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ABSTRACT
Load monitoring of the F-16 fleet of the RNLAF has been carried out by NLR as a routine program since 1990. At that time the old system was replaced by an electronic device capable of analysing in flight the signal of a strain gage bridge. In later years, updates of the hardware have been implemented in order to record also some flight and engine parameters. Furthermore, collecting of administrative data has been integrated in the routine RNLAF maintenance debriefing procedures.
In recent years development of a complete new load monitoring system took place. This system is fully integrated in the operational- and maintenance-procedures of the RNLAF.
Main characteristics are an increase of the number of strain gage bridges to five and a fleet wide implementation. Besides flight parameters, engine and avionics parameters are being measured. Ground stations for data handling are located at the squadrons and at NLR. By using up to date data base management programs, results are presented to the RNLAF on a weekly basis.

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F-16 loads/usage monitoring

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F-16 LOADS/USAGE MONITORING

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1. SUMMARY

Load monitoring of the F-16 fleet of the RNLAF has been carried out by NLR as a routine program since 1990. At that time the old system was replaced by an electronic device capable of analysing in flight the signal of a strain gage bridge. In later years, updates of the hardware have been implemented in order to record also some flight and engine parameters. Furthermore, collecting of administrative data has been integrated in the routine RNLAF maintenance debriefing procedures.

In recent years development of a complete new load monitoring system took place. This system is fully integrated in the operational- and maintenance- procedures of the RNLAF.

Main characteristics are an increase of the number of strain gage bridges to five and a fleet wide implementation. Besides flight parameters, engine and avionics parameters are being measured. Ground stations for data handling are located at the squadrons and at NLR. By using up to date data base management programs, results are presented to the RNLAF on a weekly basis.

2. INTRODUCTION

Since 1990, load monitoring of the airframe of the F-16 fleet of the Royal Netherlands Air Force, RNLAF, is carried out by the Load and Usage Monitoring group of the National Aerospace Laboratory, NLR. The main sensor for the fatigue experience of the aircraft is a strain gage bridge at one of the main bulkheads in the fuselage The measured strain is a good indicator for the wing root bending moment, see reference 1.

In 1994, an upgrade of the system to a four channel version was carried out. Besides the strain at one location also vertical acceleration, pressure altitude and calibrated airspeed are recorded. In this way more information about the usage of the aircraft in terms of flight envelope and manoeuvring becomes available, see reference 2.

In both cases, load monitoring equipment was installed only in a sample of the fleet.

In addition to the recorded "Load data" administrative information is needed like squadron, date of flight, mission type etc.

Four times per year a report is presented to the RNLAF with detailed information about the damage experience per tail number. As a damage indicator NLR uses the so called Crack Severity Index , CSI, see reference 3.

In chapter 3, an overview of the development to the present load monitoring program will be presented in more detail.

In 1993 development of a new instrumentation system started and NLR has been involved in the definition of its specification. Further, in close co-operation with the manufacturer, NLR did take part in the development and in the implementation of the system. In the new instrumentation package several functions are combined. Besides load monitoring of the airframe also engine and avionics health monitoring is carried out. In chapter 4, this new load monitoring program will be described.

Two important changes have been made with respect to the to the old load monitoring program for the airframe, namely an extension of the number of recorded strain gage bridges to five and fleet wide application. Special attention has been given to a more automated storage, analysis and reporting of the recorded and the collected administrative data.

In chapter 5 the new hardware which will be used in the F-16 fleet, namely the FACE system manufactured by RADA electronic industries inc. in Israel, will be described in more detail.

The paper ends with some concluding remarks.

3. OVERVIEW DEVELOPMENT LOAD MONITORING F-16 IN RNLAF

In references 2 and 3 it is described how the load monitoring of the F-16 fleet of the RNLAF has been taken care of since the introduction of the aircraft in 1979. It may be mentioned here that for the RNLAF this was the first weapon system which had a load monitoring system available from the very start. Till that time, load monitoring has always been retrofitted to the aircraft after so many years. So, in the case of the F-16 this was really a step forward.

3.1 Load data

The chosen instrumentation for the F-16, namely a Flight

Loads Recorder, FLR, in a sample of the fleet for Load Environment Spectrum Survey, LESS, recordings and a Mechanical Strain Recorder, MSR, from Leigh for individual aeroplane tracking was not very reliable. In combination with the long turn around times, the cassettes of both systems had to be read out by the USAF, this load monitoring program was not a success.
After an update of the Fleet Structural Maintenance Plan, FSMP, which was based on data recorded with the FLR, the FLR had been build out. Further, the RNLAF was looking for a replacement of the MSR. It was decided that the MSR was to be replaced, on a sample of the fleet, by a full strain gage bridge at the same location as the MSR. Also a choice has been made for an electronic device capable of searching peaks and troughs in a strain gage signal. Selected was the Spectrapot system produced by Spectralab in Switzerland. In 1994, the one channel version of the Spectrapot system was replaced by a 4 channel version in order to have a limited LESS capability. In the case of the RNLAF, this was recording of vertical acceleration or engine RPM, speed and altitude. Per squadron there are 3 units available and 10 aircraft have "provisions for". By replacing the equipment to another aircraft in case of long time maintenance it is possible to increase the number of recorded flights to an acceptable level.
In 1995 the Spectrapot system has been made a "tracked item" in the Core Automated Maintenance System, CAMS, of the RNLAF. From CAMS it is known in which aircraft the instrumentation package actually has been installed. Furthermore the CAMS system generates automatically work orders to replace the memory after 25 flight hours.

3.2 Administrative data

In 1995 the special debriefing form, which has been in use till that moment for only the recorded flights, has been replaced by extracting the data from the RNLAF CAMS computer. This was an important change, because the special debriefing form always did request a lot of attention from NLR in order to get the forms filled in properly. Without the data on the form the recorded load data can not be used.
It has been assured that all important administrative data, that used to be on the debriefing form, will also be available in CAMS. This lead to some changes in the CAMS input by the debriefer of the squadron. For example mission type and external store configuration have been added. Further, the decision has been taken by the RNLAF to collect this data for all F-16 flights, independent of the fact if there is a strain recording available or not. Each week this information is downloaded by NLR directly from the main CAMS computer.
In figure 1 the data flow in the present program is shown.

3.3 Individual tracking

By combining the load data from the sample measuring program and the CAMS data from all F-16 flights it is possible to present to the RNLAF information about the experienced fatigue severity per tail number. From the sample measuring program the severity per mission type, per squadron and per time period is available. By combining this information with the mission mix per individual tail number for the same period, an individual damage indication is calculated.

In the present program the damage indication used is the Crack Severity Index, CSI, which for some years has been developed by NLR. This CSI is used for quantification of the fatigue damage of recorded stress spectra in terms of crack growth potential, see reference 3. The CSI is a relative figure: in the application for the F-16 a value of 1.0 means a fatigue damage according to the usage and loading environment of the RNLAF in 1985.
On of the important features of the CSI method is, that interaction effects between large and small load cycles (or between severe and mild flights) are taken into account. As a result the fatigue damage of a flight is therefore dependent on the severity of the flights which has been flown before that flight.

3.4 Reporting

Besides the quarterly standard reports which are being made on a routine bases, in recent years also ad hoc reports have been made on request of the RNLAF. Partly these questions were raised by the standard reports, but also questions were asked in relation to the future usage and loading experience of the F-16 fleet after MLU modification. The large data base offers possibilities to investigate these questions. As an example actual and estimated take off weight distributions are presented, see figure 2.

4. NEW LOAD MONITORING PROGRAM

In 1994 an updated version of the Spectrapot system has been introduced in the fleet. At that time it was already clear that this was only a temporarily solution. Since 1990 discussions took place between RNLAF and NLR about the most favourable load monitoring program for the second half of the life of the F-16 fleet.
Two main modification projects were foreseen, namely the Falcon Up project, which is mainly a structural modification of the four main carry trough bulkheads and the Mid Life Update, MLU, which is basically an avionics upgrade of the aircraft. As a result of this structural upgrade it was expected that the mid fuselage section will give far less fatigue problems in the future. Consequently, other parts of the structure will become fatigue critical.
However, the main indicator for the loading experience of the aircraft is the strain gage bridge at one of the main

bulkheads. This is not the best location for monitoring the fatigue experience of other parts of the aircraft, like outer wing, fuselage and stabilisers. Monitoring of these parts was even more important, because the RNLAF did find already fatigue cracks in these other parts of the aircraft. The conclusion was: an increase of the number of strain gage bridges is needed.
Furthermore, one of the basic assumptions for the old "sample" program was that aircraft in the same squadron were flying more or less the same mission mixture. During the first years of operation of the F-16 in the RNLAF this was true. However, in recent years aircraft have been switched more often from squadron to squadron. Also more "out of area operations" in Canada, Goose Bay, and Italy, Villa Franca, took place with a different usage and loading experience for the aircraft as in the Netherlands, see figure 3. For these reasons a sample program will not be sufficient any more. The decision has been taken for a fleet wide implementation.

4.1 Development of new instrumentation

In the same period, the operational directorate of the RNLAF was looking for a pilot debriefing instrumentation independent of the so far used ACMI ranges. RADA electronic industries in Israel had their Air Combat Evaluation, ACE, system. A selection of the data on the Mux Bus in the aircraft is written on the video tape. In a ground station the video tapes of different aircraft are synchronised and the data on the tapes is used for creating an artificial picture in which the fight can be followed.
In 1993, test flights with this ACE system has been carried out in the Netherlands and the idea came up to combine the new system for the pilots with the need for a new load monitoring instrumentation.
The RNLAF did contract NLR for writing down the specifications for the Fatigue part of the combined system and to codevelop with the manufacturer the new "FACE" system.
During a test flight with the new system in 1994 it became clear that it was possible indeed to combine the pilot debriefing- and the load monitoring- function in one system. In 1995 the contract was signed by RNLAF to buy FACE systems for all aircraft and in 1996 the first test flights took place with the new pre production system. During the development phase close contact has been held with Lockheed Martin Tactical Aircraft Systems, LMTAS, for implementation of the system in the F-16, especially for a correct connection of the Mux Bus, hard- and software, and the wiring for the MLU configuration.
At this moment about fifty percent of the F-16 fleet of the RNLAF has been modified.

4.2 Main features of the new load monitoring program

In chapter 3 the present load monitoring program has been described. On first sight the new load monitoring program can be seen as an upscaling of the existing program: an increase of the number of straingage bridges to five and a fleet wide implementation.
However, as a result of the increased capability of the recording system, which is fully integrated with other aircraft systems, far more (flight)parameters for airframe-, for engine- and for avionics- monitoring are available. The software is very flexible in changing the parameters which will be measured. In the next chapter this recording system will be described in more detail.
The load monitoring program, which is the total of instrumentation, measuring, analysing and reporting, has to cope with all these new possibilities. Furthermore the RNLAF wants the results far more faster than in the past.

The main features of the new load monitoring program are as follow:

* Increase of the number of strain gage bridges to five. Besides the strain gage bridge on one of the main carry through bulkheads at FS 325, strain gage bridges are located at the lower skin of the outer wing at WS 120, at the keelson in the centre fuselage at FS 374, at one of the aft fuselage bulkheads at FS 479 and at one of the attach fittings of the vertical tail at FS 462, see figure 4.
For the selection of these locations a special measuring program has been carried out with two instrumented aircraft. During 330 operational flights the signal of 10 strain gage bridges have been recorded. The location of these 10 bridges have been chosen in close co-operation with LMTAS.
In our opinion, the chosen set of five strain gage bridges is a good compromise between a limited system and sufficient information about the loading environment of different locations in the airframe, see figure 5.
* World wide experience has shown that 100 % data capture is an illusion. For example sensors break down, memories get lost and wiring problems occur. This means that there must be a "backup procedure" for replacing the lost data of the flights concerned.
In discussions with the RNLAF it was stated that the results should be made available far more faster than in the old situation in which quarterly results were presented to the squadrons a long time after the end of that quarter. Conflicting with this wish was the decision taken that a memory cassette stays in the aircraft for 25 flying hours, so it may take weeks before the actual recorded data becomes available.
To find a solution it was realised, that each week administrative usage data, like mission mixture and flight hours per tail number from the CAMS system is stored in the data base at NLR. By using this data and what is called "Statistical CSI data " it is possible to calculate each week fatigue damage results per tail number. "Statistical CSI data" means the CSI values per mission type, per squadron and per time period. This is the same

procedure as has been used in the old "sample" program to calculate CSI results for not instrumented aircraft.
With the weekly update of the 5 CSI values per tail number, the RNLAF can fine tune their maintenance and show the pilots the results with respect to fatigue damage of the flights of the previous week.
After reception of the actual recorded data from an aircraft, two actions will take place: first: the so far used statistical CSI data used for that tail number will be replaced by the actual recorded data and second: the statistical CSI data for that squadron will be updated. In this way there is a continuous updating of the statistical CSI data. And of course, if recorded data is really lost, the data for replacing the actual recorded data is as accurate as possible for the average squadron experience.
* In order to make it possible to present weekly results, a large change has to be made in collecting, storing and analysing the data in comparison with the methods used so far. One has to bear in mind that there will be a large increase in the amount of data by changing from a sample program on a limited number of aircraft with one strain gage to a fleet wide program with five strain gage bridges per aircraft. To cope with this, the whole process of data handling has to be automated to a large extend. As an example, data transfer from the squadron ground station to NLR will be done automatically during the night. Special care has been taken to ensure "secure" data communication.

For storing and analysing the recorded and CAMS data and for reporting of the results the relational data base package from ORACLE has been selected. Since last year the programming of the application for the F-16 load monitoring program is under way at NLR. For storing the data, a large number of tests are included in this application program to check on the quality of the recorded data. Cross checks with other signals are carried out. Under investigation is the use of neural networks for these checks.
Further, the different structural configurations of the airframe are taken into account. For example, for the 325 bulkhead there are three different versions, namely the "early" production, the "final" production and the "Falcon Up" modified bulkhead. The program corrects the strain gage signal for not being on a "final" production bulkhead. By the way, the status of all structural technical orders for each tail number will also be included in the weekly update of the CAMS data.
The ORACLE application program is also written in such a way that recorded data from the old Spectrapot instrumentation program can be used as well. A last remark can be made with respect to the different avionics versions of the F-16 aircraft. The ORACLE application program covers the Operational Conversion Upgrade, OCU, version of the aircraft with analogue and digital engine control, EEC and DEEC, and the new Mid Life Update, MLU, version of the aircraft. This effectively means that there are three complete different sets of Mux Bus and engine data available.
With respect to analysing the data, at this time most attention is given to the calculation of the CSI values for the five strain gage locations. Especially the determination of the reference sequences for these locations for the CSI calculation are a subject of discussion with LMTAS.

The final result will be that weekly reports will be generated automatically. These reports are than on line available for the RNLAF. In the start up phase of the program this will only be a limited version. It is expected that, in the future, more results will be reported. It takes some time for RNLAF and NLR to fully realise all the new possibilities of the new integrated recording equipment. For the engine monitoring already discussions have been started with RNLAF and Pratt and Whitney about future more detailed recordings. Furthermore, information about the systems in the aircraft is available. At this time it is foreseen that more often than in the past ad hoc measuring programs will be made in assistance of avionics fault detection.

5. DESCRIPTION OF INSTRUMENTATION PACKAGE

The complete FACE system combines two major functions, pilot debriefing and load monitoring for airframe and engine. In the aircraft there is only one set of hardware. The hardware in the aircraft consists of two electronic boxes, namely the Flight Monitoring Unit, FMU, and the Data Recording Unit, DRU, see figure 6. Amplifiers for the strain gage bridges are located close to these bridges.
On the ground both functions are completely separated. At each squadron there are two ground stations: an Operational Debriefing Station, ODS, for the pilots and a Logistic Debriefing Station, LDS, for maintenance. The use of the system is quite different for both groups. The pilots use the system locally as a tool for operational debriefing for specific mission types directly after a flight. For load monitoring all flights have to be recorded and a Data Recording Cassette, DRC, will be read out only after 25 flight hours. The LDS is connected to the Central Logistic Debriefing Station at NLR.
As mentioned before, the FACE system is completely integrated with other aircraft systems. In combination with the software installed in the FMU, this makes the system a very powerful tool.
In figure 7 the general structure of the FACE system is given. From different sources information is available and there are a number of storage devices. In the FMU the selection is made which signals are to be recorded with what way of data reduction and on what device the results

are to be stored.
* Input: all digital information from the data busses is available. For the MLU configuration this means a total of four data busses. For example, information like flight parameters, attitude, accelerations and store configuration. For the engine the system is connected to the Digital Electronic Engine Controller, DEEC. This makes all the digital data of the engine available, such as Rpm's, pressures and temperatures. Both, Mux Busses and DEEC handle a few hundreds of signals. Further the FMU can adapt 15 analogue input signals. Examples are the strain gage bridge signals. Also some discrete values are monitored. A number of analogue channels are spare for future recordings. The last input signals into the FMU are video signals in the aircraft. These signals are being used for the pilot debriefing function of the system.
* Output: there are three output devices. For maintenance the most important one is the DRC on which the data for load monitoring of airframe and engine is stored. Normally, it stays in the aircraft for 25 flight hours.
The video tapes are used for the pilot debriefing function of the system. The FACE FMU writes additional digital data from the Mux Busses on these tapes. This is used on the ODS for generating an artificial replay of the fight. Normally, the tapes are removed after each flight.
As a third storage device the Voice and Data Recorder, VADR, will be present. This device is only used for mishap investigation. Normally, it stays in the aircraft and the data is overwritten all the time.
* In the FMU a choice has to be made which signals are to be used and what the data reduction has to be for those signals. For this, an input file has to be made on the LDS, which is called "Set Up Configuration file". With user friendly software on the LDS this file can be easily generated. Next step is to upload this file to the FMU. If no new SCF file is uploaded the FMU uses the resident one.
In the FMU different "processes" can run at the same time. In total up to 15 processes can be specified. A process is defined by choosing a master signal and than adding a number of slaved signals. Per master signal a maximum of 50 slaved signals can be selected. In principle each signal, which is known at the input side of the FMU, can be chosen for master or slave. Remark: in total 200 combinations of master/slave are possible.
For each process a data reduction algorithm has to be selected. At the moment this can be a "peak and trough search", PAT, a "time at level", TAL, or a "SAMPLE" data reduction, see figure 8. The PAT algorithm searches the master signal for peaks and troughs. A specified range filter is used to filter out small cycles. In this way only cycles which are important for fatigue are stored in their actual sequence. This algorithm is used for all the strain gage bridges.
In the TAL algorithm the time of crossing of specified levels are recorded in their actual sequence. Up to 100 levels can be specified. As a result the time spent in each interval between two levels can be calculated. For example, the use of the after burner of the engine during a flight. No slaved signals are possible with this algorithm.
The SAMPLE algorithm gives the possibility of skipping a number of samples in the master signal before the next recording. Again, at the moment of recording a sample of the master signal, also the values of the slaved signals are stored.
One has to bear in mind that the available sample rate for the different signals in the aircraft is not the same. For the Mux Busses the highest sample rate is 50 Hz. For example this is the case for accelerations and roll- pitch- and yaw- rates. For other Mux Bus signals the sample rates are less. The DEEC signals are at the most sampled with 5 Hz.
For the analogue signals the highest sample rate possible is 1000 Hz and this sample rate has been chosen for the strain gage signals. It is possible to specify smaller sample rates for the analogue signals in the FMU. Also for analogue signals a choice has to be made for the filter cut off frequency and the gain from a number of predefined values.
Data reduction is further possible by selecting the flight mode: ALL, AIR or GROUND during which the recording should take place. Also a time slot during a flight can be specified or a combination of two signals with a specified range for both signals. For example: only recording if Mach is between 0.8 and 0.9 and the altitude between 500 and 1000 feet.
After making all these selections a SCF will be available for uploading into the FMU in the aircraft.
It may be clear from the above, that every F-16 aircraft in the fleet can more or less be used as a fully instrumented test aircraft. Besides for the airframe and the engine a lot of data can be made available for monitoring the health of the avionics systems.
For the routine airframe and engine monitoring the SCF as presented in figure 9 is in use at the moment. As mentioned before it is expected that there will be an increase of the signals to be recorded as a result of discussions with P and W.

After 25 flight hours the memory cassette is taken from the aircraft and down loaded on the hard disc of the LDS. Once per week this data is than sent to the CLDS at NLR for further data storage and analysis as has been described in the previous chapter.
In figure 10 an example is given of a recent ad hoc recording program. A recording like this has been very easily added to the routine SCF.

6. CONCLUDING REMARKS

In this paper an overview has been presented of the development of the load monitoring program for the F-16 fleet of the RNLAF from a simple recording device to a fully integrated system into the avionics of the aircraft. The results are used for adapting operational- and maintenance- procedures within the RNLAF.

The FACE system is a very flexible instrumentation tool. To a large extend, each aircraft of the fleet can be used as a test aircraft for special ad hoc recording programs.

Communication lines between RNLAF, squadrons and air staff, and NLR are very short. This has been very favourable during the development phase of the FACE system. It is expected that this will be also the case during the implementation phase and later on.

Important is the increase of the number of strain gage bridges to five and the fleet wide installation in the nearby future.

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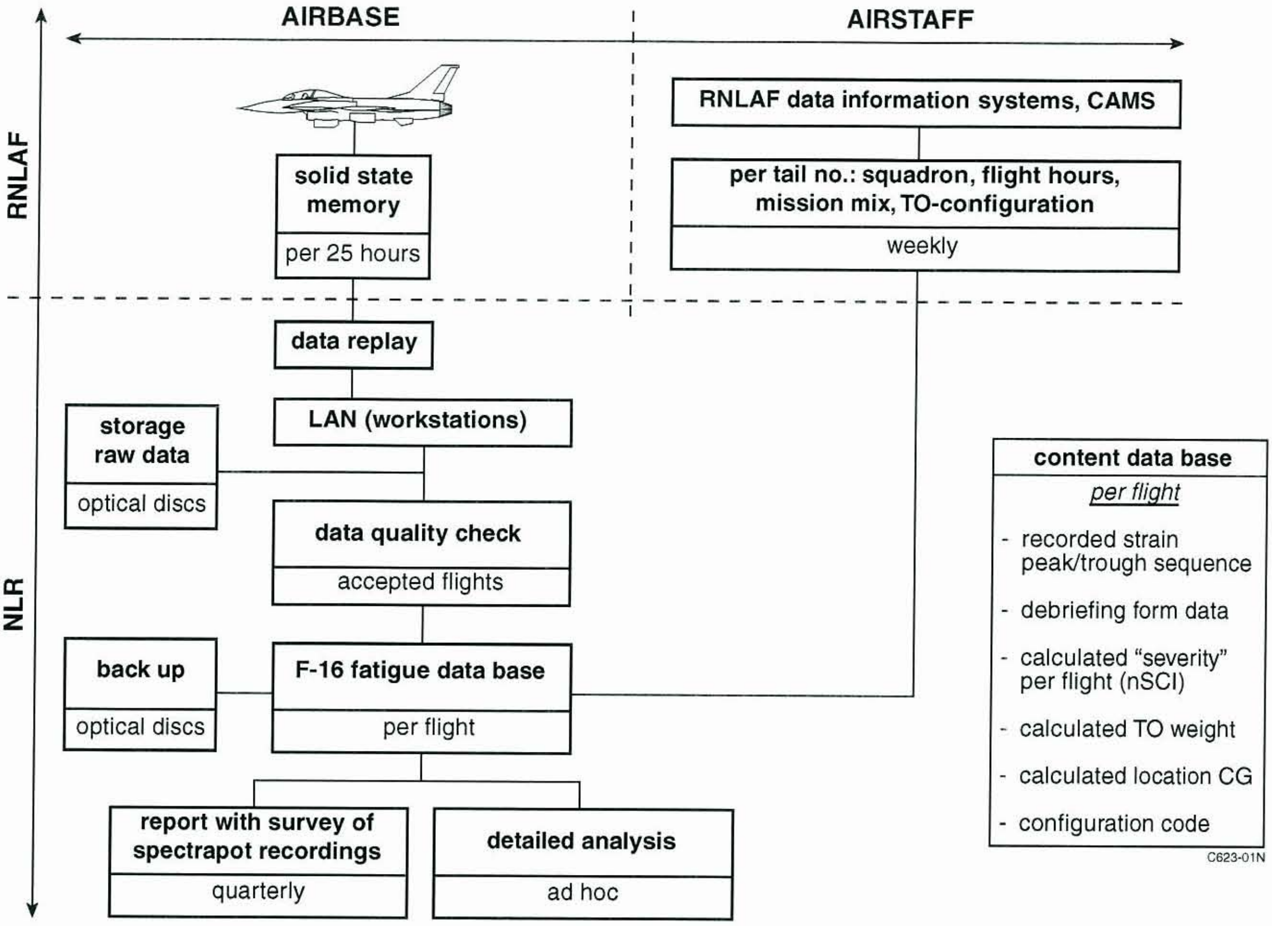

Fig. 1 Data flow in F-16 load monitoring program

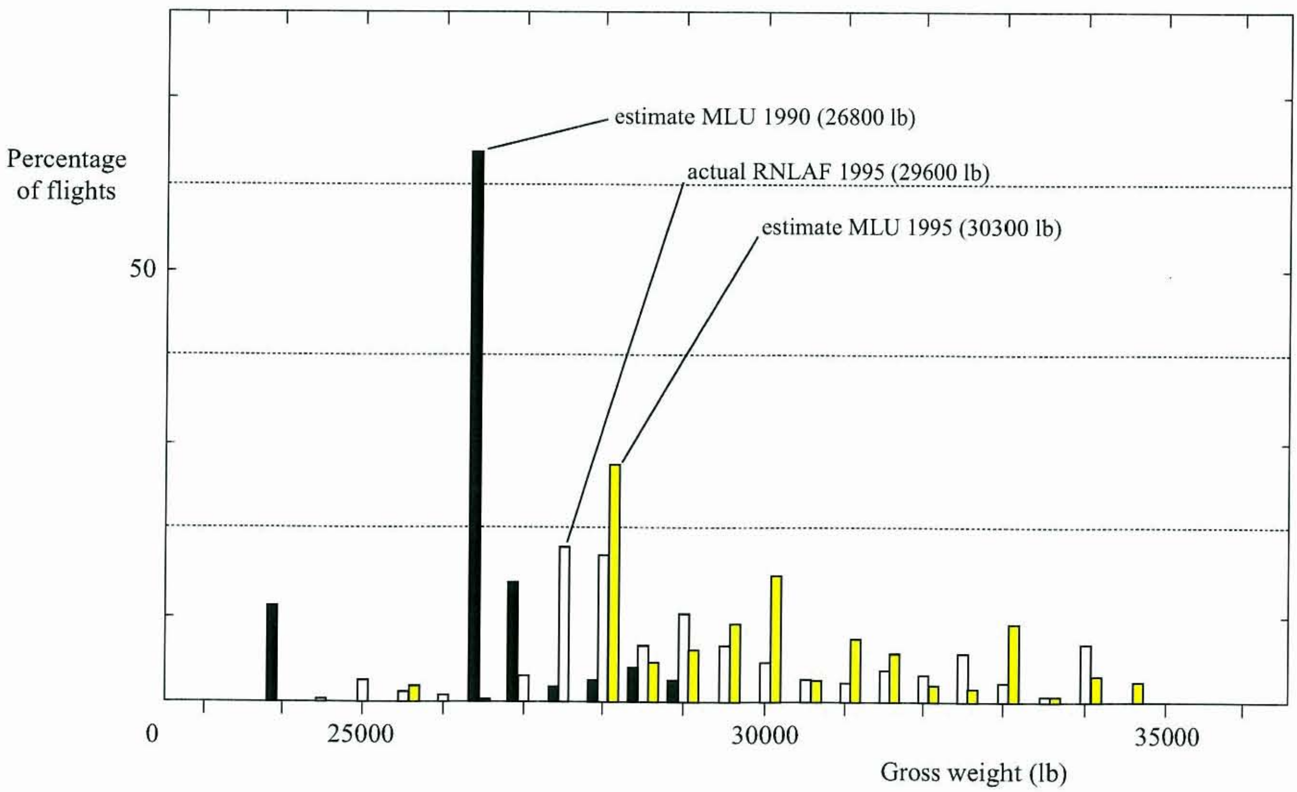

Fig. 2 Example Take Off weight distributions

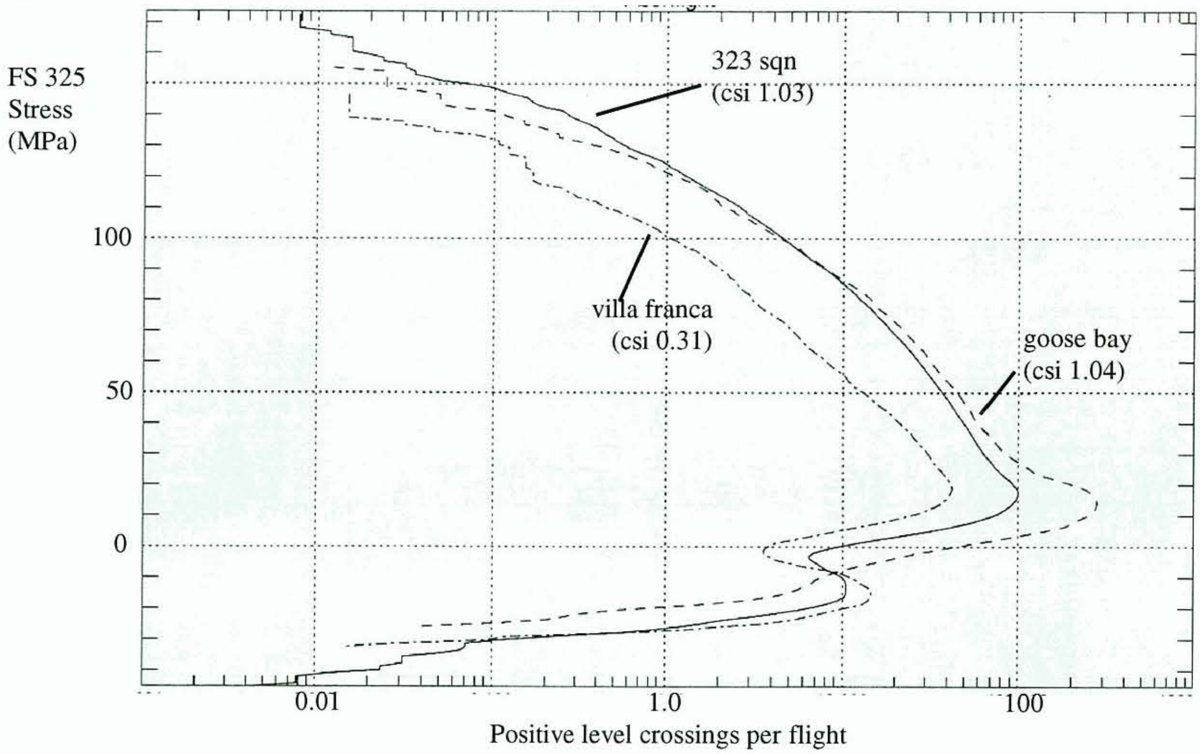

Fig. 3 Exceedance spectra for different usages

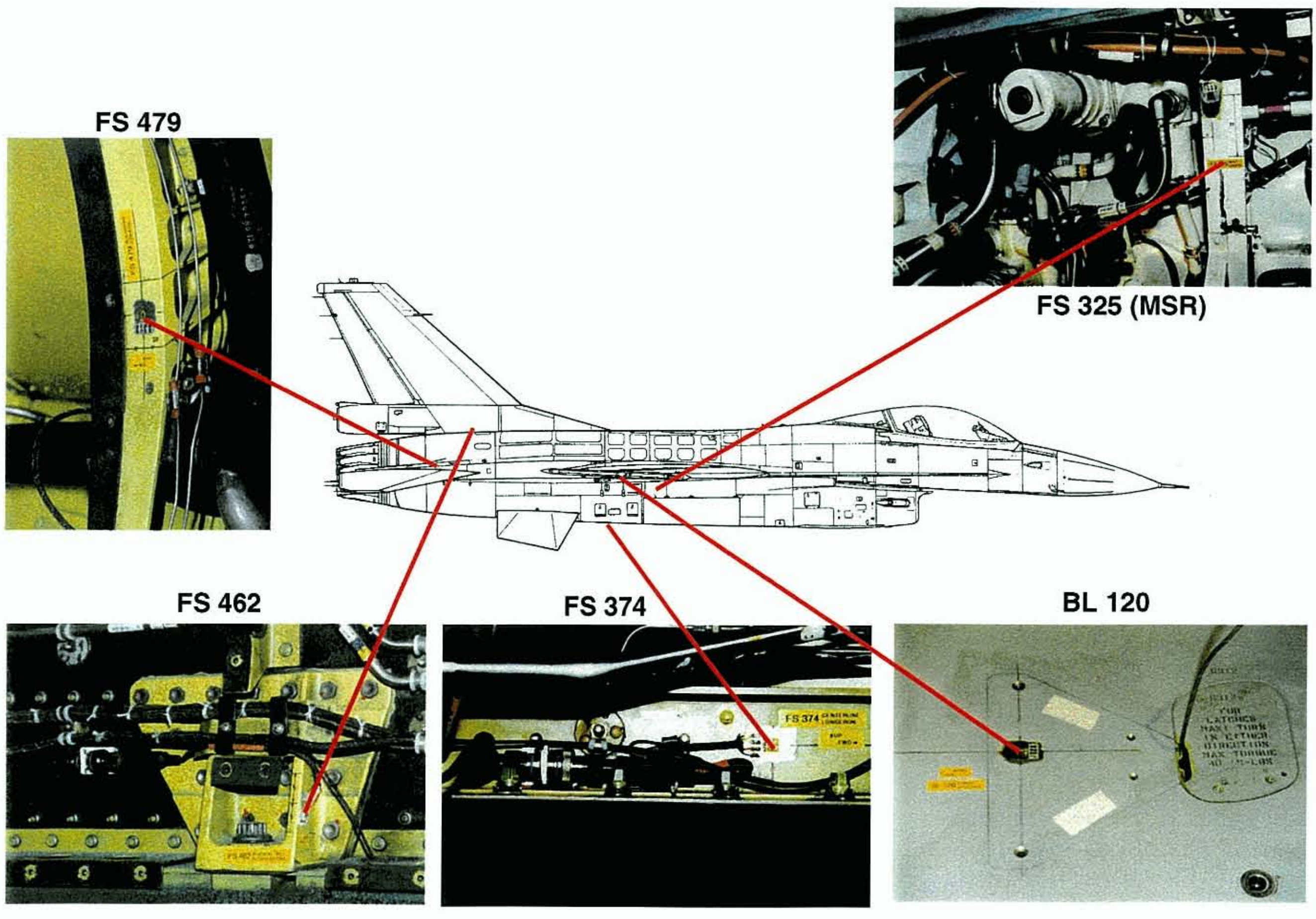

Fig. 4 Straingage Locations

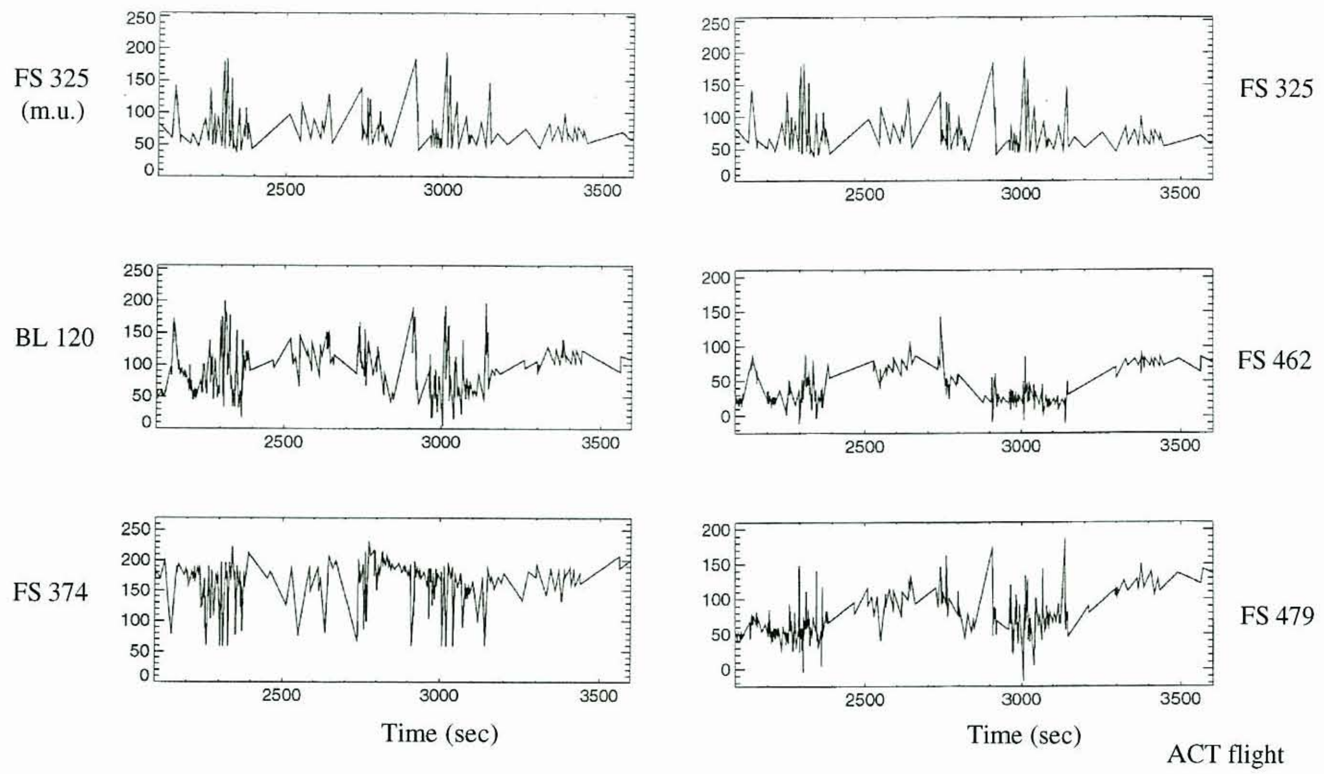

Fig. 5 Results for 5 selected strain gages

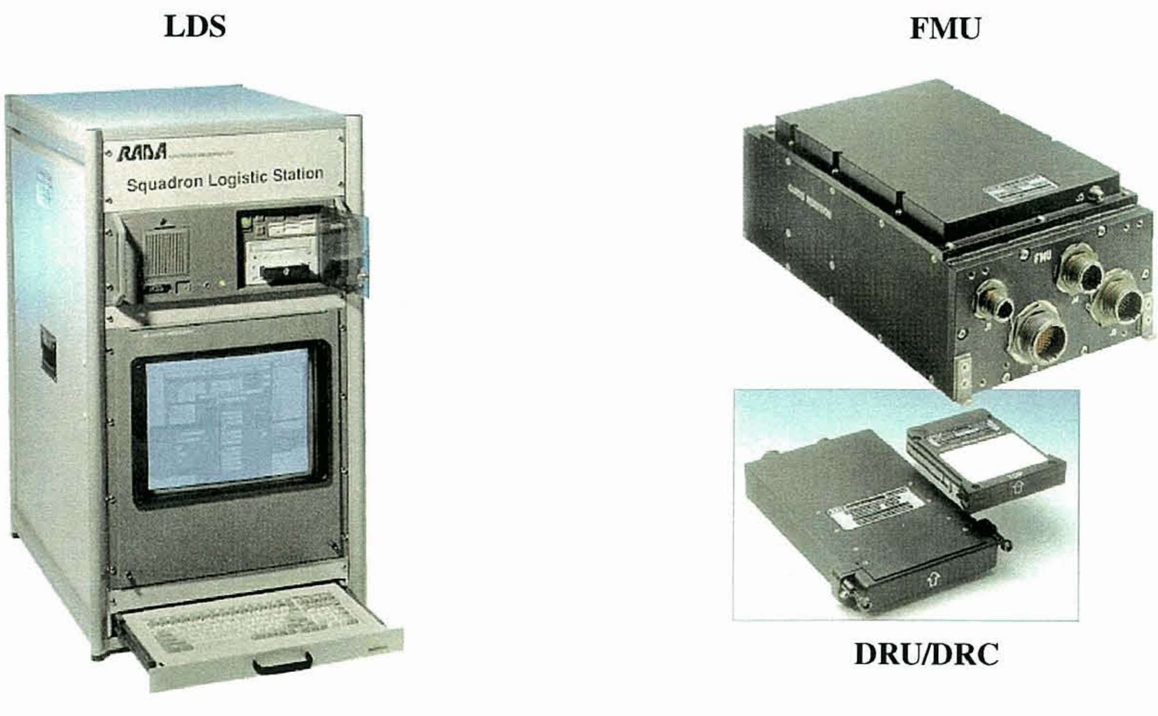

Fig. 6 Ground and airborne equipment

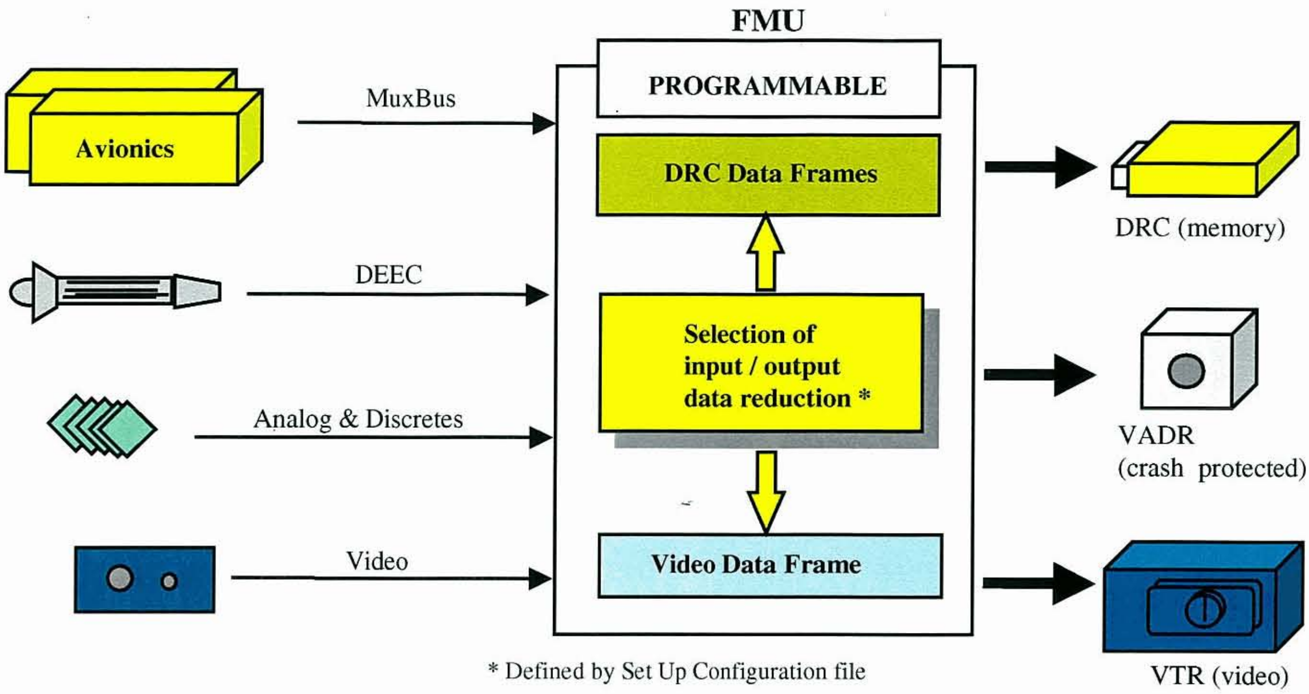

Fig. 7 Overview FACE system structure

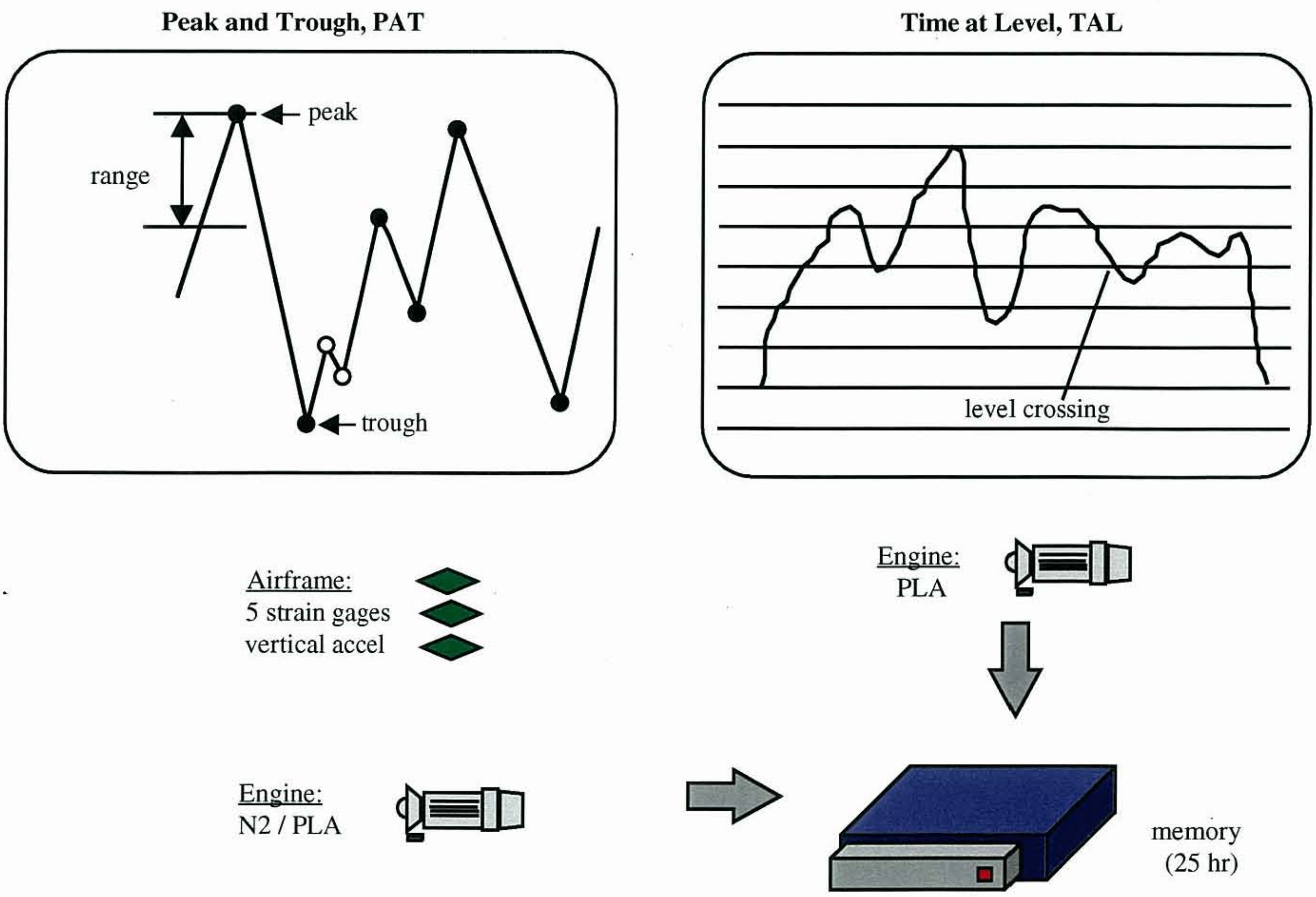

Fig. 8 Data reduction algorithms

Airframe

Process no	Master	Algorithm	Slave
1	Nn	PAT	AOA
2	FS325	PAT	-
3	FS374	PAT	-
4	FS462	PAT	-
5	FS469	PAT	-
6	BL120	PAT	-

General

Process no	Master	Algorithm	Slave
1	Nn	Sample 0.2 Hz.	Nz,Ny,Nx,FS325,FS374,FS462,FS479,BL120, Roll,Pitch,Yaw,Roll rate,Pitch rate, Yaw rate, AOA, Mach,CAS, Fq,Ph,N2,PLA, platform azimuth

Engine

Process no	Master	Algorithm	Slave
1	N2	PAT	-
2	PLA	PAT	-
3	PLA	TAL	-

Fig. 9 Default "Set up Configuration file" for OCU version

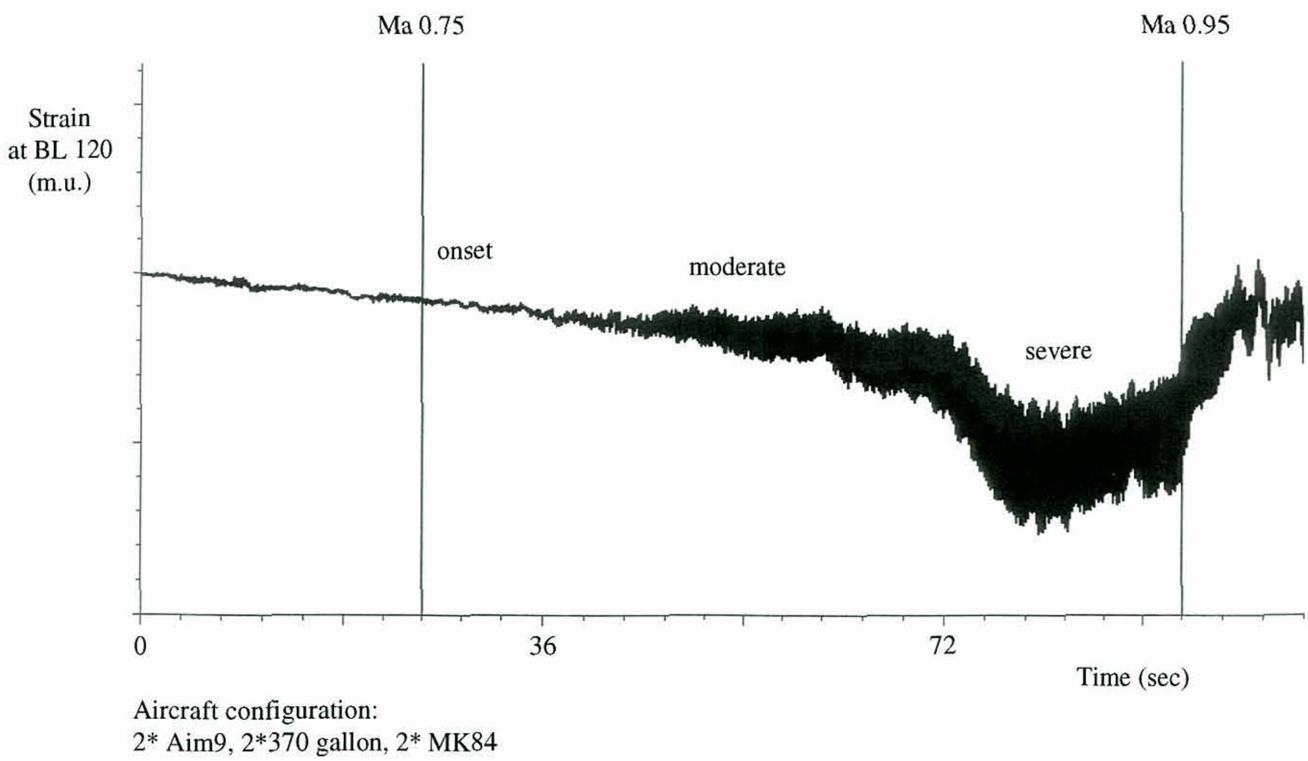

Fig. 10 Example of Limit Cycle Oscillation recording