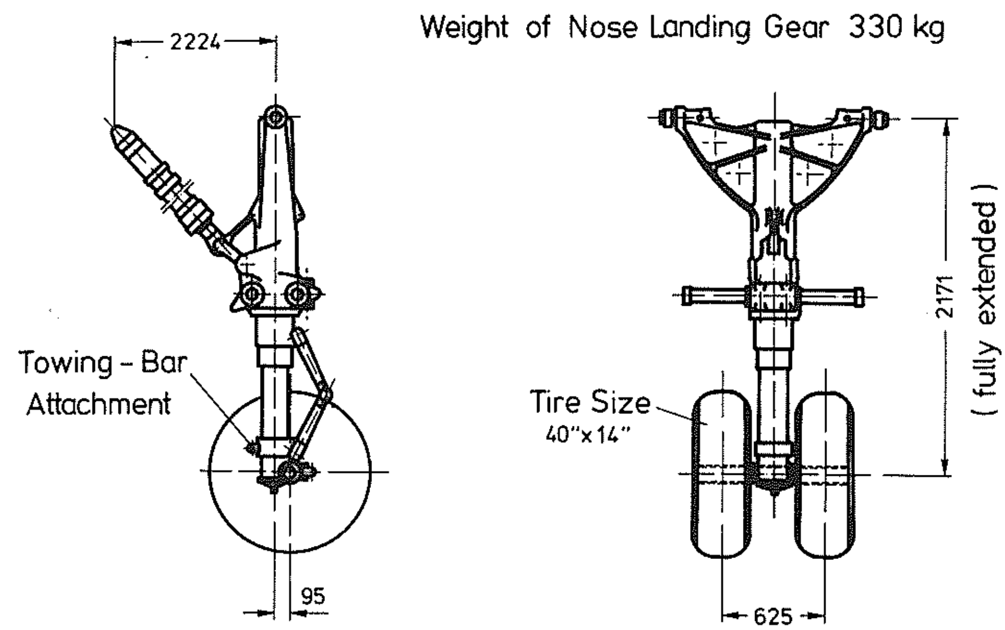
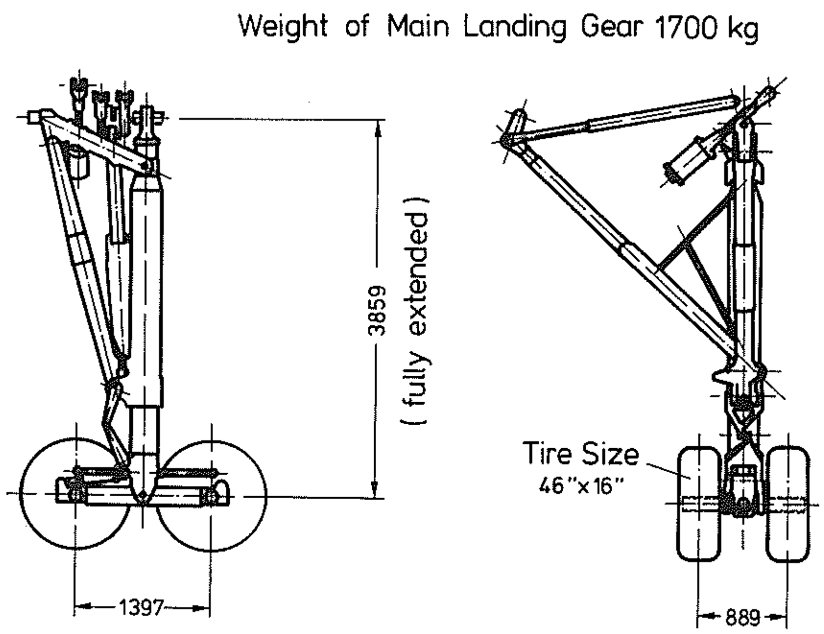

Main Gear
Nose Gear
Ground Reaction Factor
e_x
e_y
Δe_z
0.2
0
-0.2
0.2
0
-0.2
0.8
0
-0.8
10^{-2} 10^{-1} 1 10 10^{2}
Cumulative Frequency per Flight
LBF
Cumulative Frequency Distributions of Ground Reaction Factors During Take-off Run (A-300 B2)
3097

Fig. 14



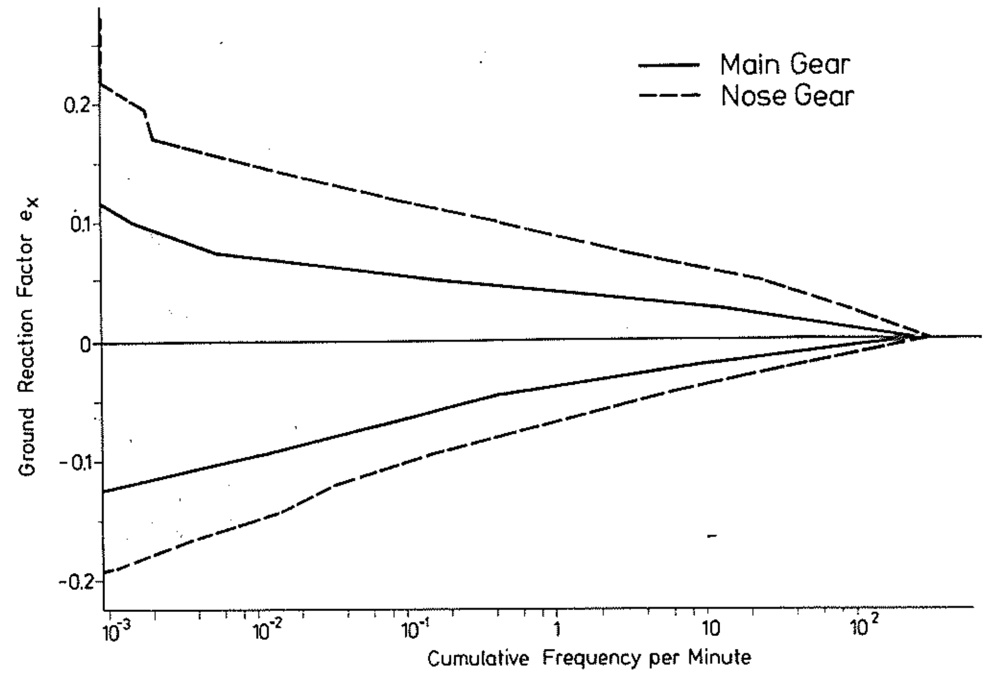
LBF	A-300 B2 Nose Landing Gear	3089

Fig. 15



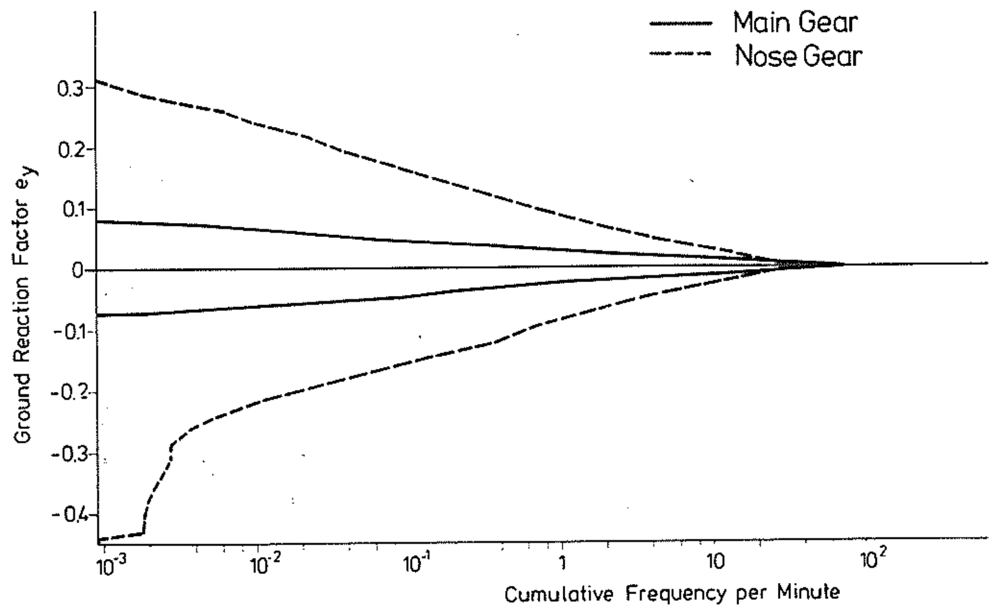
LBF	A-300B2 Main Landing Gear	3088

Fig. 16



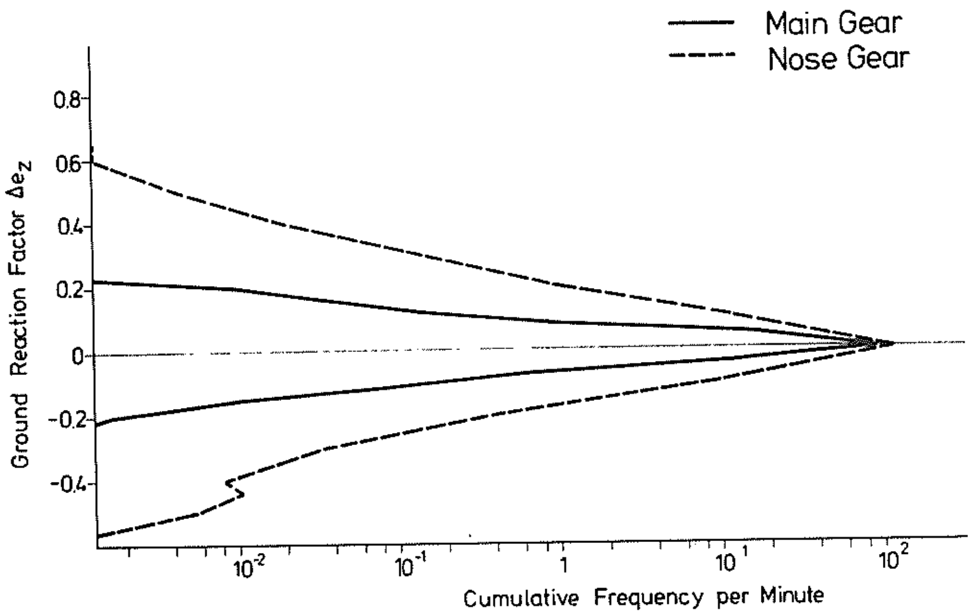
LBF	Cumulative Frequency of Drag Loads During Taxiing (A-300 B2)	2994

Fig. 17



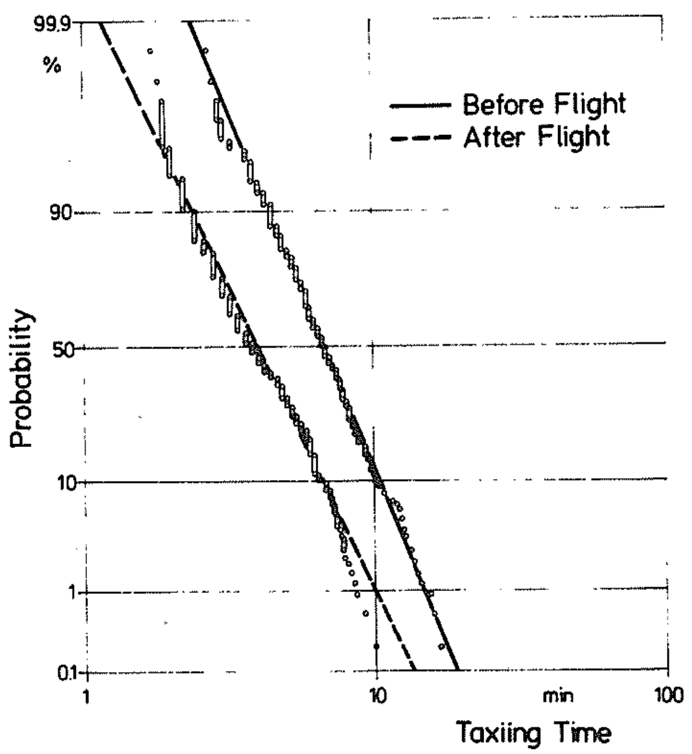
LBF	Cumulative Frequency of Lateral Loads During Taxiing (A-300 B2)	2995

Fig. 18



LBF	Cumulative Frequency of Vertical Loads During Taxiing (A-300 B2)	2996

Fig. 19



LBF
Cumulative Frequency of Taxiing Time (A-300B2)
3102

Fig. 20

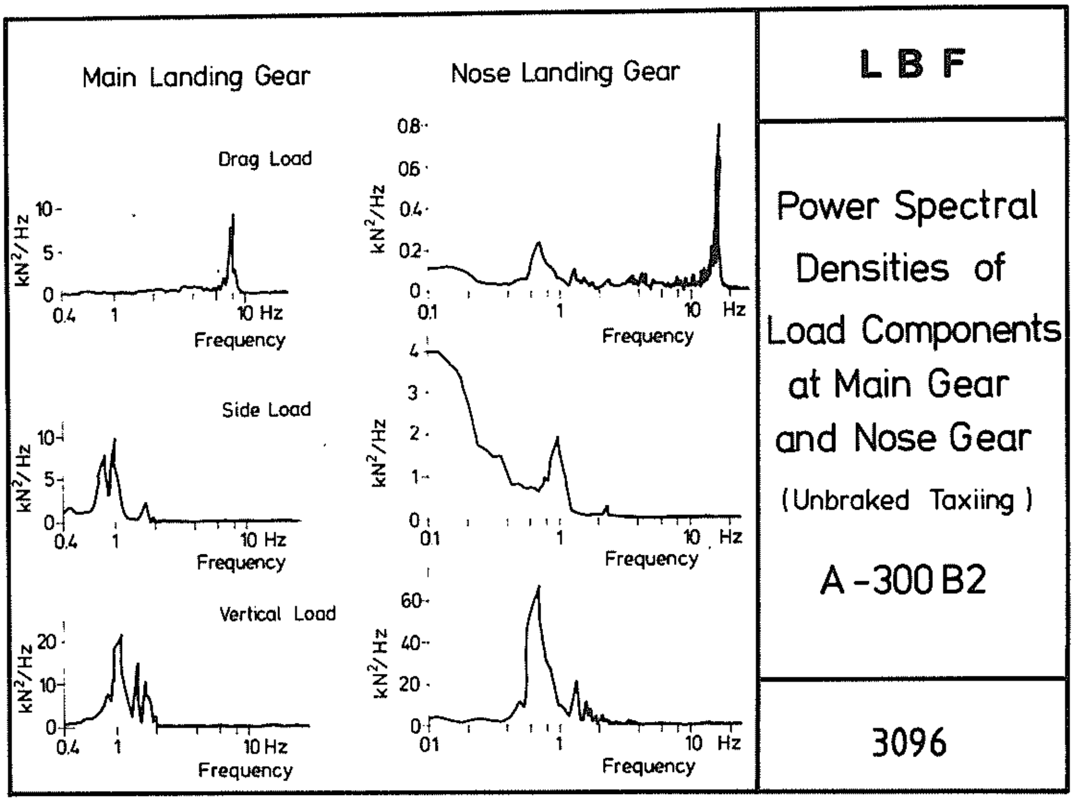

Main Landing Gear
Nose Landing Gear
Drag Load
Side Load
Vertical Load
kN²/Hz
Frequency
10 Hz
LBF
Power Spectral Densities of Load Components at Main Gear and Nose Gear
(Unbraked Taxiing)
A-300 B2
3096

Fig. 21

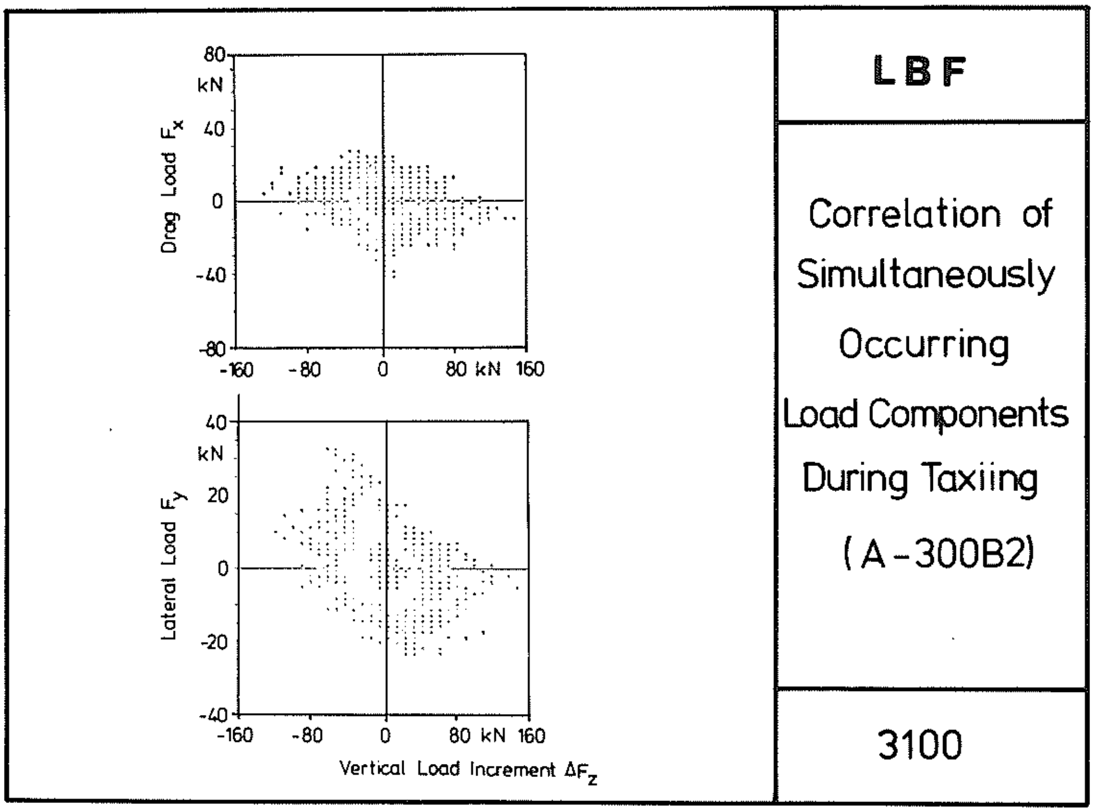
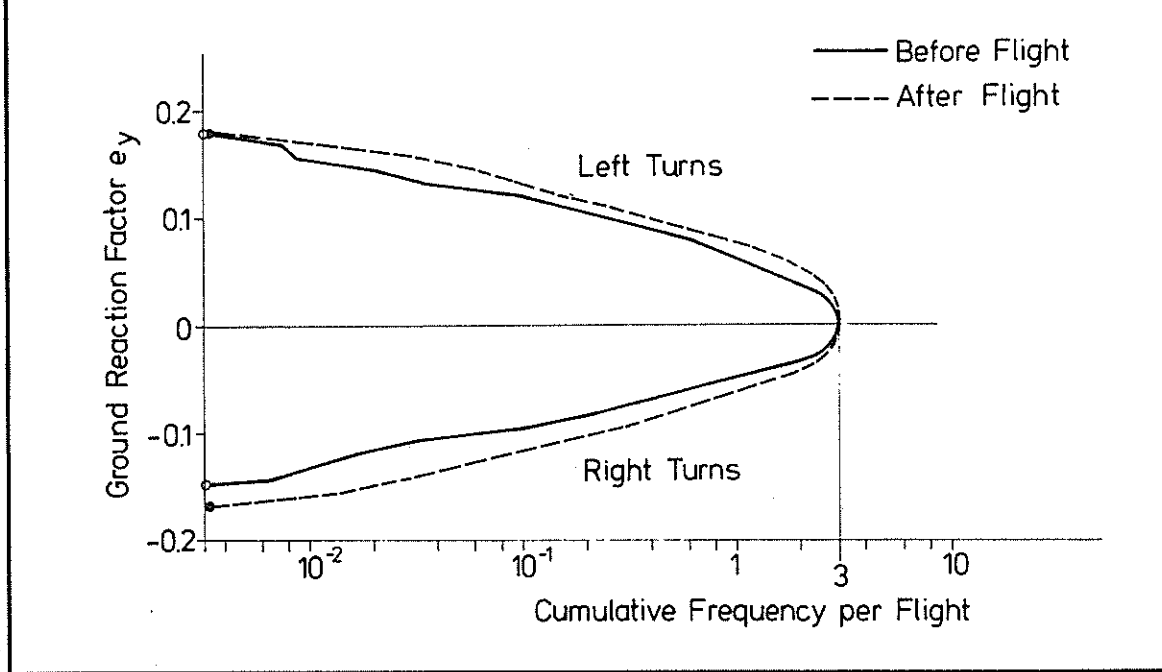
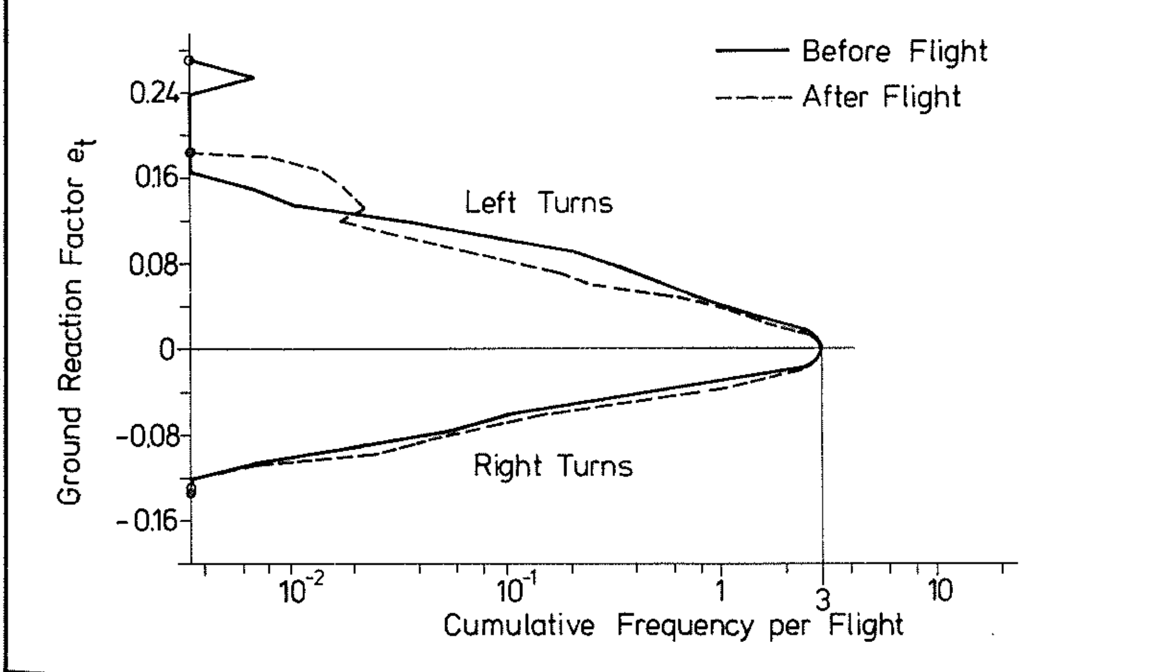

Drag Load F_x
kN
Lateral Load F_y
Vertical Load Increment ΔF_z
80 kN 160
LBF
Correlation of Simultaneously Occurring Load Components During Taxiing
(A-300B2)
3100

Fig. 22



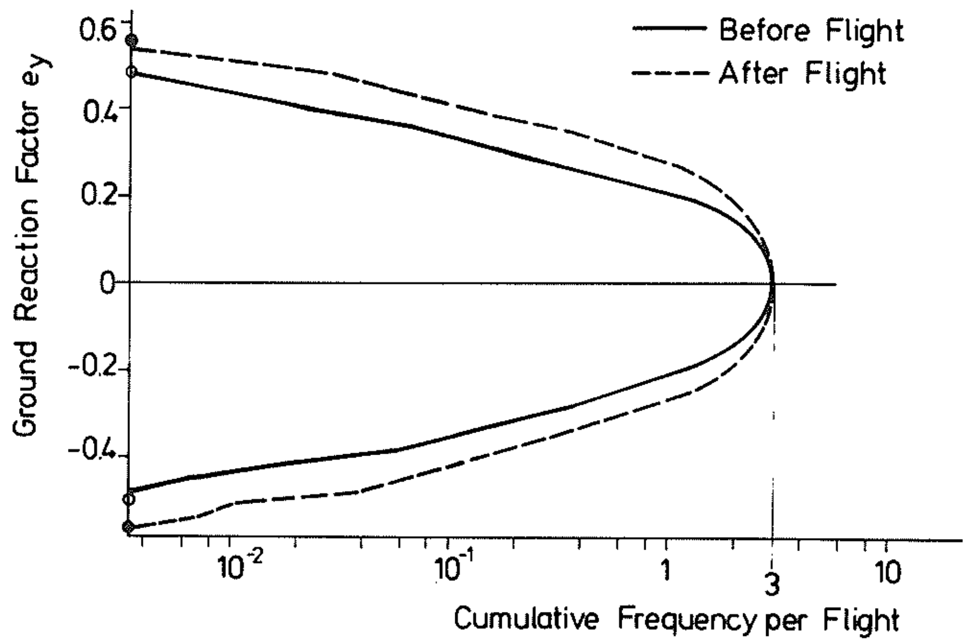
LBF	Lateral Load at Main Gear During Turning and Pivoting (A-300B2)	3095

Fig. 23



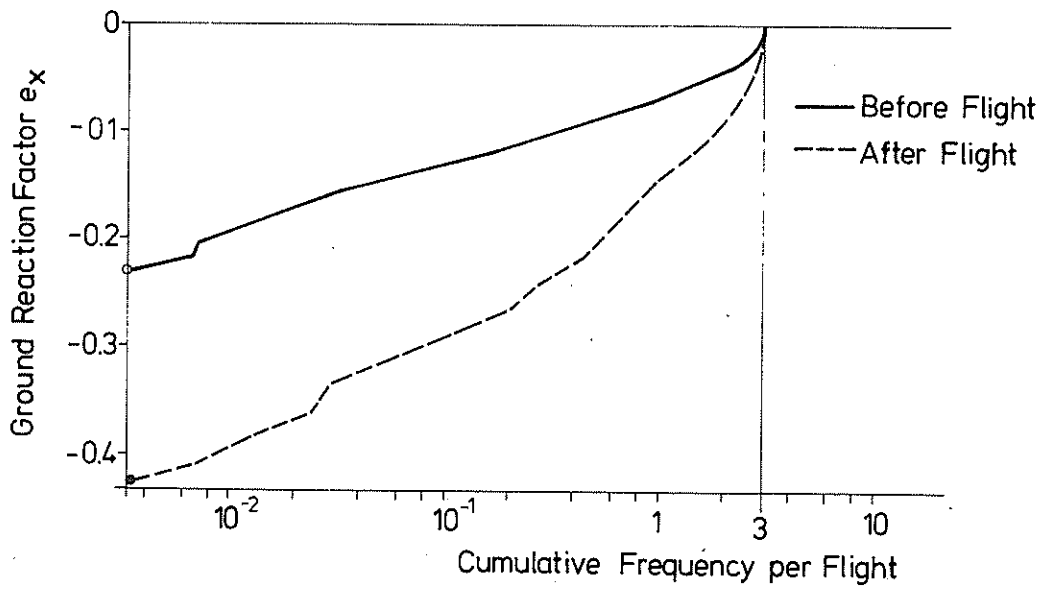
LBF	Torsion During Turning and Pivoting (A-300 B2)	3090

Fig. 24



LBF	Lateral Loads at Nose Gear Due to Steering (A-300 B2)	3101

Fig. 25



LBF	Drag Loads at Main Gear During Braking (A-300 B2)	3093

Fig. 26

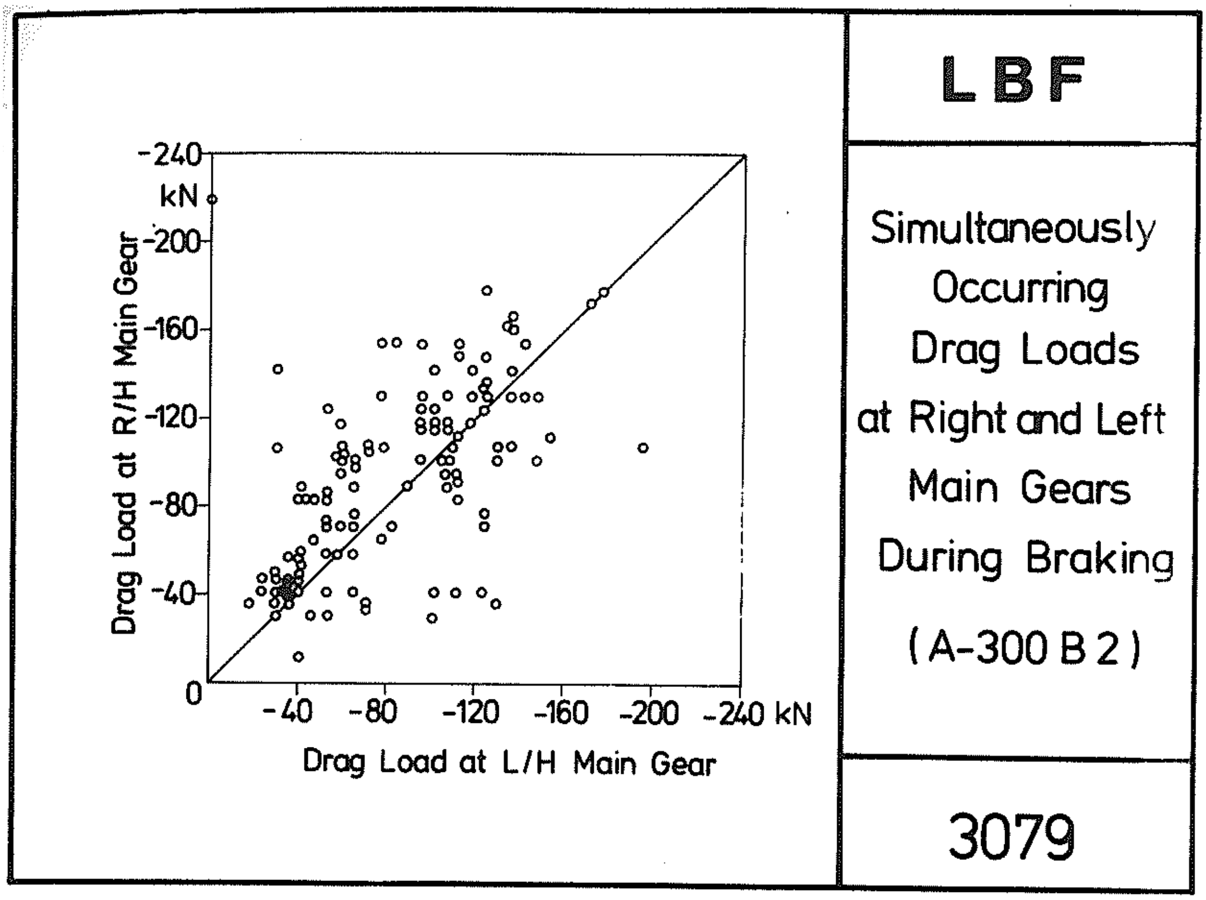

LBF
Simultaneously Occurring Drag Loads at Right and Left Main Gears During Braking
(A-300 B 2)
3079
Drag Load at R/H Main Gear
-240 kN
-200
-160
-120
-80
-40
0
-40
-80
-120
-160
-200
-240 kN
Drag Load at L/H Main Gear

Fig. 27

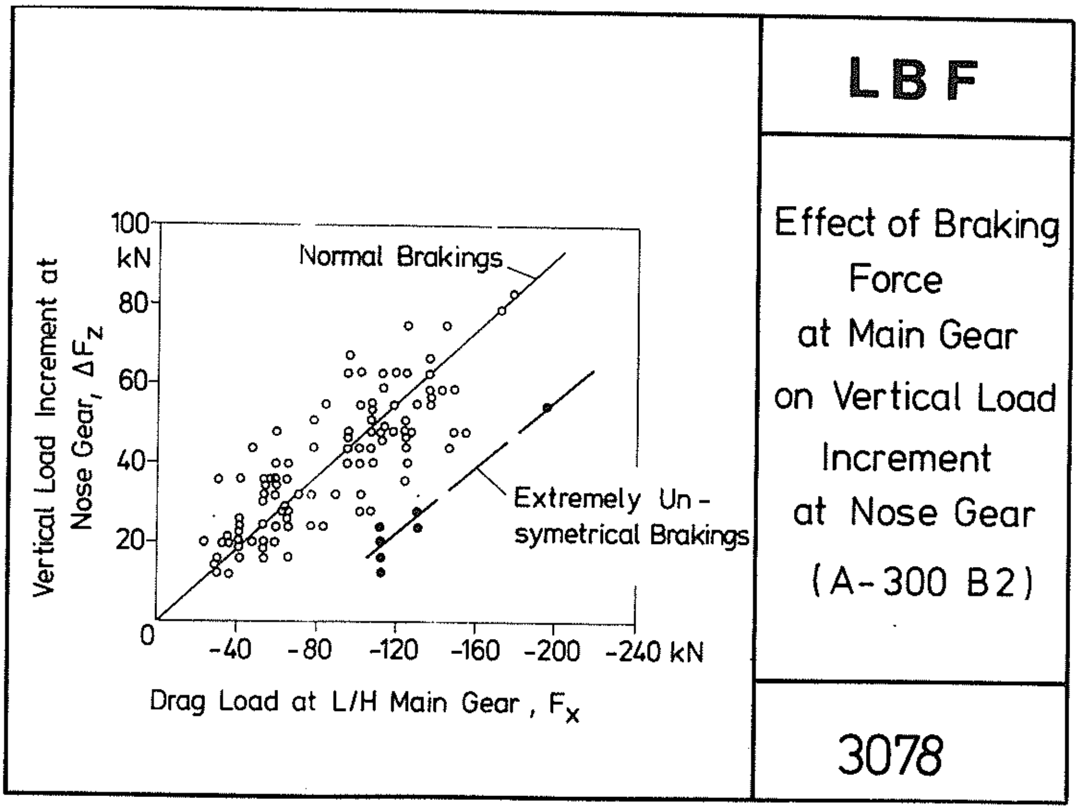
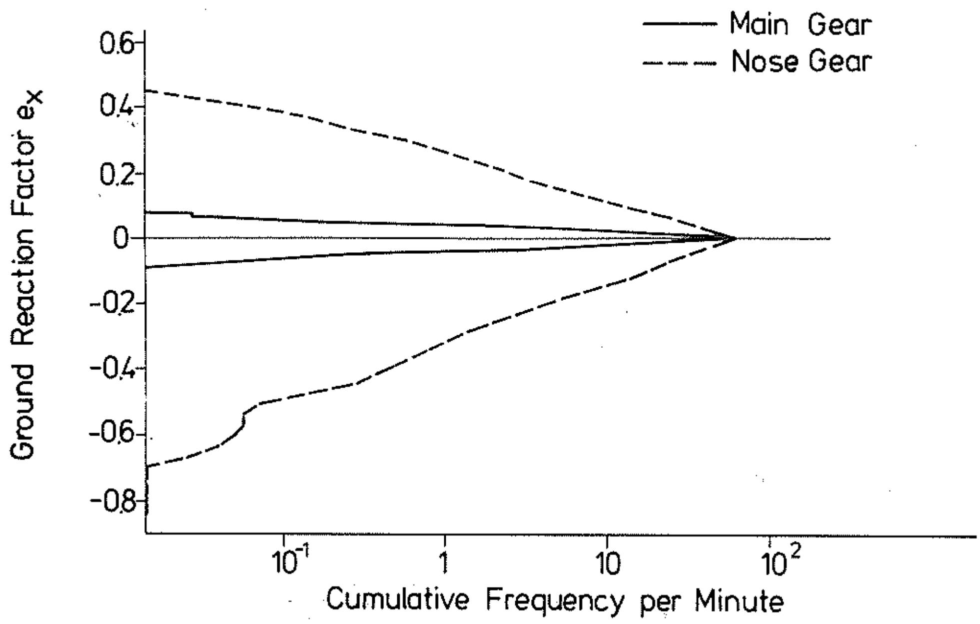
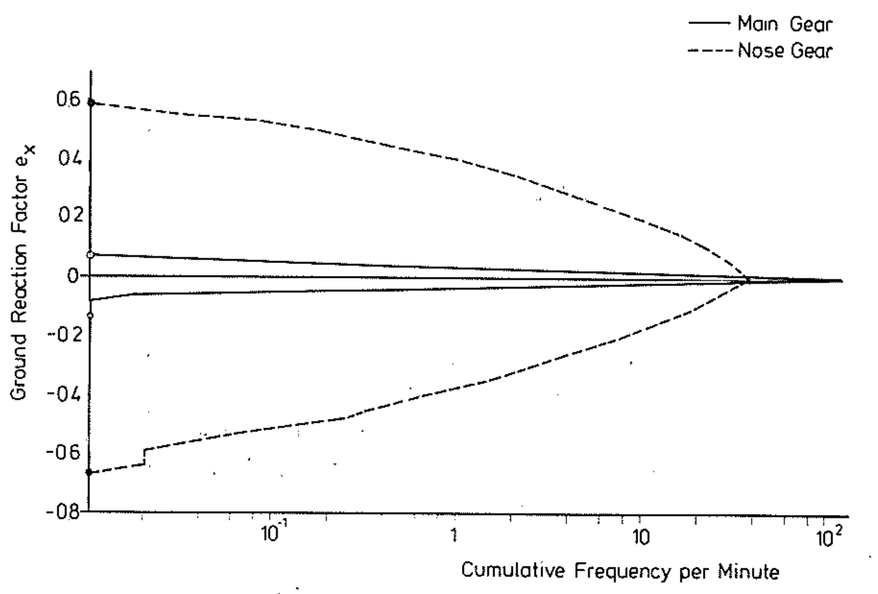

LBF
Effect of Braking Force at Main Gear on Vertical Load Increment at Nose Gear
(A-300 B2)
3078
Vertical Load Increment at Nose Gear, ΔFz
100 kN
80
60
40
20
0
-40
-80
-120
-160
-200
-240 kN
Normal Brakings
Extremely Un-symetrical Brakings
Drag Load at L/H Main Gear, Fx

Fig. 28



LBF	Cumulative Frequency of Drag Loads During Pushing from Ramp (A-300B2)	3094

Fig. 29



LBF	Cumulative Frequency of Drag Loads During Towing (A-300 B2)	3099

Fig. 30