ACQUISITION AND ASSESSMENT OF FATIGUE LOADS IN THE CN-235 AIRPLANE

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Abstract

A co-operative project between the Indonesian aircraft industry, IPTN, and the National Aerospace Laboratory, NLR, has started in 1990 to obtain information on the actual aircraft loading of the CN-235 and to train IPTN personnel involved with regard to measurements, analysis and interpretation of aircraft loads. A description of the hardware and software in this load monitoring programme has been presented and some preliminary results are shown.

Introduction

At this time IPTN is progressing to become a mature and independent aircraft industry with a complete line of small-to-medium range aircraft. As a result of this development a co-operative fatigue load monitoring project with NLR was started up for the CN-235, a 35-passenger airplane jointly developed and produced by IPTN and CASA, see also figure 1.

Fig. 1 The CN-235 airplane

Objectives of this programme are (1) the verification of the validity of the load spectra applied during the design phase and in the full-scale fatigue test; (2) building up IPTN experience and specific knowledge in the field of aircraft loading, especially the gust loading of aircraft in climatological conditions as in Indonesia and (3) gaining information in the actual usage of the CN-235 airplanes.

During the first phase of the project the specifications for the load monitoring system were defined and information on existing load monitoring devices was gathered. Based on an evaluation of three possible load monitoring devices, SWIFT's MAS-MICRO-BOX System was selected by IPTN and NLR. The main reasons for procurement of this particular system were the compact dimensions of the data-collector with no external switches or special handling requirements, its user-friendly and fool-proof data-retrieval operation, and the possibility to review on the spot the contents of the recorded flight(s) by means of a laptop computer.

During the second phase of the programme, software was developed by IPTN and NLR personnel to analyze the data monitored with the MAS-MICRO-BOX system. This software consists of programs to generate a database with recorded flight data as well as three main programs for respectively Load Spectra Analysis, Gust Load Analysis, and Mission Profile Analysis.

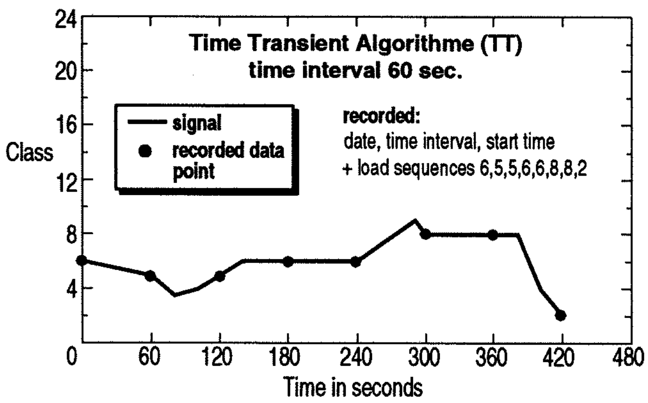
At this moment, the equipment has been installed in the second CN-235 prototype, owned and operated by IPTN, and a second set has been recently installed in a commercially operated CN-235 from the domestic Indonesian airline MERPATI. A third set of load equipment will soon be installed in a military version of the CN-235 operated by the Indonesian Air Force.

It is intended to collect data in all 3 aircraft for at least one year in order to obtain information primarily of interest from the designer's point of view. At the end of the program, a study will be made for a more operator-oriented load information system.

Specification of measured signals

The following signals were defined to be monitored and recorded:

(1)	N_z	vertical acceleration of aircraft at CG position
(2)	V	aircraft velocity
(3)	H	aircraft altitude
(4)	Φ	bank angle
(5)	BM_w	root bending moment wing
(6)	ΔP_{cabin}	Differential cabin pressure
(7)	BM_{vt}	root bending moment vertical tail
(8)	BM_{ht}	root bending moment horizontal tail
(9)	Sp	spare signal for adhoc measurements



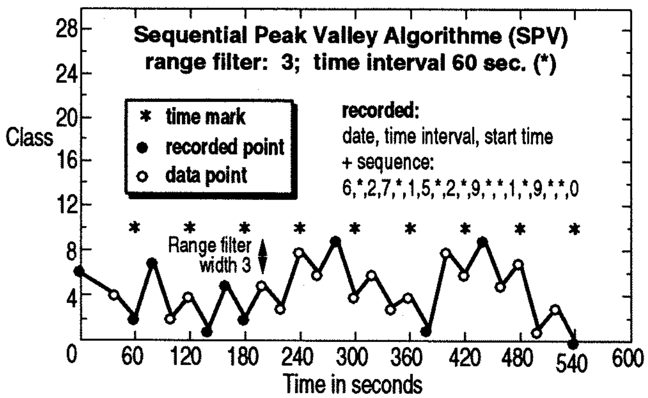


Fig. 2 Description of the two Data Reduction Algorithms

Two dataprocessing algorithms are used for the measured signals. The first algorithm, Time Transient mode (TT), stores instantaneous values of V and H at certain intervals selected by the user. All other signals were processed and stored by means of the Sequential Peak and Valley algorithm (SPV). In this algorithm, the successive extremes (peaks and valleys) differing more than a preset range-filter value R are searched for and stored in their original sequence, together with a time mark at a pre-set time interval (de Jonge (1)). In this way considerable data-reduction is possible. Figure 2 presents examples of the data reduction of both methods. In addition, some signals are crosslinked with other signals to obtain additional information. For instance, at the stored extreme values of the vertical acceleration signal N_z (so called master signal), the instantaneous values of the aircraft speed V, altitude H, bank angle Φ, and root bending moment of wing BM_w are recorded as so called slaved signals. Similarly the bending moments in the root of horizontal and vertical tail are slaved to each other. Table 1 presents the different data processing methods used for each signal, for which analysis purpose it is recorded and its role as master or slaved signal.

Hardware Description

Figure 3 presents a flow diagram of all equipment involved in the load monitoring system for the CN-235

Table 1 Comparison of Data Processing Algorithms Used and Purpose of Recorded Signals.

Signal	data processing method	analysis purpose			master signal ?	slaved signal	slaved to other signals?
		Load Spectra	Gust Analysis	Mission Analysis			
vert. acceleration N_z	SPV	x	x	x	yes	V,H,Φ,BM_w	no
speed V	TT		x	x	yes	none	yes
altitude H	TT		x	x	yes	none	yes
bank-angle Φ	--		x	x	no	--	yes
bending moment wing BM_w	SPV	x			yes	none	yes
diff. cabin pressure ΔP_{cabin}	SPV	x		x	yes	none	no
bending moment vert. tail BM_{vt}	SPV	x			yes	BM_{ht}	yes
bending moment hor. tail BM_{ht}	SPV	x			yes	BM_{vt}	yes
spare signal Sp	SPV	x			yes	none	no

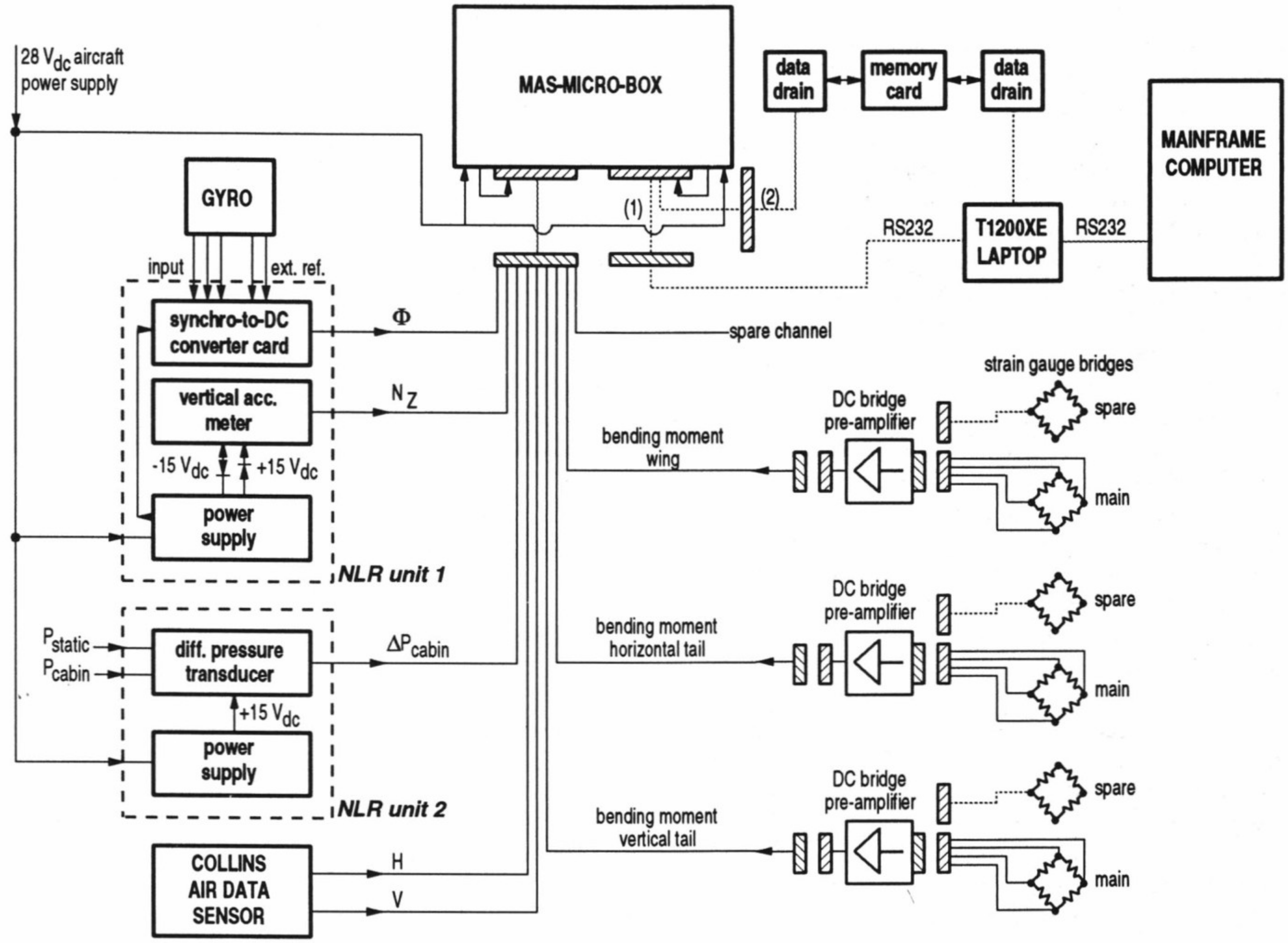


Fig. 3 CN-235 Fatigue Load Monitoring System. (Hardware)

aircraft. It consists of the following units:

In aircraft:

(1) 1 SWIFT GmbH MAS-MICRO-BOX data collector unit with internal strain gauge signal conditioners
(2) 4 pre-amplifiers for strain gauge signals
(3) 1 Sundstrand QA-1400 accelerometer
(4) 1 synchro-to-analog convertor for bank-angle signal (combined with (3) in one unit)
(5) 1 Druck differential pressure sensor
(6) Strain gauge bridges including spares

On ground:

(7) Toshiba T1200 XE laptop computer for data retrieval and adjustment of data configuration.
(8) SWIFT data-drain unit with memory cards for data retrieval and adjustment of data configuration of MAS-MICRO-BOX.

The SWIFT MAS-MICRO-BOX system is the latest development developed out of the MAS-FM-System, which is being used in among others the Tornado MCRA, the Saab 340 commuter and in the Lynx helicopters of the Royal Netherlands Navy. Figure 4 presents the MAS-MICRO-BOX with the data-retrieval equipment.

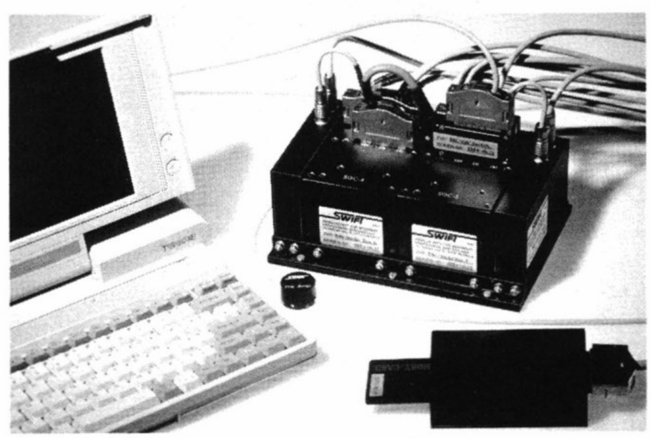


Fig. 4 SWIFT MAS-MICRO-BOX loading monitoring device, pre-amplifier and data retrieval equipment

The MAS-MICRO-BOX System consists of a small data collector with internal software controlled amplifiers and additional external pre-amplifiers for strain gauge bridge signals placed far away the data collector. In the CN-235 configuration, two processors handle the data-acquisition and processing of respectively 5 and 4 analog channels. Maximal 16 analog and digital signals can normally be processed.

Data recorded in the resident memory of the MAS-MICRO-BOX System may be extracted by connecting a data-drain unit, using memory cards of 0.5 MB capacity, or by a RS-232 high-speed serial link with a portable microcomputer (MAS-terminal). The memory capacity of the data recorded is such that it needs to be transferred only once in four weeks. The laptop PC can also be used to change the configuration, or to check/evaluate the measured signals for e.g. calibration purposes. Retrieved data may be stored on diskettes or transferred to a host computer by a RS-232 link. In addition the memory card may also be used to update the configuration file in the data collector.

Start/stop indication of each flight is by means of a relay connected to the anti-collision light. In addition the MAS-MICRO-BOX System has a programmable delay time in the software to overcome possible spikes during the start of the measurement. Sample rate for each channel is 2000 Hz. Date and time of start/end of measurement are recorded automatically. First and last point of measurement is automatically recorded. Also the most extreme peak and valley which occurred during flight after memory exceedance is nevertheless stored. The signals representing the aircraft speed and altitude are directly taken from the aircraft system (e.g. a Collins Air Data Sensor unit). The bank-angle signal is taken from the Gyro system, but needs an additional Synchro to a DC signal conversion taking place in the same unit where the accelerometer is installed. A second unit contains the differential (cabin) pressure transducer. In order to measure the bending moments six strain gauge bridges have been installed. The selection of strain gauge positions was based upon experience and results obtained with the original test instrumentation in the CN-235 prototype. More than the minimum required number of bridges were installed in order to have some spare gauges in case of malfunctioning or breakdown during testing or operation.

Since the load monitoring equipment has been installed in one commercial and will be installed in one military aircraft, the MAS-MICRO-BOX System and the two NLR modules with the accelerometer/synchro-to-analog interface and the diff. pressure transducer units were tested before acceptance for compliance with shock/vibration, EMI and temperature/humidity requirements according to MIL-STD-810D, MIL-STD-461B/462 and MIL-STD-704C on the airborne components.

Analysis Software Description

The software can be divided into two parts, namely those programs for generation of a database with all recorded data and those programs performing the actual analyses. Based on similar NLR load monitoring projects it was decided to create first a database containing all recorded data, which will be used by the analysis programs. A small interactive program, SELECT, will select the files to be analyzed in the database. Figures 5 and 6 present a flow chart of the programs for respectively the database generation part and the analysis part.

The first set of programs consists of the following programs:

(1)	BIMOTA	(BIts MOving and TrAnslating program)
(2)	FLSEP	(FLights SEParator)
(3)	DBFINPUT	(DeBriefing Form INPUT)
(4)	MERGE	(MERGEr)

The second set of analysis programs consists of:

(5)	SELECT	(SELECT database files)
(6)	LOADSPAN	(LOAD SPectra ANalysis program)
(7)	RAINFLOW	(RAINFLOW counting program)
(8)	GUSTAN	(GUST ANalysis program)
(9)	MIPRAN	(MIssion PRofile ANalysis program)

(A) Database Generation

(1): BIMOTA

BIMOTA (BIts MOving and TrAnslating program) is a conversion program that translates binary data coming from the SWIFT MAS-MICRO-BOX system into an ASCII file. The binary data contains, among other things, the recorded data, the values of the parameters of the MAS-MICRO-Boxes and the logbook data of the measurement sessions.

After conversion in ASCII format by BIMOTA, each output file from the load recording device will contain the recorded data and the internal logbook data of all flights recorded during one session for that particular airplane. This data is stored in chronological sequence.

(2): FLSEP

FLSEP will read this file and will separate all data belonging to a single flight. Before writing the recorded data of one flight to a single file, it will conduct a quality control to this data in order to achieve a good impression of the validity of the recorded data. In addition the number of datapoints per channel are

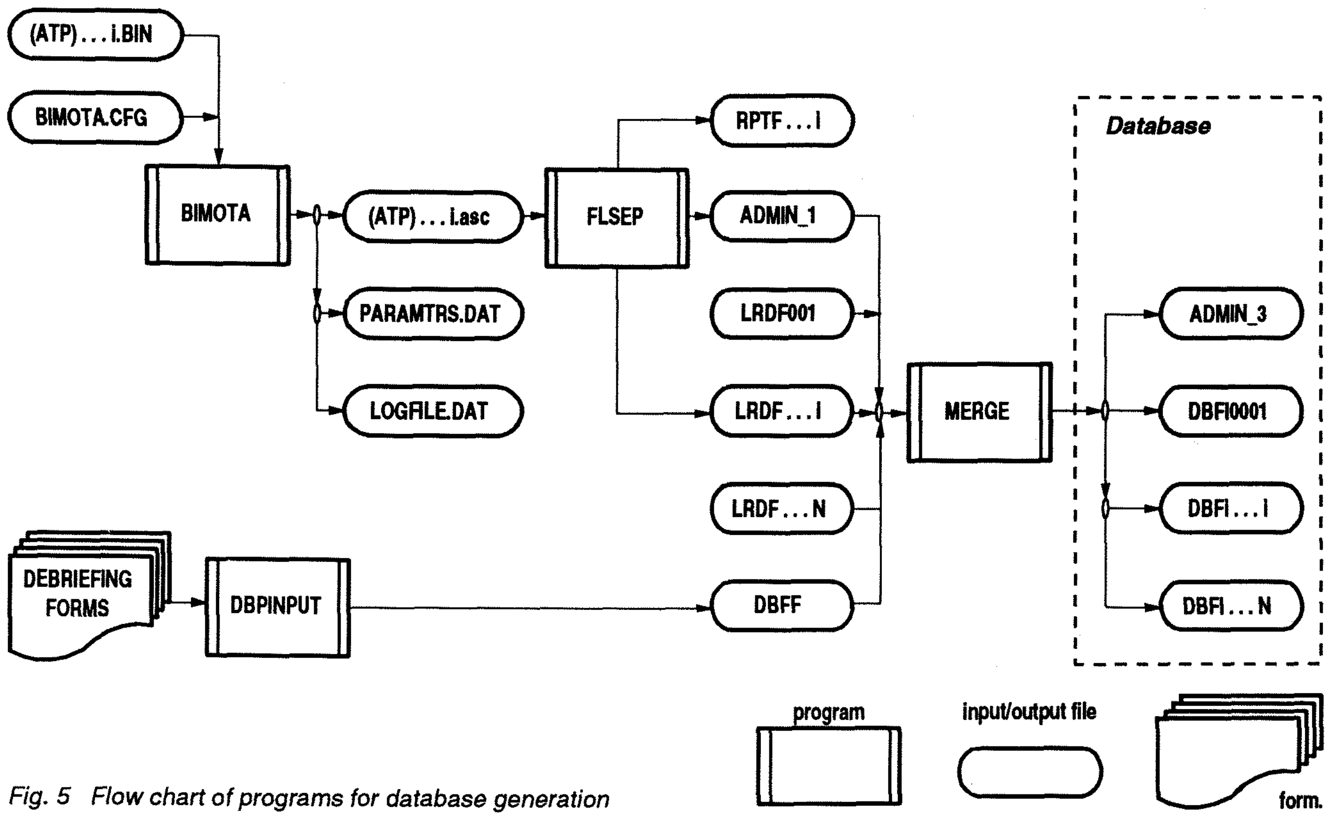


Fig. 5 Flow chart of programs for database generation

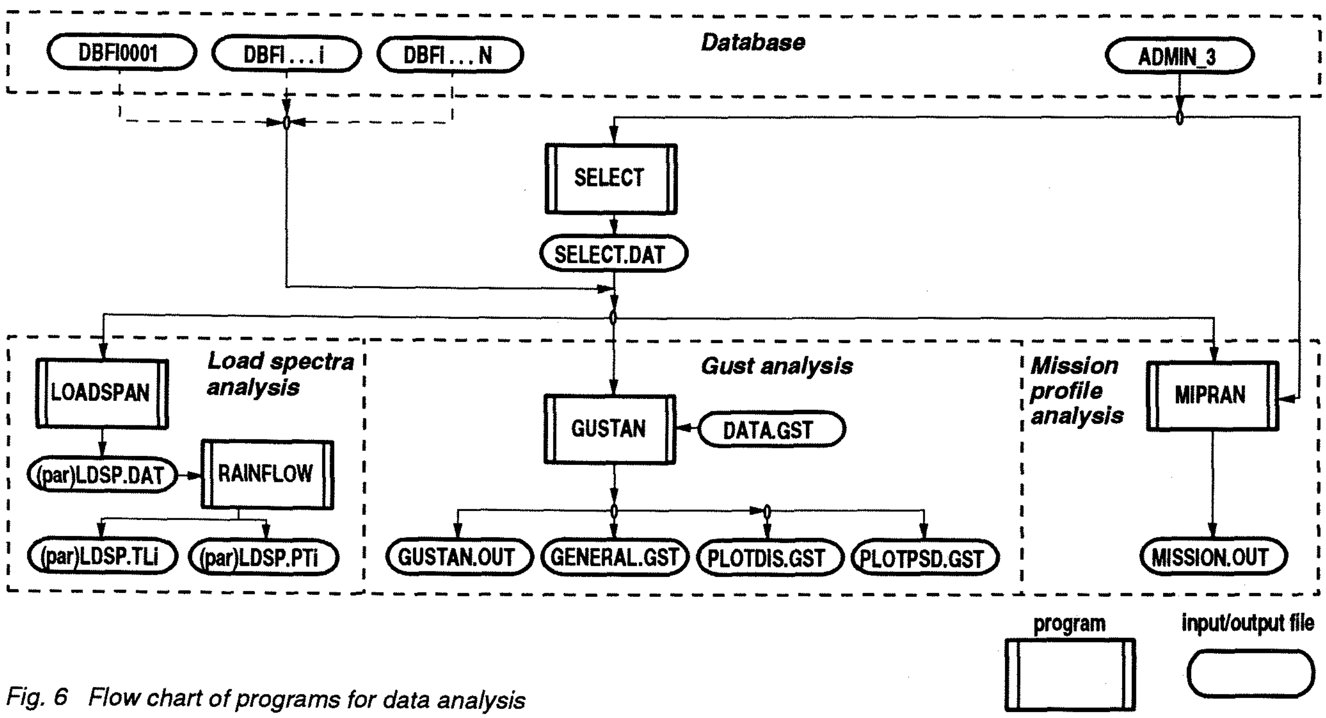


Fig. 6 Flow chart of programs for data analysis

counted to get knowledge on the averaged number of recorded datapoints per hour and/or flight.
For the convenience of the analysis programs each flight is subdivided into nine flight modes (pre-flight taxi; take-off; climb; cruise; descent; holding pattern; approach; landing and post-flight taxi). Definition of these flight modes depend on the time-dependant properties of the V and H signals. FLSEP will therefore determine from each data point the corresponding flight mode.

(3): DBFINPUT

Additional data concerning each flight which are not recorded by the Load Recording Device will be gathered by means of a debriefing form.
The debriefing form will be filled in by the operator and send to IPTN on regular bases. The information that will be on the debriefing form are:

(1) aircraft type; (2) date; (3) time of departure; (4) time of arrival; (5) Take-off weight; (6) Weather (Smooth, Moderate, Heavy); (7) field of departure; (8) field of arrival; (9) flight number of the operator. This information will be placed in the computer with the aid of program DBFINPUT.

(4): MERGE

Program MERGE will merge the output of program FLSEP and program DBFINPUT into a single file for each recorded flight. Merging will take place if in both files for a specific flight some parameters are identical.

(B) Analysis Programs

(5): SELECT

The SELECT program selects all those flights currently available in the database that meet the criteria one has selected interactively within this program.

The selection parameters are:
(1) Aircraft type; (2) Time or flight number interval; (3) Flight duration; (4) Flight route; (5) Take-off weight; and (6) Weather type.

(6+7): Load Spectra Analysis

In the load spectra analysis, the spectra of the root bending moments in wing, hor. and vert. tail (+ Nz and Diff. cabin pressure) are determined and optionally extrapolated to 60,000 flights. It is also possible to generate spectra for certain segments of the flight like climb and cruise.
The load spectra analysis will be done in two steps. The first step is being performed by LOADSPAN and consists of selecting the load parameters to be analysed and the extraction of all data from the selected database files into an array suitable for input in the second program RAINFLOW, in which the data will be processed using a "Range-Pair-Range" counting method (1), also known as "Rainflow" counting method. The results of those countings are stored in a "from-to" matrix. From such a matrix the number of crossings of various load levels can easily be derived (1). Results will be in tabular as well as in graphical format.

(8): GUSTAN

The GUST ANalysis program, GUSTAN, determines from the measured values of the vertical acceleration and the simultaneously measured values of aircraft speed and altitude in all selected flights (airborne flight modes only) the discrete gust speed, U_{de}, and the continuous gust speed, U_σ, and its distribution functions for six different altitude ranges.

The following equations are used:

mass parameter $$\mu = \frac{2 * \text{mass}}{\rho * S * c * C_{L\alpha}}$$

For the discrete gust model:

gust alleviation factor $$K = \frac{0.88 * \mu}{5.3 + \mu}$$

discrete gust speed $$U_{de} = \frac{2 * \text{mass} * g * \Delta n_z}{\rho_0 * V_E * S * C_{L\alpha} * K}$$

And for the continuous gust model, according to the formula of Houbolt, (Coupry (2)):

gust alleviation factor

$$K = \frac{11.8}{\pi^{\frac{1}{2}}} * \left(\frac{c}{2 * L}\right)^{\frac{1}{6}} * \left(\frac{\mu}{110.0 + \mu}\right)^{\frac{1}{2}}$$

continuous gust speed

$$U_\sigma = \frac{2 * \text{mass}\ g * \Delta n_z}{\rho_0 * V_E * S * C_{L\alpha} * K}$$

Before processing the N_z values, vertical accelerations will be corrected for roll manoeuvre contribution by the following equation:

$$\Delta n_{z,\text{corrected}} = \Delta n_z - \left(\frac{1}{\cos(\phi)} - 1\right)$$

Further reduction of the measured datapoints will be performed by applying a peak-between-means filter. Results will be in tabular as well in graphical format.

(9): MIPRAN

The MIssion PRofile ANalysis program, MIPRAN, determines from the files selected from the database (by means of SELECT) certain statistical values. Firstly, since each flight was divided by FLSEP in separate flight segments or modes, the distribution of relevant flight parameters (e.g. V and H) and averaged values will be determined from each flight mode. Other statistical computations include: averaged values and distributions in time and in distance of flight duration; averaged flown distance and its distribution per altitude range; and extreme values of N_z and bank angle.

Results

Due to some start-up problems only a limited number of flights have been recorded and analysed. Therefore the presented results are only indicative of the output of the different analysis programmes. No attempt has been made in this paper to present statistically relevant figures of the actual loads of the CN-235 in comparison with design spectra and of the typical gust load experiences of such a plane in a tropical environment. Some results obtained from the CN-235 measurements are presented in this paper by means of:

- presentation of general data (average flight time, distribution of flight altitudes, etc.);
- description of typical flight recordings;
- presentation of load spectra.

General data

Flight altitude distribution

Figure 7 presents the averaged kilometers flown and time spent as function of altitude ranges. Further analysis shows that most of the test flights were flown at low altitudes (< 8000 ft), while some long-range ferry flights were flown at higher altitudes.

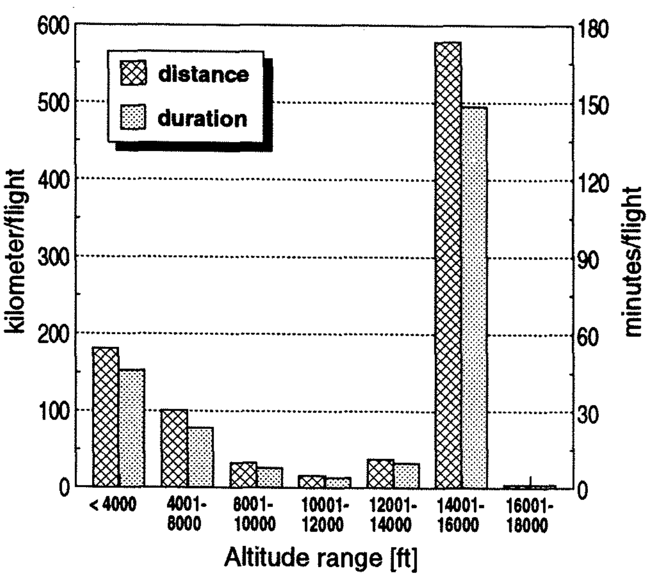


Fig. 7 Flight altitude distribution

Flight duration

The flight duration is defined as the time period, during which the anti-collision light has been switched on. The distribution of flight time is presented in figure 8. Most flights (39 %) have a duration between 90 and 135 minutes. The average flight time is approximately 122 minutes.

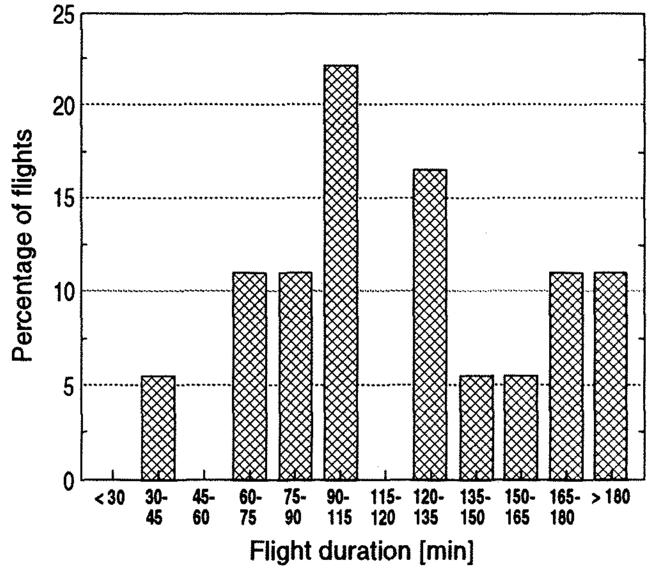


Fig. 8 Flight duration distribution

Typical flight recordings

Time histories of the most important parameters recorded during each flight can be evaluated by means of a specially written quick look program. In figure 9 an example is given of this plotting routine, which has been made for all flights as a "quick look" facility. Plotting routines to compare time history traces of one or more flight parameters have also been made and have been used on an ad-hoc basis for the purpose of more detailed evaluations of particular flights. Because the measured load data has not been recorded as time histories, accurate frequency information can not be obtained. However by simply counting the number of load cycles (=half the number of recorded peaks and valeys) per second, an indication of the frequency (pseudo-frequency) can be obtained. Figure 10 presents such pseudo-frequency plot of the horizontal tail bending moment for one flight. For purpose of clarity the altitude and the actual signal has also been plotted in the same plot.

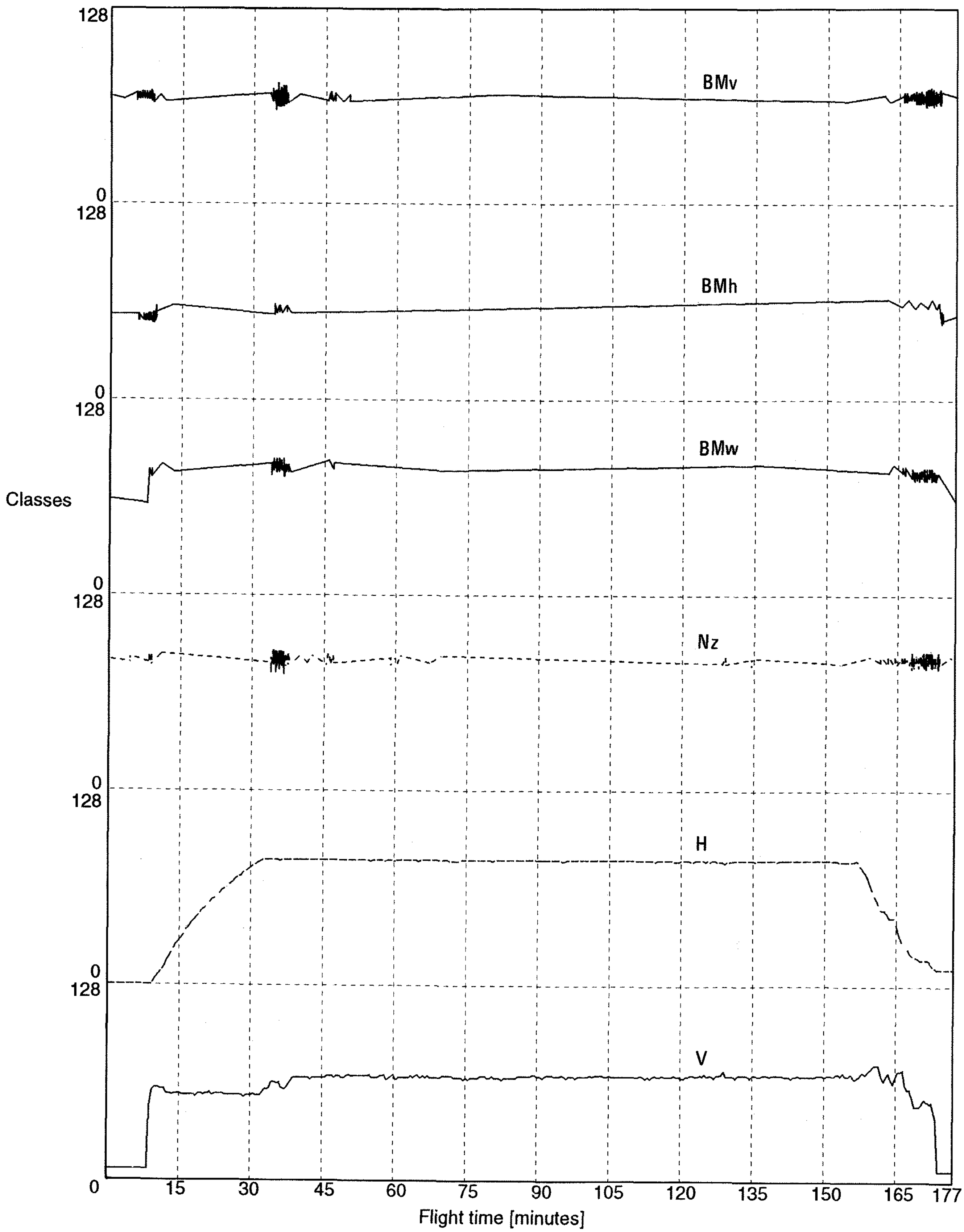


Fig. 9 Quick-look plot of main recorded parameters for one flight

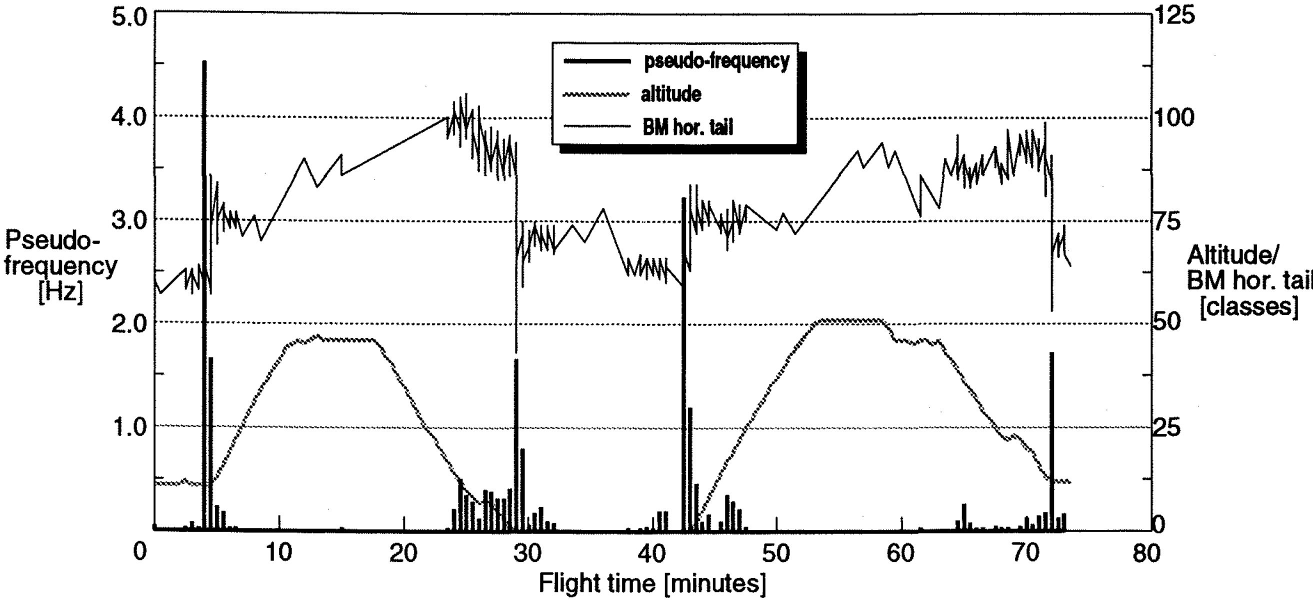


Fig. 10 Pseudo-frequency plot of bending moment horizontal tail for one flight

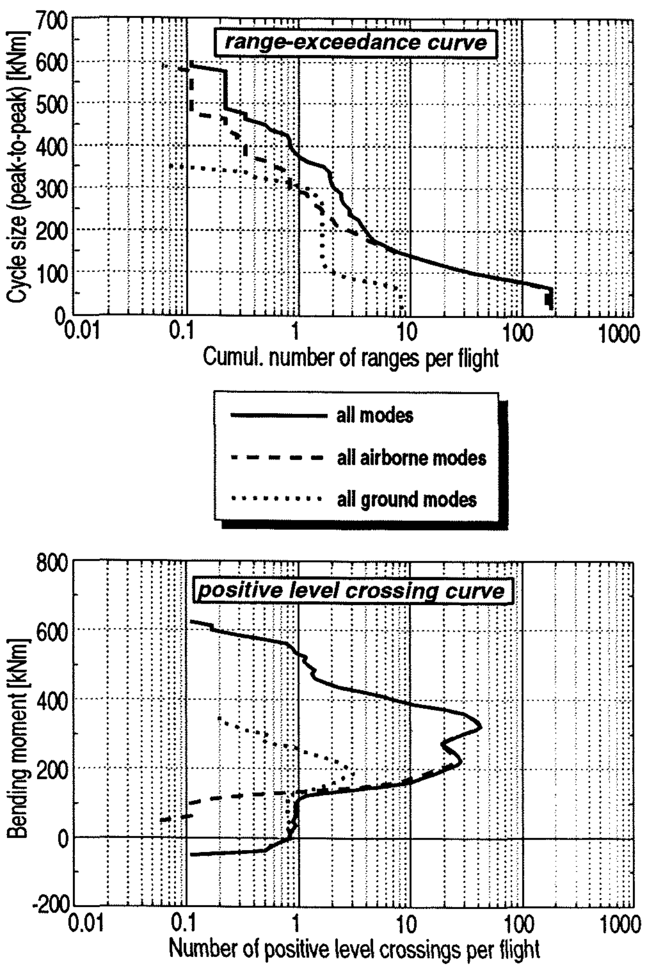


Fig. 11 Spectra of wing bending moment

<u>Load spectra</u>

Based on a limited batch of 18 flights with the prototype aircraft, the range-exceedance and positive level crossing curves of the wing bending moment is presented in figure 11. It should be noted that the batch of flights used in this analysis consisted of a number of test flights with certain maneuvres and some longe range flights with additional fuel on board.

Summary

A system has been described for the recording of flight and load parameters during operational flights based on a relatively simple load monitoring device.

A description has been presented for the software needed for the generation of a database with all relevant information as well as for the analysis and derivation of load spectra, gust load analysis and the statistical presentation of typical mission parameters.

Since only a limited batch of flights has been recorded so far, no attempt has been made in this paper to present statistically relevant figures of the actual loads of the CN-235 in comparison with design spectra and of the typical gust load experiences of such a plane in a tropical environment. It is envisaged to present such data based on a statistically relevant number of flights in the near future.

Symbols Used

BM_w = root bending moment wing (Nm)
BM_{ht} = root bending moment vertical tail (Nm)
BM_{ht} = root bending moment horizontal tail (Nm)
c = wing chord (m)
$C_{L\alpha}$ = slope of the lift curve (-)
Δn_z = incremental load factor due to vertical gust (-)
ΔP_{cabin} = differential cabin pressure (Pa)
H = aircraft altitude (m)
K = gust alleviation factor (-)
L = integral scale of turbulence (m)
μ = mass parameter (-)
N_z = vertical load factor (-)
ρ = air density (kg/m^3)
ρ_0 = air density at sea level (kg/m^3)
S = wing area (m^2)
Sp = spare signal
U_{de} = discrete gust speed (m/s)
U_σ = continuous gust speed (m/s)
V = aircraft velocity (m/s)
V_E = equivalent airspeed (m/s)
Φ = bank angle (°)

References

(1) De Jonge J.B., "Manual on the Flight of Flexible Aircraft in Turbulence", AGARD, AGARD-AG-317, chapter II, 1991.

(2) Coupry G., "Manual on the Flight of Flexible Aircraft in Turbulence", AGARD, AGARD-AG-317, chapter III, 1991.