MEASUREMENTS OF LANDING GEAR LOADS OF A COMMUTER AIRLINER

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Abstract

One of the components of modern transport aircraft which is most liable to collapse due to fatigue failure is the landing gear. The design of landing gears features several complicated topics from a fatigue point of view, such as severe environment, multi-axial loads, and a complicated mechanism with non-linear response. This paper discusses strain-gauge measurements of forces acting on the nose gear and main gears of a commuter airliner, SAAB SF-340. Forces in the longitudinal, transversal and vertical directions are presented for various manoeuvres such as take-off, landing, taxiing and towing. The investigation reveals unexpectedly high transversal loads at the main gears at touch-down. The nose gear is most severely strained when steering during taxiing run and when the aircraft is towed, connected to a tractor with a tow-bar.

The results of the measurements above, formed the basis for a subsequent investigation with on line data acquisition of landing gear loads on a commuter airliner in service. Such measurements reveal differences in load environment due to different pilots, runways and weather conditions including seasonal variations. The data acquisition system and the data analysis methods are described in some detail.

I. Introduction

Historically, landing gear loads have been treated scarcely in the literature[1] and not until 1957[2] was a first attempt made to establish a main landing gear load spectrum. Still 25 years later, the landing gear is one of the fixed wing aircraft's structural components that is most liable to collapse due to fatigue failure[3].

In modern airliners, the landing gear weight constitutes about 2-3 percent of the take-off weight and the landing gears often have to travel total distances in the same order of magnitude as buses and trucks do during a life time. In addition, high running speeds are reached at take-off and landing[4]. Furthermore, the landing gear environment features temperature cycling, moisture, de-icing fluids, oil and shots from sand which has to be considered in the fatigue design besides the multi-axial loads. In Fig. 1, three load components have been defined for the nose gear and the main gear. A vertical torque may be included too.

When deriving the ground load spectrum for the SAAB SF-340 commuter airliner little statistics were available in the literature for this category of aircraft. Statistics had to be taken from larger aircraft, e.g. the Airbus A300 measurements[5] or smaller aircraft, e.g. of FAR23 category[6]. Consequently, this research project was started which aims at producing landing gear load statistics for commuter airliners.

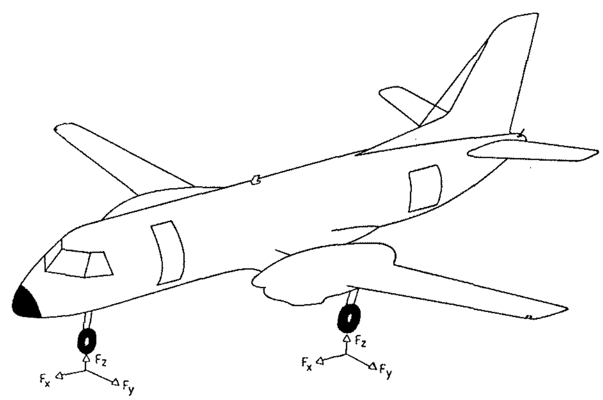

FIGURE 1. Definition of load components at nose and main gear.

This paper shortly describes the first part of this project: flight test measurements of various manoeuvres on the ground such as landing, taxiing and towing. The second part of the project, the in service measurement is also briefly discussed in the paper.

Generally, flight test measurements give an opportunity to study different load cases under controlled circumstances and, also, to record time histories of several quantities. For instance, in this flight test about 40 different quantities were recorded simultaneously. Since time histories for several quantities are sampled, the data amount quickly grows to large volumes and, therefore, the amount of recorded data has to be limited. This fact implies that either the number of load cases or the number of repetitions of each load case have to be restricted, for a given sample frequency and set of quantities. In this flight test it was judged that as many load cases as possible should be observed in order to provide information for various ground handling of SAAB SF-340 for the forthcoming in service measurements where the statistical aspects would be considered.

II. Instrumentation and Calibration

Strain gauges were applied to the aircraft nose and left main gears in order to measure forces acting on the gears during ground operation as seen in Figs 2 and 3.

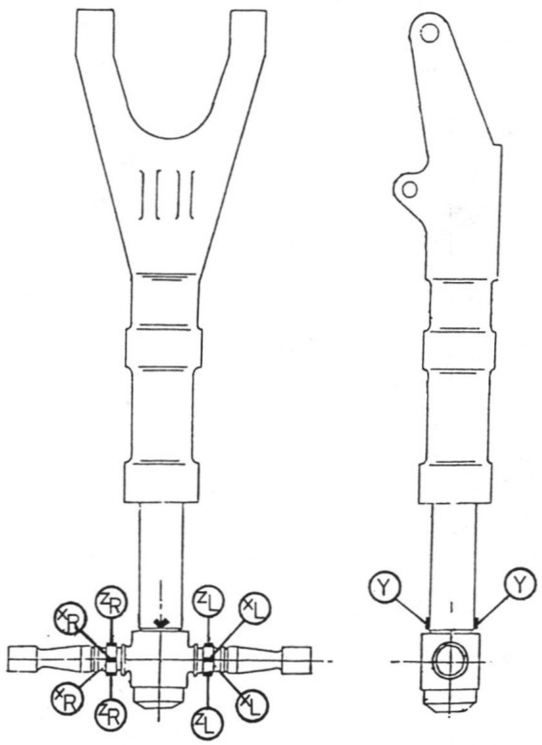

FIGURE 2 Strain gauge installation at the main gear of SF-340. The nose gear is instrumented in the same way

FIGURE 3 SF-340 nose gear shock strut during strain gauge application

The ten strain gauges formed, on each gear, four half bridges and one full bridge. The half bridges were mounted on the wheel hubs in order to measure strains due to bending of the hubs caused by vertical and longitudinal forces. The bridges are denoted X_L, X_R, Z_L and Z_R in Fig. 2 and correspond, mainly, to the forces F_x and F_z acting on left and right wheel, respectively. The full bridge, Y, was mounted on the shock strut forming a shear bridge which was believed to give signals proportional to F_y.

All gauges were applied below the shock strut to avoid the influence of the variable length of the strut on the forces calculated from the measured strains. Hence, the strain signal would be almost proportional to the force between tyres and ground.

The strain gauge signals were amplified and recorded on a tape recorder using PCM technique. The strain gauge signals were sampled at a frequency of 64 Hz.

The aim of this flight test was to record the forces acting on the landing gear during ground operation. Consequently, a careful calibration had to be performed to evaluate the relation between measured strains and applied loads. Thus, the loads applied during the calibration must, be introduced in a way that corresponds to the loads applied in the test on the runway as closely as possible.

During the calibration, the applied load was recorded together with the simultaneously occuring strains in all bridges. Thus, in the general case, a non-linear system of equations were obtained which relates five force components with five bridge signals. The calibration loads were applied stepwise and the obtained non-linear calibration curves were assumed to be stepwise linear, between each calibration point. This can be justified due to the very smooth, almost linear, relationship between strains and loads. The system of non-linear equations was solved for each time-step of recorded strains during the flight test to yield the desired force components. However, the cross influences from one force to another strain gauge bridge were negligible and, hence, the bridge signals were proportional to respective force.

Seven calibration cases were carried out for each gear comprising symmetrical and unsymmetrical forces in both positive and negative x and y directions and in the positive z direction. It is to be noted that force components (F_x and F_z) for each wheel were evaluated but in this paper only the resultants F_x and F_z are presented together with F_y.

III. Description of Load Cases

Four main load cases were considered in the flight test:
- towing
- taxiing
- take-off
- landing

These cases were performed as follows. During towing a tractor connected to the aircraft nose gear wheel hub with an ordinary tow-bar towed and pushed the aircraft over a hangar threshold. The threshold was passed at different angles between the towing path and the threshold: approximately 90°, 70° and 50°, respectively. During the towing and pushing recordings both the nose gear and left main gear passed the threshold. In this case, the threshold consisted of two parallel 40 mm high steel bars separated 165 mm.

The taxiing case consisted of several events as pivoting, symmetrical and unsymmetrical braking, engine run-up and turns. The events took place on the runway. The brakings and the steering manoeuvres were carried out at two different taxi speeds, one referred to as normal taxi-speed and one slower. During the steering manoeuvres the aircraft followed a zigzag path.

Four take-off and landings were performed. The aircraft status at touch-down are presented in Table 1. The landings, performed in relatively high crosswinds, can be classified as rather hard landings which would occur seldom in service (every hundred to every ten thousand landing according to sink speed statistics[6]).

Landing	Weight 10^{-3} kg	Angle of climb degree	Sinking speed m/s	Bank angle degree
1	11.0	5.79	0.76	-1.97
2	11.0	6.07	1.46	-8.14
3	10.9	5.16	0.76	0.14
4	10.9	3.50	2.13	0.01

TABLE 1 Landing conditions during flight test measurements

IV. Results

The results were originally presented in Ref. (7) as time-history plots and rain-flow count [8] data in tables and graphs. Far from all that data will be presented here but the interest will be focussed upon the most revealing results.

The severity of nose gear longitudinal loads during towing and pushing has been pointed out earlier[9]. The high load intensities emanates from the connection of the tow-bar to the nose gear. However, the results should be interpreted carefully since the load application during calibration was different from that when using the tow-bar. F_x measured during towing may thus be too high.

For obvious reasons the nose gear will be strained at starting and stopping during towing as seen in Fig. 4. Furthermore, when the main gear passes an obstacle, in this case the hangar threshold, a high peak load on the nose gear occurres as seen at the arrow in Fig. 4. From a fatigue point of view load ranges rather than individual load peaks are of relevance. Therefore, data may be presented as in Fig. 5. This figure displays both full and half cycles[8] of ground reaction factors from rain-flow count analyses of the individual towing records. The ground reaction factor is defined as the ratio between the studied load component and the static vertical load of that gear, e.g. $e_x = F_x / F_{z,stat}$.

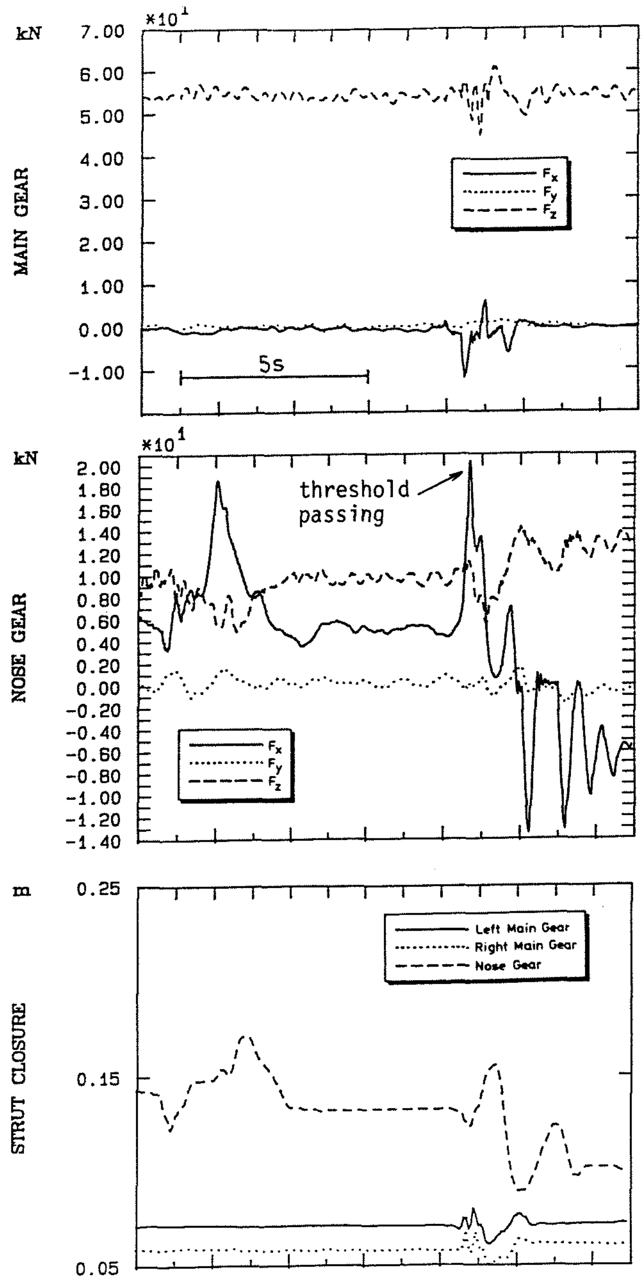

FIGURE 4 Time-histories of towing over a hangar threshold at 90° angle between towing path and threshold

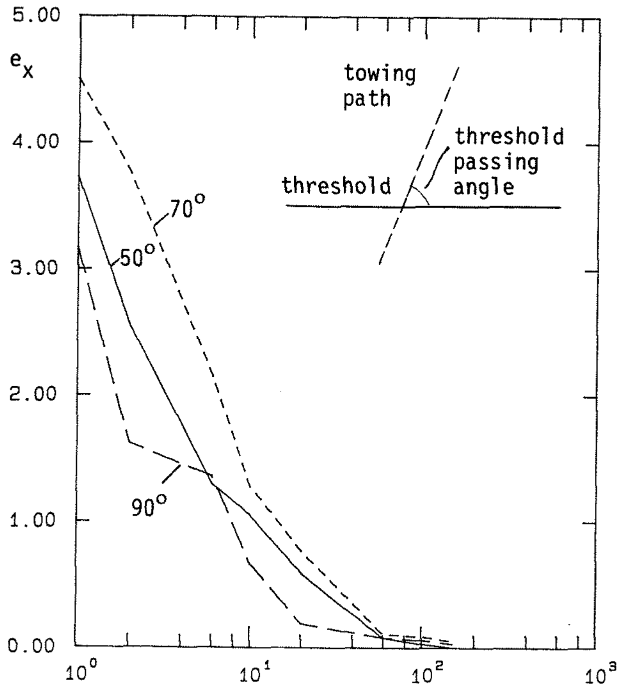

FIGURE 5 Cumulative frequency distribution of range-pair ranges of longitudinal ground reaction factor, e_x, at nose gear at towing. Ranges are presented as half cycles

Fig. 6 shows a record of the main gear loads from the zigzag taxiing case at normal taxi speed. The variation in loads due to steering is clearly seen. By combining the peak values of each individual steering manoeuvre and evaluating the ratio $(F_z - F_{z,stat})/F_y$ a good correlation was found between F_z and F_y for the main gear when separating left and right turns as seen in Table 2. The difference between right and left turn results diminished when the taxi speed was lowered. Rain-flow count ranges of the lateral loads at zigzag taxiing are presented in Figs 7 and 8, together with lateral loads at touch down, for the nose and left main gear.

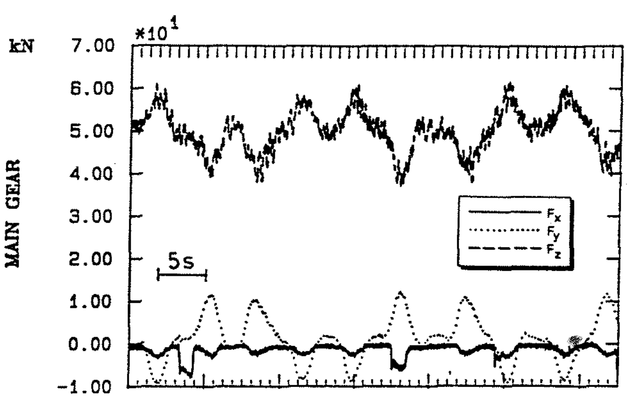

FIGURE 6 Main landing gear loads at normal speed during zigzag taxiing

Turning direction	Normal speed Mean	Normal speed Standard deviation	Low speed Mean	Low speed Standard deviation
Right	-0.86	0.12	-1.06	0.15
Left	-1.28	0.13	-0.94	0.13

TABLE 2 Relation $(F_z - F_{z,stat})/F_y$ of left main gear during zigzag taxiing

Finally, a typical landing record is shown in Fig. 9. The three events, landing impact (L.I.), spin-up (S.U.) and spring-back (S.B.) can be seen first for the main gear and, slightly afterwards, for the nose gear. In Table 3, several ratios defined earlier[9] are presented. It should be noted that the load F_y does not necessarily occur simultaneously as $F_{z,L.I.}$ but at the same landing. Also, worth noticing is the difference in the recorded dynamic $F_{x,S.B.}$ in this investigation and that of Ref. (9). In the latter, the dynamics of almost the entire landing gear is included since the strain gauges are applied high up on the shock strut whereas the present study only includes the dynamics of the wheels; the strain gauges are positioned on the wheel hubs. The ratios for the nose gear seem to be more unanimous than for the main gear. This may be a consequence of more uniform conditions when the nose gear reaches the ground i.e. both main gears in contact with ground. As mentioned above, the lateral load factors at touch down are presented in Figs 7 and 8 as rain-flow count ranges. It is clear that the load factor ranges are smaller at the main gear in general and that steering load ranges at the nose gear is much more pronounced compared to the landing loads than for the main gear. On the other hand, one shall bear in mind that the static vertical load at the main gear is about 5 times higher than at the nose gear. This obviously influence the magnitude of the ground reaction factors for the gears under consider- ation. The main gear maximum transversal ground reaction factors at landing was -0.53, 0.35, -0.33 and 0.39, respectively.

Landing No.	Nose Gear $\frac{F_{x,S.B.}}{F_{x,S.U.}}$	Nose Gear $\frac{F_{x,S.U.}}{F_{z,L.I.}}$	Left Main Gear $\frac{F_{x,S.B.}}{F_{x,S.U.}}$	Left Main Gear $\frac{F_{x,S.U.}}{F_{z,L.I.}}$	Left Main Gear $\frac{\lvert F_y \rvert}{F_{z,L.I.}}$
1	-0.26	-0.62	-0.12	-0.79	0.92
2	-0.26	-0.66	-0.52	-0.55	0.33
3	-0.22	-0.69	-0.53	-0.49	0.42
4	-0.30	-0.65	-0.23	-0.70	0.48
Mean	-0.24	-0.66	-0.35	-0.63	0.54
Standard deviation	0.06	0.03	0.21	0.14	0.26

TABLE 3 Certain load ratios[9] obtained at landing with SAAB SF-340

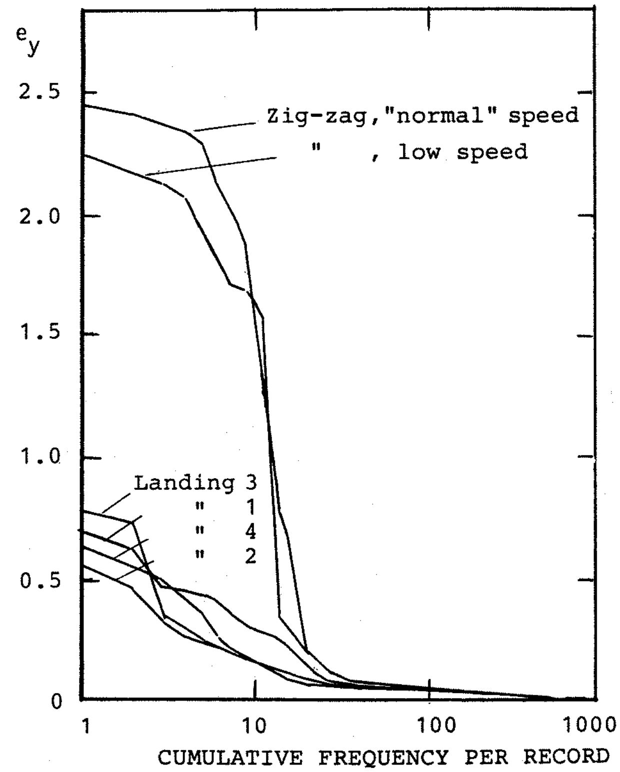

FIGURE 7 Cumulative frequency distribution of range-pair ranges [8] of transversal ground reaction factors, e_y, at nose gear at zigzag taxiing and landing. Ranges are presented as half cycles.

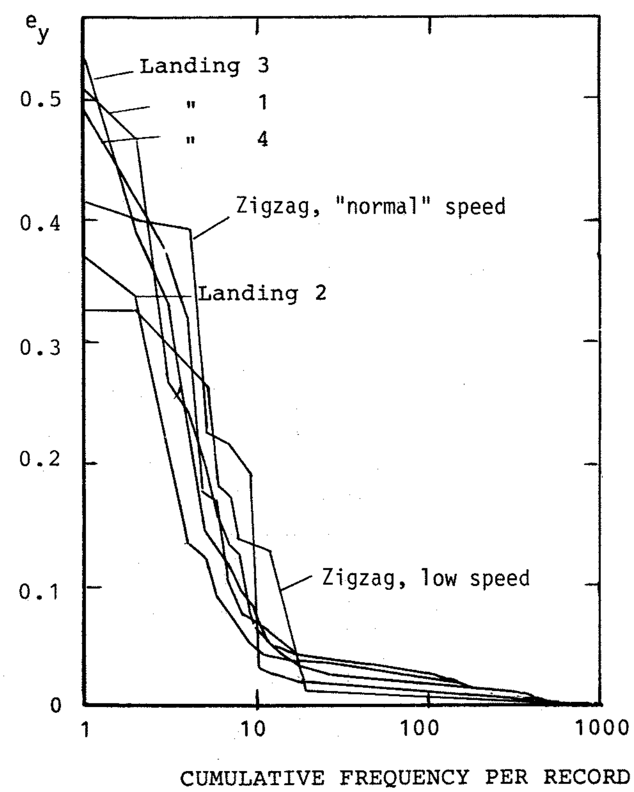

FIGURE 8 Cumulative frequency distribution of range-pair ranges [8] transversal ground reaction factors, e_y, at left main gear at zigzag taxiing and landing. Ranges are presented as half cycles.

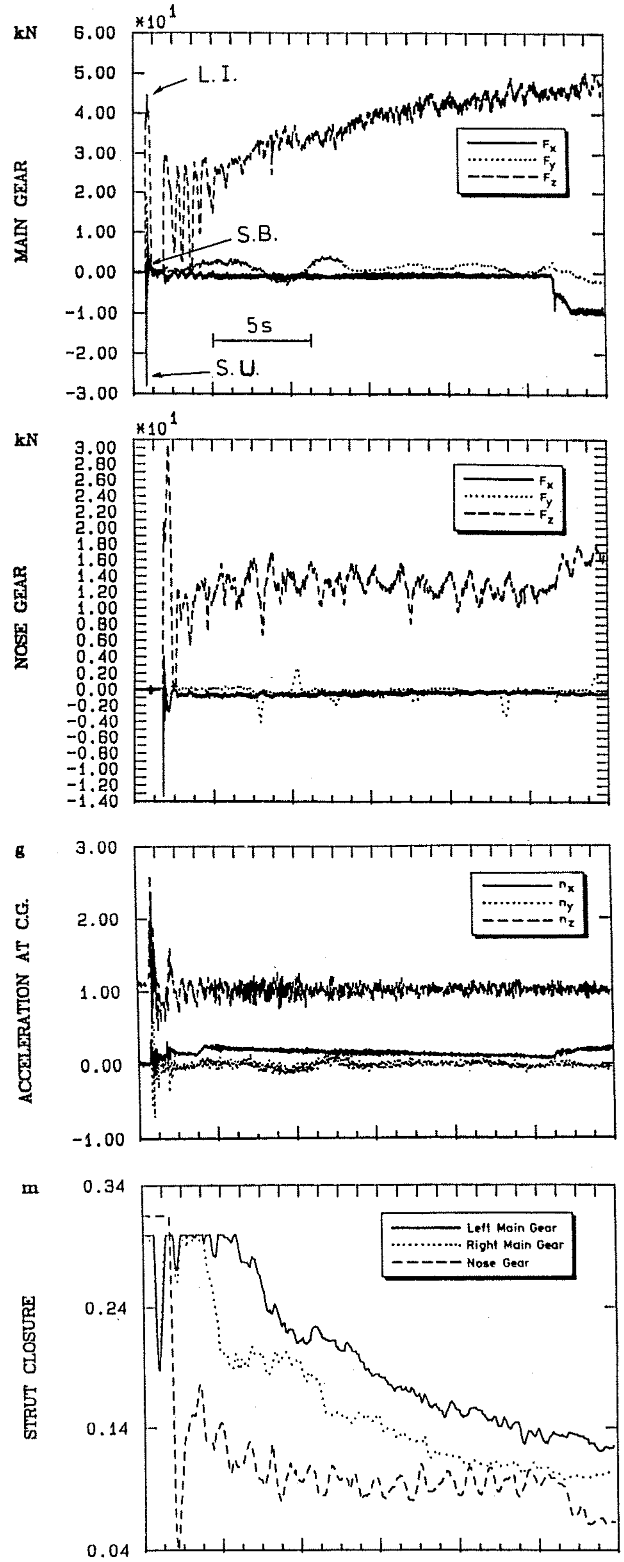

FIGURE 9 Time-histories of a landing

V. Planning of in Service Measurements

The flight measurements briefly outlined above were a first step in a research project of recording landing gear loads in service. Data from these measurements provide a sound basis for the second phase of the project, the in service measurements.

The in service measurements are planned to be carried out with a computer based data acquisition system installed in a single commuter airliner. The computer, designed for long-time measurements, performs the rain-flow count analysis[8] on-line for six independent channels, i.e. data are saved in six Markov-matrices[8]. This procedure, however, does not preserve any information of the time history and particular events, or load cases, can not be traced. Therefore the rain-flow count procedure will be combined with event recordings where certain signal peaks or troughs are recorded together with a time code.

The system to be installed in the aircraft consists of strain gauges, wires, signal amplifiers and a computer. The amplifiers and the computer have a total weight of 7.5 kg and a volume of 300 mm × 250 mm × 150 mm which fulfils the maximum size requirements due to limited installation volume available. The flight measurement results provided information necessary for the establishment of the in service equipment. It was deduced from the calibrations that the strain signals were proportinal to the applied loads and, mainly, only to the loads in the direction which the strain gauges were intended for. This means that the same strain gauge set-up, as shown in Fig. 2 can be used during the in service measurements without losing to much accuracy.

Furthermore, frequency content of the signals can be estimated from the flight measurements, e.g. as seen in Fig. 10, where the power

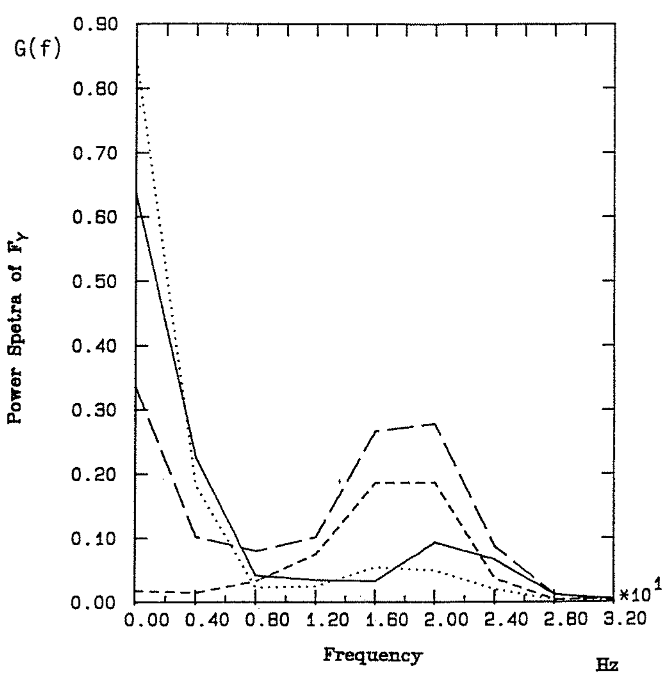

FIGURE 10 Power spectra of transversal load, F_y, on nose gear at 4 landings

spectra[10], G(f), of F_y at the nose gear for the four landings are seen. The power spectral density describes the general frequency content of the first four seconds of each landing record in terms of the spectral density of its mean square value. Also, a check of what load levels that are liable to occur in service can be estimated. These two latter features are important for in service data quality assurance.

VI. Discussion

This paper presents some results obtained during flight test measurements of the commuter airliner SAAB SF-340 landing gear loads. As presented elsewhere[9], high longitudinal loads at the nose gear can be measured at towing. However, it is important to consider the effect of load introduction when connecting a tow-bar to the nose gear.

High transversal loads occur at both nose and main gears during taxi and landing. It was shown that the difference between these two load cases was smaller for the main gear than for the nose gear. Furthermore, the flight test[7] revealed that steering with unsymmetrical brakings diminished the transversal nose gear loads radically. It should also be noted that the performed landings should be considered as rather hard landings and zigzag taxiing manoeuvres which would occur seldom in service.

When establishing a load spectrum to be used in fatigue evaluations several aspects of the loads have to be considered. As mentioned earlier, the rain-flow count algorithm[8] presents data which is believed to be relevant from a fatigue point of view. Therefore data may be presented as in Figs 7 and 8. However, these flight test measurement data contain almost no statistics at all and, thus, long time in service measurements have been initiated as a second part of this project. The in service measurements will provide statistical information presented in the same form as Figs 7 and 8. But in this case long-time effects of different pilots, weather and runway conditions will be included.

Also the combination of certain loads is important when performing a fatigue evaluation (still commonly from a safe-life approach rather than by damage tolerance concepts) or establishing a fatigue test sequence for landing gears. Such data are presented in Tables 2 and 3. Finally, in addition to load spectra and load combinations, environmental effects also have to be considered when estimating the fatigue resistance of landing gears.

Acknowledgements

The author would like to thank Mr. Bengt Johansson and Mr. Rickard Vinthagen at SAAB-SCANIA AB for their skilful co-operation during this work. Also Ms Gunn Ahlberg is acknowledged for her very patient typing of this manuscript.

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