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Development of Analytical Techniques
for Calibration of F/A-18
Horizontal Stabilator and Wing Fold
Strain Sensors

L. Molent, R. Ogden
and Y. Guan Ooi

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Development of Analytical Techniques for Calibration of F/A-18 Horizontal Stabilator and Wing Fold Strain Sensors

L. Molent, R.W. Ogden and Y. Guan Ooi

**Aeronautical and Maritime Research Laboratory
Airframes and Engines Division**

DSTO-TR-0205

ABSTRACT

Two nominally independent analytical calibration techniques have been developed for each of the F/A-18 horizontal stabilator and wing fold "Maintenance Signal Data Recording Set" (MSDRS) sensors. Repeatable and consistent results over different flying periods, with good statistical correlation values, were achieved for the candidate RAAF aircraft considered. Scaling factors were also calculated for Canadian Forces aircraft used in the International Follow On Structural Test Program spectra development.

These techniques will enable scale factors, defined as the ratio of the responses between two gauges positioned at nominally identical locations on different aircraft, to be calculated using operational MSDRS data. These results will allow comparisons to be made between aircraft in terms of operational usage or against fatigue test results.

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Published by

*Aeronautical and Maritime Research Laboratory
PO Box 4331
Melbourne Victoria 3001 Australia*

*Telephone: (03) 9626 7000
Fax: (03) 9626 7999*

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AR-009-333
August 1995*

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Development of Analytical Techniques for Calibration of F/A-18 Horizontal Stabilator and Wing Fold Strain Sensors

EXECUTIVE SUMMARY

Determination of accurate strain response at fatigue critical locations on the F/A-18 is essential in order to assure safe and economical operation of the aircraft throughout its complete service life cycle. A fatigue life monitoring program has been implemented for the aircraft, which essentially compares the usage of an individual aircraft to that of a representative fatigue test article (ie subject to a similar operational load spectrum). As the aircraft was designed and certified to a safe life philosophy, when the damage accumulated on a particular aircraft matches that calculated to have been imparted to the test article at the completion of testing, with appropriate safety factors applied, the aircraft is said to have consumed its safe life.

One of the systems available to aid the fleet manager in achieving the required fatigue life, is the "*Maintenance Signal Data Recording Set*", (MSDRS). The MSDRS is essentially an omnibus system which records time based data from the aircraft's data bus and strain sensors located to monitor fatigue critical locations on the airframe. This system relies on a number of strain sensors positioned throughout the aircraft. The positions of these sensors were chosen to monitor specific fatigue critical areas on the aircraft. For instance, the life of the wing and centre fuselage is currently monitored by a MSDRS sensor positioned at the wing root lug at fuselage station Y470.5.

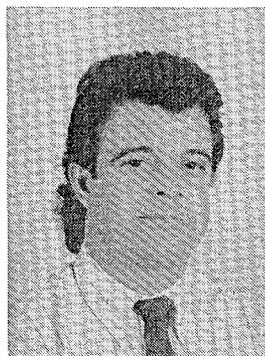
Before the raw operational MSDRS data for a specific aircraft and sensor can be used to assess the life of a location, the response of that gauge to a specific load must be ascertained, so that it can be normalised to the response of the sensor placed at that location on the fatigue test article. Differences in strain response have been noted between various airframes, and these are thought to be primarily associated with such factors as gauge alignment, gauge factor variation and also slight structural build differences. This normalising is commonly referred to as scaling a sensor, and is defined as the ratio of the responses between two gauges positioned at nominally identical locations on different aircraft, one of which is defined as the 'reference'.

Although the ideal solution is to calibrate each aircraft's strain gauges through simple ground testing, (ie application of static load and measurement of induced strain), logistically this is not a practical or viable option. This report summarises an alternative method, namely the development of a number of analytical techniques for calibration of aircraft to aircraft wing fold and horizontal stabilator MSDRS strain sensors, using F/A-18 flight test and MSDRS operational data. The advantages of an analytical approach are associated with simplicity, physical aircraft safety, time savings and cost effectiveness. Also, periodical assessment of the scaling factors can be used to monitor possible irregularities with the system.

Authors

L. Molent

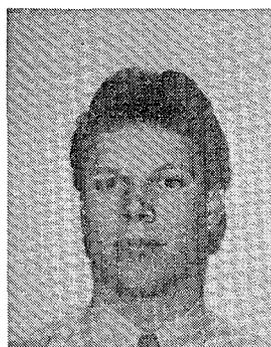
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Mr Molent graduated in 1983 with a Bachelor of Engineering (Aeronautical). Since commencing employment at the then Aeronautical Research Laboratories in 1984, Mr Molent has worked in the fields of aircraft structural integrity, structural and fatigue testing, aircraft accident investigation and aircraft vulnerability. He has numerous publications in these technical areas. He has been attached to both the Civil Aviation Department (1985) and the US Navy (NAVAIR, 1990 - 1991) as an airworthiness engineer. Mr Molent is currently task manager F/A-18 life assessment, at the Aeronautical and Maritime Research Laboratory.

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Mr. Ooi completed a Bachelor of Aerospace Engineering degree (honours) at RMIT in 1994. Since commencing employment at the Aeronautical and Maritime Research Laboratory as a contract engineer in 1993, he has been assigned to the F/A-18 Life Assessment Task. Mr. Ooi was involved with the F/A-18 Airframe Fatigue Data Analysis System and development of multi-parametric regression equations for monitoring strain gauge response. He is currently involved in the development of analytical strain gauge calibration techniques.

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1. Introduction

Determination of accurate strain response at fatigue critical locations on the F/A-18 is essential in order to assure safe and economical operation of the aircraft throughout its complete service life cycle. A fatigue life monitoring program has been implemented for the aircraft, which essentially compares the usage of an individual aircraft to that of a representative fatigue test article (ie subject to a similar operational load spectrum). As the aircraft was designed and certified to a safe life philosophy, when the damage accumulated on a particular aircraft matches that calculated to have been imparted to the test article at the completion of testing, with appropriate safety factors applied, the aircraft is said to have consumed its safe life.

To aid the fleet manager in achieving the required fatigue life, the RAAF have data available from two fatigue monitoring systems, namely the "Aircraft Fatigue Data Analysis System", (AFDAS) see Ref [1], and the "Maintenance Signal Data Recording Set", (MSDRS). The MSDRS is essentially an omnibus system which records time based data from the aircraft's data bus and strain sensors located to monitor fatigue critical locations on the airframe (see Ref [1]). The AFDAS stores strain and accelerometer data in terms of range-mean-pair matrices, see Ref [2], without any time correlation. Both systems rely on a number of strain sensors positioned throughout the aircraft, Ref [1]. The positions of these sensors were chosen to monitor specific fatigue critical areas on the aircraft. For instance, the life of the wing and centre fuselage is currently monitored by a MSDRS sensor positioned at the wing root (WR) lug at fuselage station Y470.5.

Before the raw operational WR data for a specific aircraft can be used to life its wing and centre fuselage, the response of that gauge to a specific load must be ascertained, so that it can be normalised to the response of the sensor placed at that location on the fatigue test article. A further criterion for selecting sensor location was that the location should have a uniform stress field and only be influenced by one primary loading action (eg bending moment). The differences in strain response noted in various articles are thought to be primarily associated with such factors as gauge alignment, gauge factor variation and also slight structural build differences. This normalising is commonly referred to as calibrating or scaling a sensor, and is currently routinely performed for the MSDRS WR sensor through analysis of flight data.

Two other particular areas requiring attention are the horizontal stabilator (HS) spindle attachment frame (at fuselage station Y651) and the outer mould line wing fold (WF). Both are designated as fatigue critical locations, and in particular the HS attachment spindle is essentially the only non-fail safe structure on the aircraft (ie providing no load path redundancies). The WF sensor can also provide an alternative to, or confirmation of the damage calculated at the WR.

Maintaining structural integrity at the HS and WF locations requires careful monitoring of strain results obtained from the MSDRS, in an effort to match the aircraft's usage or fatigue damage accrual with the fatigue life obtained or proved through the structural fatigue test. As with the WR, a difficulty with this task arises due to the fact that strain response differences will exist between aircraft throughout the fleet with respect to the fatigue test article, (or any other baseline eg. aircraft used in the ground calibration or flight tests). Therefore a valid fatigue life demonstrated through test, is only applicable to an aircraft whose strain gauges have been scaled accordingly. To achieve this the appropriate scaling factors need to be determined.

Although the ideal solution is to calibrate each aircraft's strain gauges through simple ground testing, (ie application of static load and measurement of induced strain) to obtain scaling factors, logistically this is not a practical or viable option, (note that the scale factor is defined as the ratio of the responses between two gauges positioned at nominally identical locations on different aircraft, one of which is defined as the 'reference'). This report summarises an alternative method, namely the development of a number of analytical techniques for calibration of aircraft to aircraft MSDRS strain sensors, using F/A-18 flight test and MSDRS operational data. The advantages of an analytical approach are associated with simplicity, physical aircraft safety, time savings and cost effectiveness. Also, periodical assessment of the scaling factors can be used to monitor possible irregularities with the system.

2. MSDRS Data Sources

2.1 Operational Data

Operational usage of the F/A-18 Hornet results in accumulation of large quantities of data through the aircraft's on-board data acquisition system, MSDRS. Developed by the McDonnell Douglas Aircraft Company (MDA) as part of a fatigue life monitoring system, the MSDRS records major mission computer parameters such as fatigue sensor data, stores/weapons configuration data and flight incident (parameter) data, see Ref [3,4]. The MSDRS flight data is stored on a magnetic tape media in a form known as a flight data set (FDS), representing a collection of individual flights. Periodically the magnetic tape is removed from the aircraft and forwarded to Hawker de Havilland, Victoria (HdHV) for data processing and to provide fleet usage monitoring reports (usually on a per quarter basis).

Extracting information from the binary format FDS data files requires the use of a program, (AMRL)¹ version called EXTRACT, see Ref [5]) to access the relevant codes. Data stored on the tape is collected together or grouped into specific codes, where each code refers to a set of related flight information. Typically there are codes that record :

¹ DSTO, Aeronautical and Maritime Research Laboratory

- Flight parameter data
- Fatigue occurrences
- Stores information
- Take-off data
- Landing data etc.

For the purposes of this report the relevant codes are, (see Ref [4]) :

- Code 46 - Flight incident record data
- Code 48 - Strain gauge initialisation (before take-off)
- Codes 49 to 62 - Fatigue triggered codes (*all codes*)

The latter records the following parameters:

Time

Nz

Strains at: left wing root, left wing fold, forward fuselage, left and right horizontal and vertical tails MSDRS sensors

Fuel quantity

True Air Speed (TAS)

Altitude

Roll Rate

For the purpose of the analyses conducted in this report, the required HS and WF strains were extracted from the FDS using *all codes* fatigue triggers in order to obtain larger data sets.

The flight incident parameters recorded under Code 46 along with their respective recording rates, are shown in Table 1. Note that the Code 46 flight parameters are not time correlated with strain recordings.

Due to the availability of operational MSDRS data for each aircraft in the RAAF fleet, it is desirable to develop calibration techniques which utilise these data. Note in this report, various periods of MSDRS operational data were used from the following aircraft :

- A21-32 (*Used in ARDU flight test*)
- A21-107 (*Used to derive IFOSTP pre-lex fence load spectrum*)
- A21-38 (*Used to derive IFOSTP post-lex fence load spectrum*)
- A21-44

Table 1 : Flight Incident Record (MSDRS Code 46)

| Parameter | Once per second [1 Hz] | Once per 5 seconds [0.2 Hz] | Resolution |
|--|------------------------|-----------------------------|-----------------------|
| Elapsed Time | | x | |
| Pitch | | x | 1.4 deg |
| Outer Roll | | x | 1.4 deg |
| Magnetic Heading | | x | 1.4 deg |
| Pitch Rate | x | | 1°/sec |
| Roll Rate | x | | 2°/sec |
| Yaw Rate | x | | 1°/sec |
| Normal Acceleration | x | | 4 ft/sec ² |
| Lateral Acceleration | x | | 4 ft/sec ² |
| True Angle of Attack | x | | 1.4 deg |
| Indicated Airspeed | x | | 4 kts |
| Pressure Altitude | | x | 1024 ft |
| Barometric Corrected Pressure Altitude | x | | 32 ft |
| Radar Altitude # | x | | 32 ft |
| Longitudinal Stick Position/Force | x | | 1 lb/.0625 in |
| Lateral Stick Position/Force | x | | 1 lb/.0625 in |
| Rudder Pedal Force | x | | 1 lb |
| Left Stabilator Position | | x | 0.35 deg |
| Right Stabilator Position | | x | 0.35 deg |
| Left T.E. Flap Position | | x | 0.35 deg |
| Right T.E. Flap Position | | x | 0.35 deg |
| Computed Max G Limit | | x | 0.125 g |
| Left Outbd/Inbd L.E. Flap Position | | x | 0.35 deg |
| Right Outbd/Inbd L.E. Flap Position | | x | 0.35 deg |
| Left Rudder Position | | x | 0.35 deg |
| Right Rudder Position | | x | 0.35 deg |
| Left Aileron Position | | x | 0.35 deg |
| Right Aileron Position | | x | 0.35 deg |
| Left Power Lever Angle | x | | 0.7 deg |
| Right Power Lever Angle | x | | 0.7 deg |
| Left Exhaust Gas Temperature | | x | 8° C |
| Right Exhaust Gas Temperature | | x | 8° C |
| Left High Pressure Rotor Speed | | x | 128 rpm |
| Right High Pressure Rotor Speed | | x | 128 rpm |
| Left Main Fuel Flow | | x | 64 PPH |
| Right Main Fuel Flow | | x | 64 PPH |
| Total Fuel Quantity | | | 128 lb |
| Spin Recovery Mode Engaged | } | | |
| Spin Switch On | } | RECORD | |
| Takeoff Trim Set | } | ON | |
| Heading Hold Engaged | } | CHANGE | |
| Attitude Hold Engaged | } | ONLY | |
| Baro Altitude Hold Engage | } | | |
| Radar Altitude Hold Engage | } | | |
| Cautions | } | | |
| Advisories | } | | |

2.2 Flight Test Data

An additional source of data used in this report, as opposed to operational data, was that acquired during the Aircraft Research and Development Unit, (ARDU) Phase I & II F/A-18 flight trials, conducted in support of the "International Follow-On Structural Test Project", (IFOSTP), Ref [6]. These flight trials were performed using a single place F/A-18A aircraft (A21-32), equipped with a recording system known as the programmable data acquisition system (PDAS), enabling flight parameter and fatigue sensor data to be recorded continuously at 20 Hz (amongst other frequencies). Strain data from MSDRS sensors and flight parameters obtained from the flight trials covered an extensive range of manoeuvre and mission profiles, and as such is considered representative of operational usage, see Ref [7]. Note MSDRS (FDS) data was also recorded during these flight trials.

For the purpose of researching and developing an analytical technique to determine aircraft to aircraft strain scaling factors, the data provided by the ARDU flight trials gave the favoured source, providing time correlated reliable data, with the MSDRS FDS data providing a source for subsequent validation of the techniques. Note however that it is the intent of the derived calibration technique to ultimately use operational MSDRS data for the purpose of checking data integrity and in the routine calculation of aircraft to aircraft strain sensor scaling factors. The flight parameters available in the ARDU data base and applicable to this analysis are shown in Table 2.

Table 2 : ARDU [20 Hz] Flight Parameters

| Acronym | Parameter | Units |
|---------|---|---------------|
| M33378 | RH MSDRS Horizontal Stabilator gauge(@Y651) | $\mu\epsilon$ |
| M33377 | LH MSDRS Horizontal Stabilator gauge(@Y651) | $\mu\epsilon$ |
| M15301 | LH MSDRS Outer Mould Line Wing Fold | $\mu\epsilon$ |
| AoA | True Angle of Attack | deg |
| Mn | Mach number | - |
| Q | Compressible Dynamic Pressure ϕ | inHG |
| RStab | Right Hand Stabilator Deflection | deg |
| LStab | Left Hand Stabilator Deflection | deg |
| Nz | Vertical Load Factor β | $g's$ |
| PR | Pitch Rate | deg/sec |
| YR | Yaw Rate | deg/sec |
| RR | Roll Rate | deg/sec |
| W | Weight | lb |
| CG | Centre Of Gravity | % MAC |
| RTef | Right Hand Trailing Edge Flap Deflection | deg |
| LTef | Left Hand Trailing Edge Flap Deflection | deg |
| LAil | Left Hand Aileron Deflection | deg |
| Altd | Barometric Altitude | ft |

ϕ ARDU refer to this parameter as "Impact Pressure"

β Nz normalised with respect to Basic Fighter Design Gross Weight (BFDGW) of 32,357 lb.

Note: Most parameters available on the PDAS system are obtainable from MSDRS Code 46. Note however that the units of some parameters are different. Also some of the above terms are not available directly from Code 46, but can be derived from other available parameters as defined in Appendix 1.

2.3 Deficiencies in the MSDRS system

Research completed recently at AMRL, aimed at modelling F/A-18 strain response at AFDAS² strain gauge locations, based purely on a knowledge of the aircraft's flight parameters, yielded very promising results, see Ref [8]. However difficulties were experienced in relation to modelling strain response using MSDRS data particularly at the HS location. These findings are applicable to the analysis conducted in this report.

A problem highlighted referred to the sampling rates and resolution of flight parameter data, Code 46, see Table 1. With the majority of parameters recorded at 1 Hz and control surface deflections recorded at 0.2 Hz, it was necessary to interpolate between recorded flight parameter values to obtain an estimated value at a recorded fatigue event (achieved through the *extract* program). The Ref [8] report indicates that during severe aircraft operations, with flight parameters varying at a rapid rate, the linear interpolation used can be grossly inadequate, especially for those parameters sampled at 0.2 Hz, (ie control surfaces), for example see Figure 1.

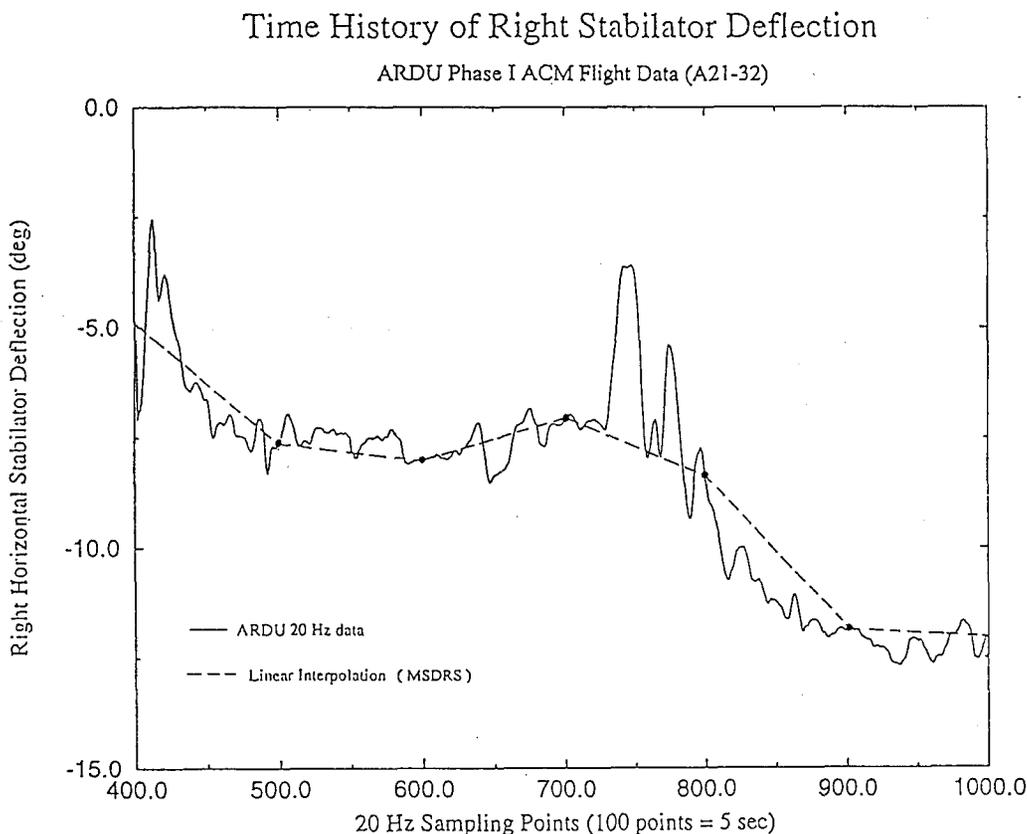


Figure 1 : Stabilator Deflection Time History

² Some AFDAS strain gauges are at similar or "mirrored" locations to MSDRS gauges.

A further problem highlighted concerned the existence of time lags in the MSDRS system, between the occurrence of an event and its recording, particularly those associated with the angle of attack (ie up to 0.5 sec), and vertical load factor N_z (ie up to 0.15 sec), see Ref [9].

Despite these problems, the development of parametric equations in Ref [8] indicated that the strain response at the relevant locations, (namely AFDAS gauge locations) could be modelled, at any time during the flight, using a combination of the following flight parameters:

Horizontal Stabilator Location

- Horizontal Stabilator Deflection
- Angle of Attack
- Dynamic Pressure
- Roll Rate
- N_z
- Pitch Rate
- Mach Number
- Trailing Edge Flap Deflection

Outer Mould Line Wing Fold

- N_z
- Dynamic Pressure
- Angle of Attack
- Roll Rate
- Weight and CG
- Left Aileron and Trailing Edge Flap Deflection

It was indicated in Ref [8] that the interpolation errors and time lags detrimentally influenced the strain prediction. When dealing with these parameters in the MSDRS system, due consideration must be given to the potential difficulties mentioned above.

In the following sections, analytical calibration techniques are developed for the HS and WF MSDRS sensors respectively. Note at this stage that work done previously at AMRL, in particular Ref [10,11], aimed at providing calibration factors for the HS location, while providing promising results, were not considered appropriate for routine fleet calibration purposes. In the former case, the parameters used for the binning technique, led to a situation where insufficient data points were produced even from large flight data sets, and is not considered as providing a high degree of confidence. The latter technique used enhanced³ MSDRS data, requiring large amounts of processing time, making it unsuitable for routine fleet application. Also as both techniques were not developed for a fleet wide calibration application, they failed to address or to provide evidence that reproduction of scaling factors could be achieved for the same aircraft using different periods of data. A promising technique for calculating vertical tail MSDRS gauge scaling factors is presented in Ref [11].

³ MSDRS data is reconstructed at fatigue turning points by applying a full dynamic system model of the F/A-18

3. Horizontal Stabilator Analytical Calibration Procedure

In this section two separate analytical calibration techniques have been developed to allow scaling between HS sensors of different aircraft (or against baselines, such as the fatigue test article). Also, as each aircraft contains both a left and right HS spindle sensor, the technique also determines the ratio of strain response between the two sides. By applying the respective right or left sensor scale factors, each sensor should produce a similar strain response under symmetric flight conditions.

3.1 Horizontal Stabilator Strain Response

Understanding the nature of the strain response at the HS spindle required an investigation of the flight parameters contributing to or in fact dominating loading on the structure, (control surface). The key to obtaining a successful gauge calibration technique relied upon finding a point in the sky (PITS), (ie combination of flight parameters), at which the strain response was stable and predictable. A linear result which predicts strain based on one other parameter at a particular PITS would give the most efficient result, the resulting slope differences between aircraft providing the calibration scaling factor.

The initial steps taken in producing an analytical calibration technique were based on observations of data from recent extensive F/A-18 flight and wind tunnel tests, Ref [12]. These tests revealed the following :

- F/A-18 MSDRS strain sensors respond primarily to applied bending.
- Under symmetric, high angle of attack (ie $10^\circ < \text{AoA} < 25^\circ$) loading conditions, a trend was recognised relating HS bending moment coefficients and the flight parameters, angle of attack and stabilator deflection.
- F/A-18 stabilator loads are largely independent of Mach number for cases where the Mach number is less than 0.9.
- The inertial component of stabilator bending moments experienced in flight is small compared to that due to aerodynamic loading.

Following an investigation of these findings, in conjunction with results obtained in Ref [8], an approach was adopted whereby two separate techniques would be developed concentrating directly on the relationships between HS strain and AoA and HS strain versus stabilator deflection. The two techniques are based initially on the observations depicted in Figures 2 and 3 presented below, which show the strain responses, at all PITS (ie no limitations) with respect to these flight parameters, using ARDU Phase II flight test profiles, (ie ACM and Ground Attack).

From these figures, quasi linear regions, albeit with large scatter, could be identified. Therefore an investigation was undertaken to identify which PITS led to data which provided a clean stable linear response, and which parameter range produced the minimum scatter. Each approach is developed in the following sections.

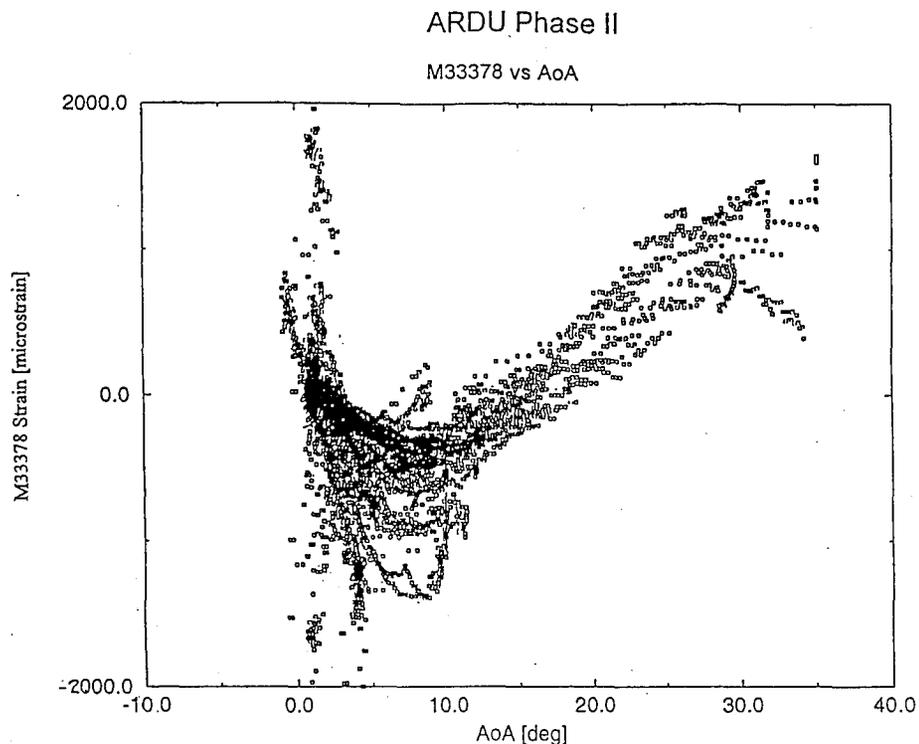


Figure 2 : Horizontal Stabilator Gauge (M33378) vs AoA

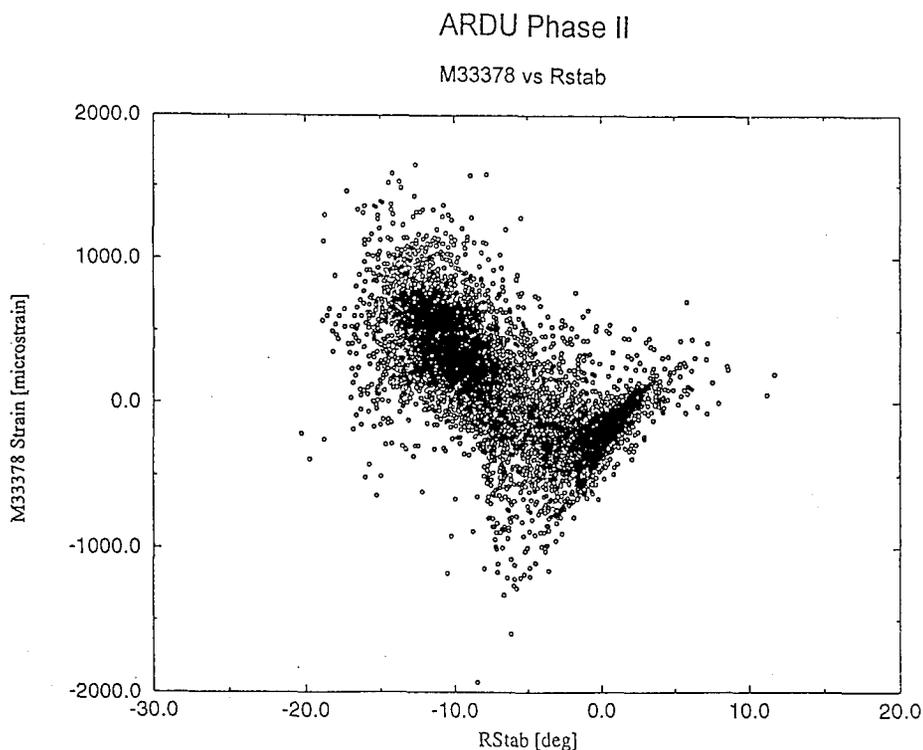


Figure 3 : Horizontal Stabilator Gauge (M33378) vs RStab

3.1.1 Strain vs Angle of Attack Results

In an effort to find the PITS or conditions which produced a linear relationship between strain and AoA, experimentation with and refinement of flight parameter limitations was performed, looking specifically at a symmetric high alpha flight regime (see Fig 2). Scaling factors between F/A-18 fleet aircraft could be obtained by determining and comparing the slopes of strain against AoA for each aircraft over this particular regime, using operational fleet data from the MSDRS system.

Part of the investigation was also driven by the inherent problems, (discussed briefly in section 2) associated with the MSDRS system in relation to interpolation of the Code 46 flight parameter data, and the time lags that exist in the system. As such the technique developed needed to be robust enough to handle scatter in the MSDRS data and still be able to return a stable well defined slope, using hopefully a limited data set (ideally 4 months operational data).

In Figure 4, the results of applying the following data restrictions to the ARDU Phase II data set are shown, (note also that the HS strain has been normalised with respect to dynamic pressure Q^4):

1. $\{ 15 \leq \text{AoA} \leq 25 \}$
2. $\{ 0.35 \leq \text{Mn} \leq 0.9 \}$
3. Absolute Value (ABS) [RStab - LStab] ≤ 1.0
4. Air Combat Manoeuvre [TOF 300⁵] flights > 100
5. Data Points > 1400
6. No Wing Stores other than Wingtip AIM9's (clean configuration)

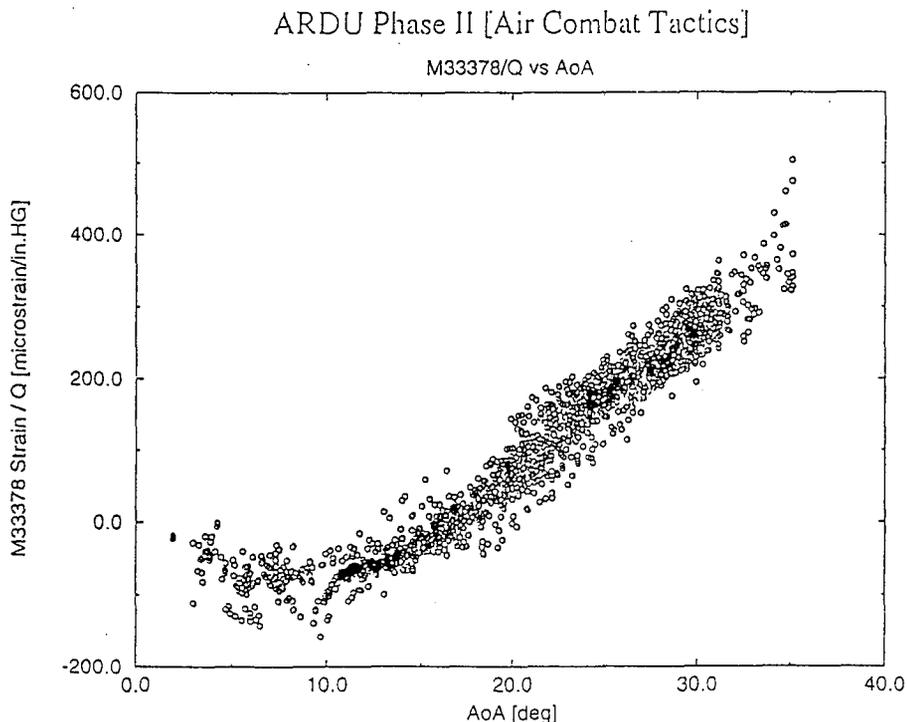


Figure 4 : M33378 vs AoA [ARDU Symmetrical Conditions]

⁴ It was observed that this procedure reduced the scatter band.

⁵ Type of Flying Code (TOF 300) refers to all 300 series TOF codes, which are ACM flights.

From Figure 4 a linear response over the AoA range (15° to 30°) is seen.

The following analysis involved applying the above limitations, (ie derived using ARDU flight test data) to an operational MSDRS data set, (FDS files) and then plotting HS strain divided by dynamic pressure (normalising to remove altitude effects) against true AoA, where the AoA range (15 - 25 deg) has been broken up into 10 equal bins (ie 1.0 deg), with only the average strain divided by the pressure value plotted for each bin. The resulting slope obtained through a regression analysis on these ten points gave the strain response for this particular sensor. The success of the method therefore relied upon obtaining a large enough sample of data on which to perform the filtering and averaging (binning) of the data, hence the restrictions 4 and 5 above. Note also that to obtain similar clean airflow conditions over the stabilator, a restriction on the allowable wing stores was included. An investigation was also carried out looking specifically at the effects on HS strain, of varying trailing edge flap deflection, and this was found to be insignificant under the limited high AoA flight conditions, (essentially the trailing edge flap deflection follows the AoA, and thus does not appear to be an independent parameter).

The following example illustrates the process of HS strain response determination. The data (operational MSDRS) was taken from aircraft A21-32, with the average values of strain divided by dynamic pressure plotted against the average AoA values for each bin. The results are shown in Table 3 and are plotted in Figure 5.

Table 3 : Operational (MSDRS) ACM Data 1988/89 [Aircraft A21-32]

Raw data set : 58,200 pts

Data set filtered to above limitations = 2,236 pts

| AoA BIN [deg] ⁶ | Num. Points | Average M33378/Q | Standard Dev M33378/Q | Average AoA |
|-------------------------------|-------------|---------------------|--------------------------|----------------|
| 15 - 16 | 319 | -8.8 | 52 | 15.41 |
| 16 - 17 | 327 | 20.0 | 54 | 16.64 |
| 17 - 18 | 216 | 36.9 | 59 | 17.47 |
| 18 - 19 | 264 | 53.1 | 61 | 18.46 |
| 19 - 20 | 126 | 73.4 | 72 | 19.45 |
| 20 - 21 | 253 | 99.0 | 59 | 20.27 |
| 21 - 22 | 211 | 121.7 | 71 | 21.54 |
| 22 - 23 | 131 | 154.8 | 63 | 22.47 |
| 23 - 24 | 208 | 191.6 | 66 | 23.4 |
| 24 - 25 | 181 | 214.8 | 51 | 24.56 |
| | Σ 2236 | | | |

⁶ Although the resolution of AoA in the MSDRS is 1.4°, as the average value within a bin is used, 1° increments have been used here for convenience.

MSDRS ACM DATA 1988/89 [A21-32]

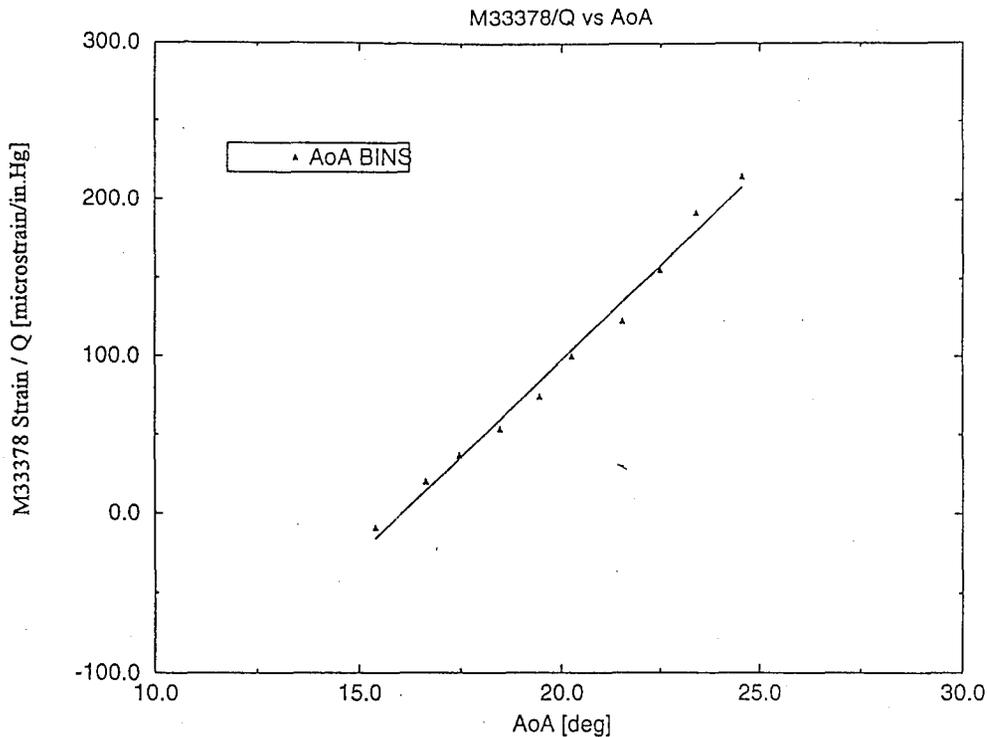


Figure 5 : M33378/Q vs AoA (MSDRS Data)

The standard deviation for each bin in the example indicates a consistent spread or scatter within each, and provides confidence that the resulting slope has not been biased by a concentration of data points at any one location in any one bin. This is also aided by having a sufficiently large number of points in each AoA range.

Operational MSDRS data obtained for a number of fleet aircraft enabled the theory to be further tested, with the resulting strain responses represented in the following form:

$$\frac{M33378 [\mu\epsilon]}{Q} \text{ RHS} = X * \text{AoA [deg]} + Y$$

$$\frac{M33377[\mu\epsilon]}{Q} \text{ LHS} = Z * \text{AoA [deg]} + W$$

Where : $\frac{M33378/7 [\mu\epsilon]}{Q}$ and AoA represent the mean values within each AoA bin.

Analysis of the data was conducted using the previously defined symmetric limitations, to investigate the responses of both left and right stabilators, with results presented in Table 4.

Table 4 : HS Strain response [MSDRS and ARDU ACM Data]

| Aircraft | Period | Flights | Pts | X (stdE) | Y | R ² | Z (stdE) | W | R ² |
|----------|------------------------|---------|------------------|------------|------|----------------|------------|------|----------------|
| A21-32 | 1988 / 89 | 104 | 2236 | 24.4 (1.0) | -393 | 0.987 | 24.0 (0.8) | -391 | 0.991 |
| " | ARDU | 17 | 2117 | 24.1 (0.5) | -392 | 0.992 | 23.7 (0.4) | -390 | 0.996 |
| A21-38 | 1989 / 90 | 101 | 1700 | 23.3 (0.9) | -372 | 0.986 | 23.1 (0.7) | -367 | 0.994 |
| " | 1991 ^π | 79 | 909 ^φ | 22.9 (1.2) | -370 | 0.987 | 23.0 (1.0) | -371 | 0.985 |
| " | 1992 | 50 | 1201 | 22.7 (0.9) | -362 | 0.988 | 21.3 (0.7) | -342 | 0.992 |
| A21-44 | 1990 | 53 | 1183 | 24.2 (0.7) | -391 | 0.992 | 24.3 (0.7) | -388 | 0.993 |
| " | 1991 | 84 | 1584 | 24.5 (0.9) | -403 | 0.985 | 23.4 (0.6) | -363 | 0.988 |
| " | + 1993 ^φ | 59 | 504 | 24.6 (1.5) | -386 | 0.970 | 22.9 (1.3) | -330 | 0.972 |
| A21-107 | 1986 / 87 | 170 | 1842 | 25.9 (0.6) | -414 | 0.996 | 25.8 (1.3) | -413 | 0.973 |

© - Data Set did not contain > 1400 points, but was included here for comparison.

π - 1991 period refers to the quarter Apr to Sept

φ - 1993 period refers to the quarter Oct to Dec

stdE : Standard error of the slope

The results show high regression coefficients, with an acceptably small standard error on the slope, (ie $\pm 4\%$). Note also that separate sets of data obtained for the same aircraft show very promising results, indicating that given a sufficiently large data set, (ie Num Points > 1400) and adhering to the derived limitations, the technique does appear reproducible, and can be used to determine scaling factors. It will also detect if variations in strain response for each individual strain sensor occur over time. At this stage, it appears however that at least a six month data period will be required in order to obtain sufficient data points to satisfy the data limitation criteria for this technique.

The scaling factor is obtained by taking the ratio between individual aircraft, or aircraft sides, as presented in Section 3.1.3.

3.1.2 Strain vs Horizontal Stabilator Deflection Results

In parallel with the analysis conducted on the HS strain versus AoA relation, an investigation was conducted looking specifically at the apparent trend between HS deflection and strain, see Figure 3. As with the previous relation, initial findings Ref [8] and observations of the data from Ref [12] indicated a correlation or dependence of HS deflection on induced strain, (ie RHS M33378 and LHS M33377 sensors). Therefore the investigation was again aimed at discovering the PITS at which this relation is strongest, giving a linear response, in order to provide another strain relationship to validate the HS strain versus AoA approach.

Using all available ARDU Phase II flight test data in the preliminary analysis, it was discovered that a definite band could be established by applying near symmetrical flight parameter limitations, followed by further restrictions associated with those flight parameters affecting longitudinal motion, ie pitch rate and trailing edge flap deflections. The derived limitations were as follows :

- ABS [RR] ≤ 5.0
- ABS [YR] ≤ 5.0
- ABS [Roll Acceleration (RAcc)] ≤ 10
- {0 \leq AoA ≤ 10 }
- {1 \leq Nz ≤ 6 }
- {0.3 \leq Mn ≤ 0.9 }
- Trailing Edge Flap deflections (Left and Right) ≤ 8.0
- {0 \leq PR ≤ 7 }

Note that these limitations do not correspond to the same AoA region as used in the strain vs AoA method, (ie section 3.1.1), due to the fact that a relationship could not be established here between HS strain and HS deflection.

Roll acceleration, which was considered relevant, was not recorded in the ARDU flight trials, nor on the MSDRS, and thus it was derived from the derivative of a quadratic roll rate approximation (see Ref [8]).

The correlation between HS deflection and strain, Figure 6, was found to be further improved by normalising with respect to altitude by dividing the strain by the compressible dynamic pressure (Q).

ARDU Phase II Data (A21-032)

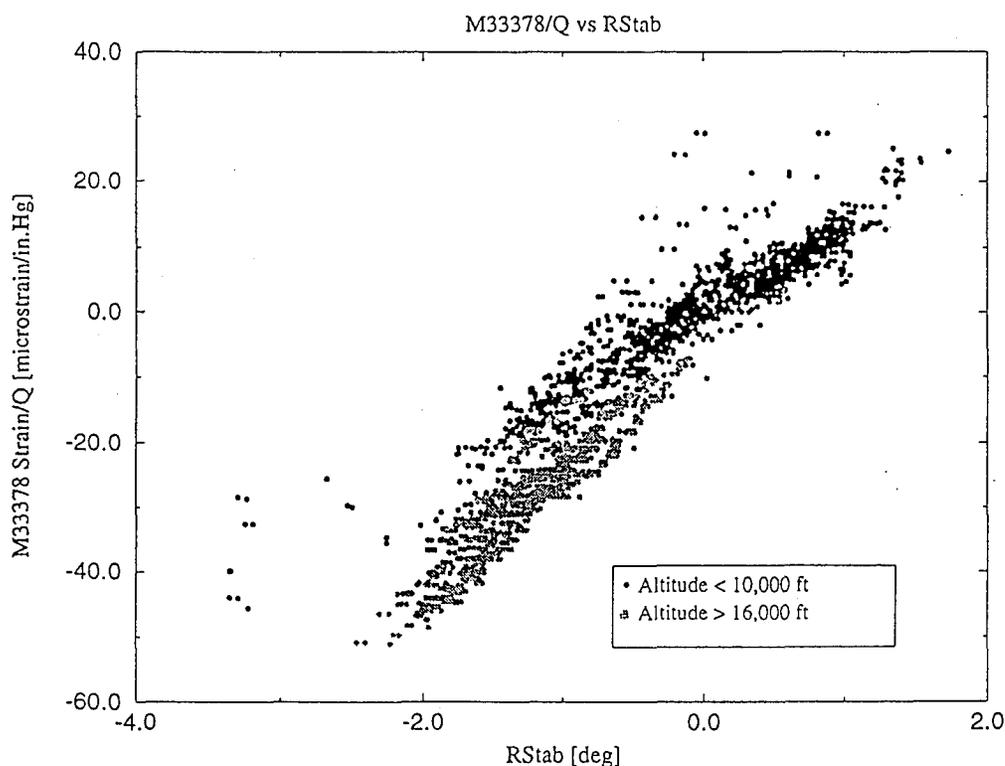


Figure 6 : M33378/Q VS RStab (ARDU Data)

The distinct band shown in this plot is considered as the response of the gauge for this particular aircraft. Note however that the data appears to be divided into two bands, with an offset existing between them (as each band encompasses a different range of strain and HS deflection). It was determined that this effect was due to different altitude ranges. As the distribution of data in the series would influence the slope or response of the gauge, it was considered essential in the calibration work to ensure that altitudes used for different aircraft are within a specific range, (ie data sets are binned into altitude ranges).

Applying the above method to operational MSDRS data, required some modification, due to the inherent problems or deficiencies discussed earlier (section 2.3) regarding the MSDRS system. The major difficulty here being with the inadequate interpolation of the 5 second resolution control surface deflections, (see Figure 1). It was thus considered necessary to apply a further criterion of using only the strain data points (*all codes*) that were "triggered" within ± 0.5 seconds of the recorded (actual) HS deflections. This was achieved by writing a short code to retrieve only those strain turning points, (ie Peak/Valleys) that are triggered within 0.5 seconds of a recorded Code 46 control surface deflection value. Due to this severe restraint, limited data points were obtained, and it was decided to relax some of the initial symmetry restraints in order to gain more data points. The final conditions applied to the MSDRS data were as follows :

- ABS [RR] ≤ 30.0
- ABS [YR] ≤ 5.0
- $\{0 \leq \text{AoA} \leq 10\}$
- $\{1 \leq \text{Nz} \leq 6\}$
- $\{0.3 \leq \text{Mn} \leq 0.9\}$
- Trailing Edge Flap deflections (Left and Right) ≤ 8.0
- $\{0 \leq \text{PR} \leq 7\}$
- *Time between stabilator strain event (all codes) and Code 46 (Stabilator deflection) $\leq \pm 0.5$ sec*

The results of applying the above conditions to MSDRS data is shown in Figure 7, (MSDRS data corresponds to ARDU flight test period). Note that applying this new set of criteria to the previous ARDU Phase II data set, (ie Figure 6) results in slightly more scatter.

MSDRS Data (A21-032)

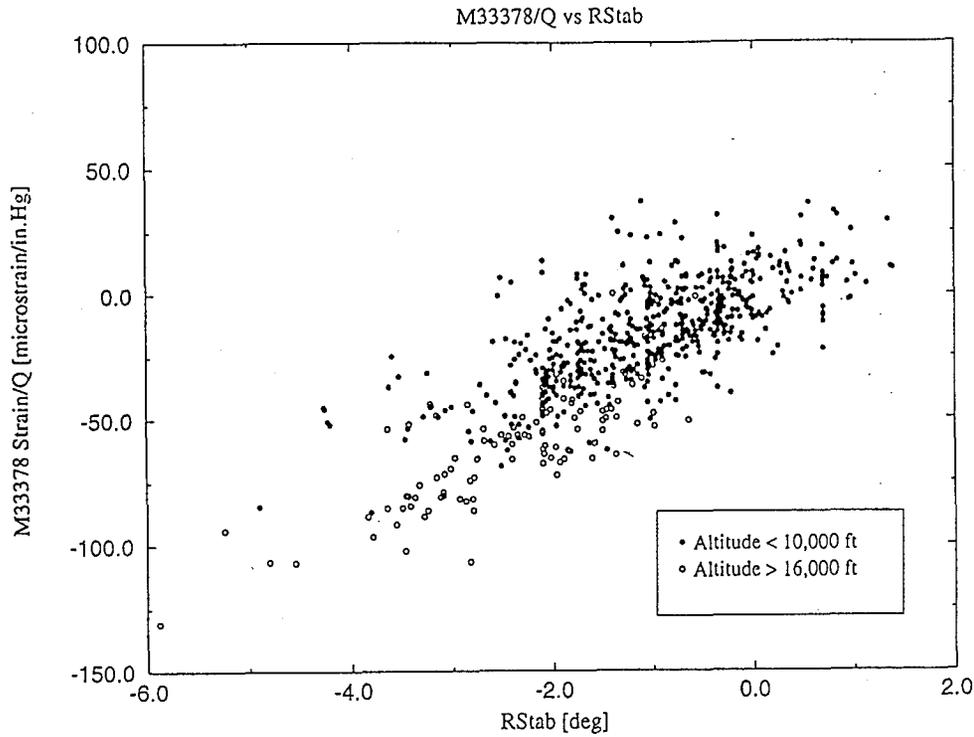
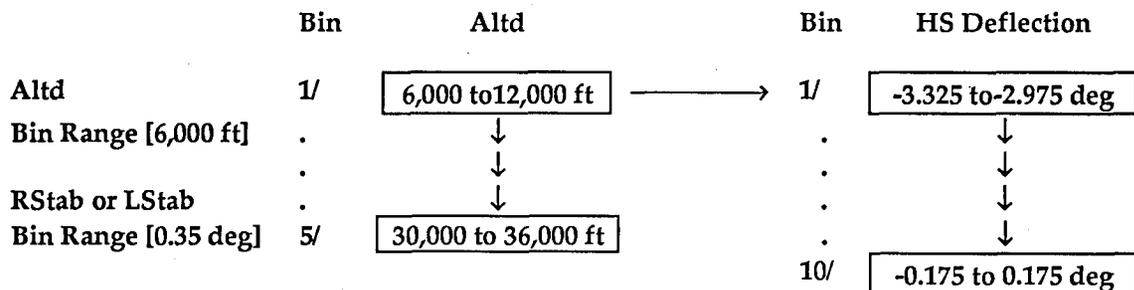


Figure 7: M33378/Q VS RStab (MSDRS Data)

Due to the easing of restraints, it was expected that slightly more scatter would result, therefore a filter was applied to the data set to remove those data points falling 2 standard deviations outside of the regression, (ie $\approx 5\%$). In order to use the filtered data for the purpose of calculating the strain sensor scaling factors, it was necessary to address the problem discussed previously concerning strain response differences due to altitude effects. To account for this a "binning" technique was adopted, whereby the data is binned into ranges of altitude and stabilator deflection, where for each bin the average value of strain divided by pressure was obtained. The binning process is as follows :



Binning under these conditions results in a maximum of 50 bins, but this is dependent on whether or not enough data points are collected for each bin. In order to increase the reliability of results, only those bins having more than 10 points are used for further analysis. The calibration technique, is based on plotting the average strain divided by pressure value for each bin from one particular aircraft against the baseline aircraft (A21-32 in this case). The resulting slope obtained through a regression analysis on these points, yields the scaling factor for this gauge. An example is shown in Table 5 and Figure 8. In this example the scaling factor for A21-107 against the reference aircraft A21-032 is 1.04.

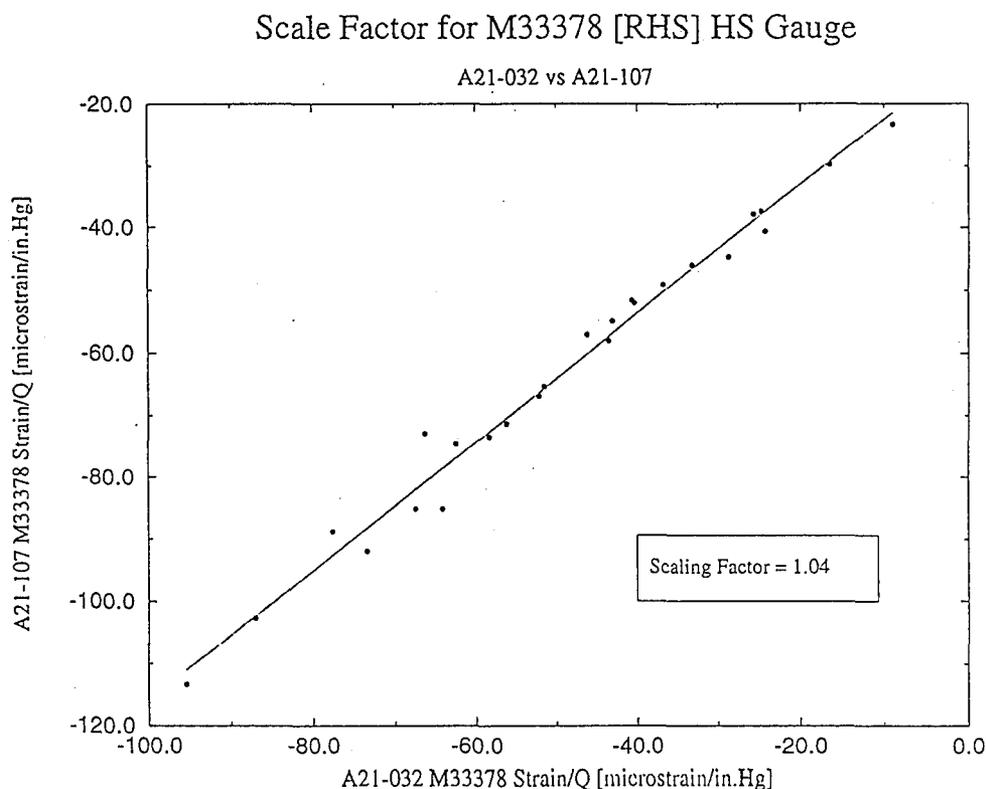


Figure 8 : M33378 Scaling Factor Plot [A21-107]

Calculation of strain sensor scaling factors is achieved by performing this operation for all of the aircraft considered using the available MSDRS data. The scaling factor is obtained by taking the ratio between individual aircraft, or aircraft sides, the results of which are presented in the following sections. Note that the above analysis required at least a 6 month data period on which to apply the derived conditions.

Table 5 : Example [MSDRS] Scaling Factor Data

Raw data set : 72,937 [1986 / 87 : A21-107], 58,186 [1988 / 89 : A21-32]
 Selected (Filtered) data set : 1,086 [1986 / 87 : A21-107], 830 [1988 / 89 : A21-32]

| RStab [⊕] Bin | Altitude [⊕] Bin | A21 - 32 | | A21 - 107 | |
|---------------------------|------------------------------|------------------|---------------------|------------------|---------------------|
| | | Number Points | Average M33378/Q | Number Points | Average M33378/Q |
| 1 | 4 | 19 | -95.42 | 26 | -113.38 |
| 2 | 2 | 80 | -62.4 | 32 | -74.6 |
| 2 | 3 | 27 | -73.37 | 15 | -91.97 |
| 2 | 4 | 24 | -87.07 | 51 | -102.78 |
| 3 | 2 | 65 | -56.29 | 51 | -71.42 |
| 3 | 3 | 32 | -64.11 | 21 | -85.18 |
| 3 | 4 | 28 | -77.54 | 39 | -88.81 |
| 4 | 1 | 50 | -46.22 | 23 | -57.02 |
| 4 | 2 | 55 | -51.52 | 79 | -65.28 |
| 4 | 3 | 32 | -58.4 | 28 | -73.58 |
| 4 | 4 | 23 | -67.4 | 35 | -85.1 |
| 5 | 1 | 24 | -40.36 | 30 | -52.09 |
| 5 | 2 | 67 | -43.59 | 112 | -58.05 |
| 5 | 3 | 32 | -52.2 | 32 | -66.85 |
| 5 | 4 | 13 | -66.26 | 35 | -73.02 |
| 6 | 1 | 30 | -33.24 | 58 | -45.98 |
| 6 | 2 | 34 | -36.76 | 90 | -49.17 |
| 6 | 3 | 33 | -43.1 | 22 | -54.95 |
| 7 | 1 | 30 | -25.7 | 64 | -37.8 |
| 7 | 2 | 36 | -28.8 | 109 | -44.72 |
| 7 | 3 | 24 | -40.67 | 20 | -51.67 |
| 8 | 1 | 22 | -16.47 | 44 | -29.73 |
| 8 | 2 | 23 | -24.77 | 37 | -37.38 |
| 8 | 3 | 12 | -24.27 | 14 | -40.57 |
| 9 | 1 | 15 | -8.97 | 19 | -23.32 |

⊕ - Only those bins having more than 10 points have been included here. (ie this must be satisfied by both aircraft being considered)

3.1.3 Horizontal Stabilator Strain Scaling Factors

Using the strain gauge response results (ie. slopes) presented in Table 4 and also those calculated using the method detailed in section 3.1.2, it was possible to calculate the aircraft to aircraft strain sensor scaling factors for the candidate aircraft, see Table 6. This was achieved by a comparison of slopes for each aircraft, using a particular aircraft as a base value, (ie. denominator). In this case, as aircraft A21-32 has been previously statically calibrated as part of the IFOSTP task, see Ref [13 and 14], it was used for the base or common denominator to provide the scaling factors, ie:

$$\text{Scaling Factor [M33378] A/C A} = \frac{X_{[A]}}{X_{[32]}} \quad ; \quad \text{Scaling Factor [M33377] A/C A} = \frac{Z_{[A]}}{Z_{[32]}}$$

Note as a comparison, separate work conducted in Ref [11] has been included here, as well as the RHS to LHS HS ground calibration results for aircraft A21-32 Ref [13].

ie. A21-32 Ground calibration scaling factor result : $\frac{M33378}{M33377} = 0.97$

As briefly discussed earlier (Section 2), the method developed in Ref [11] does show considerable promise, albeit using enhanced data, and as such has been used in the following comparison of calibration methods.

Table 6 : F/A-18 [MSDRS] Horizontal Stabilator Scaling Factors

| Ratio | Method. 1 | Method. 2* | Method. 3 |
|-----------------------------------|-----------|------------|-----------|
| $\frac{A21-38}{A21-32}$ [M33378] | 0.92 | 0.95 | 1.05 |
| $\frac{A21-38}{A21-32}$ [M33377] | 0.96 | 0.96 | 1.08 |
| $\frac{A21-107}{A21-32}$ [M33378] | 1.02 | 1.06 | 1.04 |
| $\frac{A21-107}{A21-32}$ [M33377] | 1.06 | 1.08 | 1.05 |
| $\frac{A21-44}{A21-32}$ [M33378] | - | 1.01 | 1.12 |
| $\frac{A21-44}{A21-32}$ [M33377] | - | 0.99 | 1.14 |
| $\frac{M33378}{M33377}$ [A21-32] | 1.03 | 1.02 | 1.01 |
| $\frac{M33378}{M33377}$ [A21-38] | 0.99 | 1.00 | 1.00 |
| $\frac{M33378}{M33377}$ [A21-44] | - | 1.05 | 0.99 |
| $\frac{M33378}{M33377}$ [A21-107] | 0.99 | 1.00 | 1.02 |

Note : Where dashes appear in the table, the analysis was not conducted for this aircraft

* Average value of all periods considered in Table 4.

Method. 1 : AOA/HS Deflection Binning Technique [Results obtained from Ref 11 as at May 1995]

Method. 2 : Strain/Q vs AoA linear analysis

Method. 3 : Strain/Q vs HS Deflection linear analysis [Actual stabilator deflection within ± 0.5 sec]

The results indicate that good correlations have been achieved between methods 1 and 2, particularly when the error bounds on the results in Ref [11] are considered, but that some discrepancies exist on comparison with method 3, and thus will require further investigation. At this stage one of the envisaged potential difficulties with the third method is that the PITS selected for analysis do not provide a large number of data points, (ie a criterion for using a bin is that it contains more than 10 points) and also the HS strains and stabilator deflections experienced are relatively small, and thus may provide additional difficulties in establishing small scaling factor differences between gauges.

Further discussion on the discrepancies are provided in the recommendations section of this report.

3.1.4 Aircraft Right to Left HS Strain Response

As an independent analysis, due to the lack of experimentally determined scaling factors, work was also conducted to provide additional validation, looking specifically at the right to left HS strain response using more stringent symmetrical flight conditions. The approach taken was to basically "plot" the right HS strain (M33378) against left HS strain (M33377) using MSDRS operational data, and was intended to confirm those results obtained in the previous section, (Table 6). The limitations are as shown below with the results presented in Table 7.

Clean Configuration (AIM 9's only)

All TOF codes

ABS [RR] ≤ 1.0 deg/sec

ABS [YR] ≤ 1.0 deg/sec

ABS [RStab - LStab] ≤ 1.0 deg

$$A = \frac{M33377 \mu\epsilon}{M33378 \mu\epsilon} \quad B = \frac{M33378 \mu\epsilon}{M33377 \mu\epsilon} \quad C = \frac{\left(\frac{1}{A} + B\right)}{2}$$

Where C is the average of the two (1/A,B) regressions, see Ref [11]. This was done as the least squares regression technique assumes that one variable is independent of the other. In this particular case, both sets of data can be said to be indirectly dependent upon the structural response of the empennage to its load environment. In this case the scale factor was defined as the average of the two estimates.

Table 7 : F/A-18 Right to Left Strain Response

| Aircraft | Period | 1/A | B | C | R ² | Table 6 |
|-------------|---------------|------|------|------|----------------|---------|
| A21-32 | ARDU I | 0.98 | 0.96 | 0.97 | 0.989 | |
| A21-32 | MSDRS 1988/89 | 1.01 | 0.94 | 0.97 | 0.965 | |
| A21-32 | MSDRS 1992/93 | 1.00 | 0.96 | 0.98 | 0.980 | |
| average-32 | | 1.0 | 0.95 | 0.97 | | 1.02 |
| A21-38 | MSDRS 1991 | 1.03 | 0.97 | 1.00 | 0.971 | |
| A21-38 | MSDRS 1993 | 1.08 | 0.92 | 1.00 | 0.920 | |
| average-38 | | 1.05 | 0.95 | 1.00 | | 1.00 |
| A21-44 | MSDRS 1991 | 1.00 | 0.95 | 0.98 | 0.974 | |
| A21-44 | MSDRS 1993 | 1.03 | 0.96 | 1.00 | 0.962 | |
| average-44 | | 1.02 | 0.96 | 0.99 | | 1.05 |
| A21-107 | MSDRS 1986/87 | 1.01 | 0.96 | 0.98 | 0.978 | |
| A21-107 | MSDRS 1991* | 1.12 | 1.04 | 1.08 | 0.963 | |
| average-107 | | 1.06 | 1.00 | 1.03 | | 1.00 |

* gauge reported unserviceable shortly after this period

Taking into account any error bounds that may exist between the method presented here and those of Table 6, the results achieved compare favourably, giving further confidence in the techniques. (Results of Tables 4 and 6 indicate that potential error bounds for these two methods are approximately ± 4 %).

Note also that whilst the limitations for this method appear severe, and it was conducted for comparative purposes only, the results achieved provided good linear correlations and did not require large numbers of points.

4. Wing Fold Analytical Calibration Procedure

A number of analytical calibration techniques have been developed to allow scaling between WF sensors on different aircraft. The methods developed are discussed in the following sections.

4.1 Wing Root Calibration

Before considering the WF calibration requirements, it is instructive to summarise the current calibration procedures adopted for the WR sensor calibration.

As early studies by the manufacturer indicated that the response of the WR sensor at specific PITS was proportional to N_z , pre-delivery calibration flights were initiated to measure the response of the sensor. The current PITS definition for a new aircraft are:

N_z : 3.5, 4.5 and 5.5g's \pm 0.2g's
Altitude: 5000 or 10000 ft \pm 1000 ft
Mach No.: 0.80 \pm 20 KCAS

As sensors become unserviceable during the life of the aircraft and need replacing, it was proposed to calibrate the new sensors by extracting data for similar PITS from the MSDRS FDS and thus calculate its response to N_z .

In the early 1990's *Rider* of AMRL noted a phenomenon occurring to the response of the WR sensor [see Ref 15]. It was noted by comparing the response of the WR sensor to a 'reference' WR bending moment (BM) of 6439 in.kip, [which in turn leads to a reference strain value of 1808 $\mu\epsilon$], over different periods of flying for a given aircraft gave different strain values. It was further noted that the response decayed over a period of time until a plateau was reached at which point the response remained constant. This became known as WR "drift". This behaviour was subsequently confirmed by MDA and the USN, indicating that it was a "fleet" problem. This phenomenon effectively invalidated the calibration values calculated from the pre-delivery flights. In turn, the fatigue life expended calculated from the WR sensor was compromised (in many cases conservatively so).

To address this, MDA developed a drift/calibration analytical technique which is now incorporated into the Structural Appraisal of Fatigue Effects "SAFE" software Ref [16] used to calculate fatigue life expended. The procedure (from Ref [17]) is summarised below:

- obtain FDS strain files,
- extract WR and HS strains, total flight hours, Mach No., normalised Nz and altitude for each WR peak/valley (PV) trigger,
- further extract those triggers which have a roll rate less than 20 deg/sec to obtain symmetrical manoeuvres,
- refine data using the following restrictions:
 - Nz: 3 to 7 g's
 - ALT: 3000 to 8000 ft
 - Mach No.: 0.75 to 0.85
- if data shows a lot of scatter, then HT strains can be restricted to limit effect of roll acceleration,
- calculate expected bending moment at the PITS using interpolated loads data,
- calculate the expected strain using the following equation:
 - $\mu\varepsilon = (BM + 200,000)/36447$
- calculate percentage of expected strain:
 - %expected strain = (actual strain/expected strain)*100
- calculate average percentage of expected strain for desired flight hours, (this depends upon the total flight hours and distribution of points)
- plot the results to show drift trends over time,
- factor PV by calibration/drift factor and calculate fatigue life expended.

Details of the RAAF implementation of this procedure by HdHV, and known as the Wing Root Gauge Calibration Program (WRSGCP), can be found in Ref [18]. It should be noted that HdHV has made slight adjustments to the MDA procedure described above.

Since the WF response should be related to that of the WR at specific PITS, the data restrictions noted in Ref [18] were used as a starting point in the derivation of WF scaling factors.

4.2 Wing Fold Strain Response

Using the assumption that at various PITS, WR strain is proportional to WF strain, the approach undertaken for the WR calibration can be considered here. The main point of which is, that under restricted near symmetrical flying conditions a linear response exists between WR strain and Nz.

⁷ If reference BM used, the reference strain will result.

Since it is reasonable to expect some relation to exist between the strain response of the WR and WF locations (see Ref [19]), it was considered appropriate to use the conditions specified in the Ref [18] report in the initial stages of the analysis to determine WF scaling factors. These were as follows :

- $\{3 \leq N_z \leq 6\}$
- $\{3,000 \leq \text{Altd} \leq 15,000\}$
- $\{0.75 \leq M_n \leq 0.85\}$
- $\text{ABS [RR]} \leq 10$
- $\text{Total Fuel Weight} \leq 9,000 \text{ lb}$
- $\text{Maximum stores configuration (AIM7 and AIM9)}$

Using all available ARDU Phase I Air Combat Manoeuvring flights, (represented by some 20 flight profiles) filtered to the above limitations, a plot of WF strain versus N_z was constructed, see Figure 9.

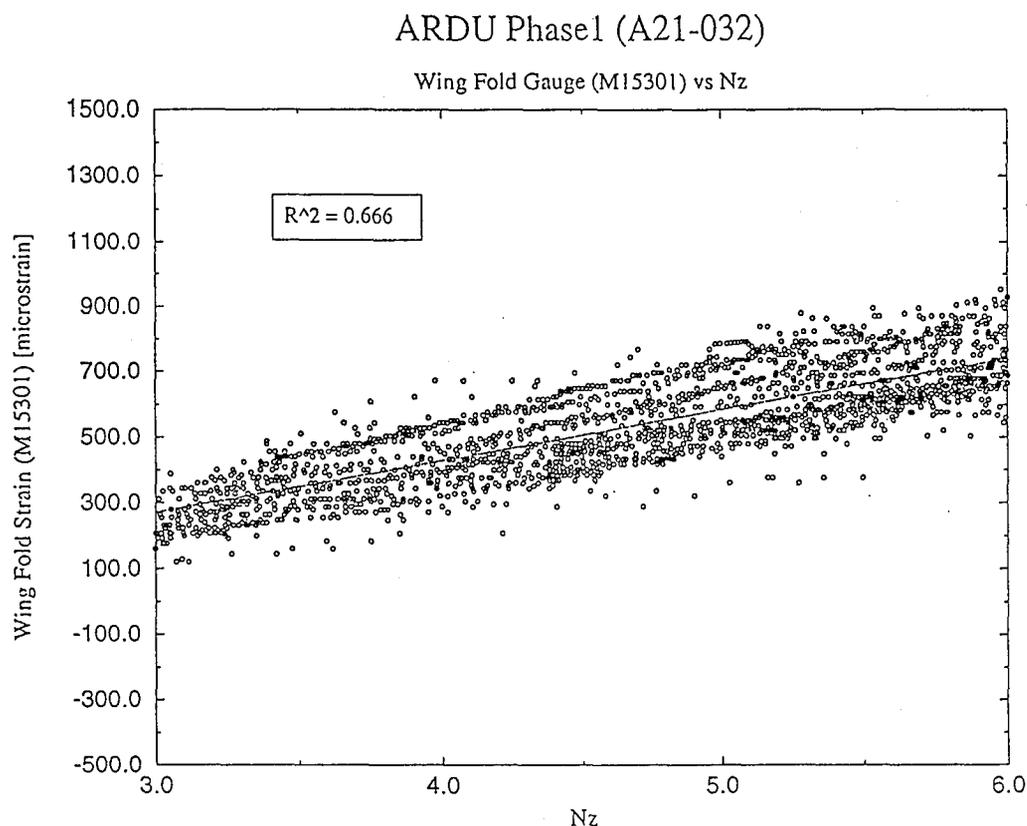


Figure 9 : M15301 vs N_z [ARDU A21-32 Limited Conditions]

This indicates that a relationship exists between WF strain and N_z , but that further investigation was required, in order to obtain a stable linear response, of sufficient accuracy to be of use in a calibration technique (ie $R^2=0.666$ is poor). Note also that the limitations appear restrictive and thus when used with operational MSDRS data, may not produce enough points for the calibration analysis. The scaling factor was defined as the difference in slope between WF strain and N_z between different aircraft.

4.2.1 Strain vs Nz Results

In an effort to produce a stable linear response, using sufficient data points, refinement of and experimentation with the flight parameter limitations, led to the following, (ARDU data derived) flight limitations. Note that these investigations essentially involved determining how to expand the initial WR limitations, to give additional data points, and produce a linear relationship between WF strain and Nz with little scatter. In essence this involves expanding the region of investigation to include a larger Nz band, thereby increasing the X - axis range considered in the regression analysis.

- $ABS [RR] \leq 20$
- $\{3,000 \leq Altd \leq 15,000\}$
- $\{0.7 \leq Mn \leq 0.9\}$
- Total Fuel Weight $\leq 9,000$ lb
- $Nz > 0$
- Max stores configuration-Centre line pylon & tank, AIM7 and AIM9.

Applying these limitations to the same ARDU ACM data set, resulted in the following plot, (see Figure 10). Note the expanded X - axis range (Nz) provides for a higher regression and more accurate determination of slope, (ie $R^2 = 0.959$ as opposed to 0.666).

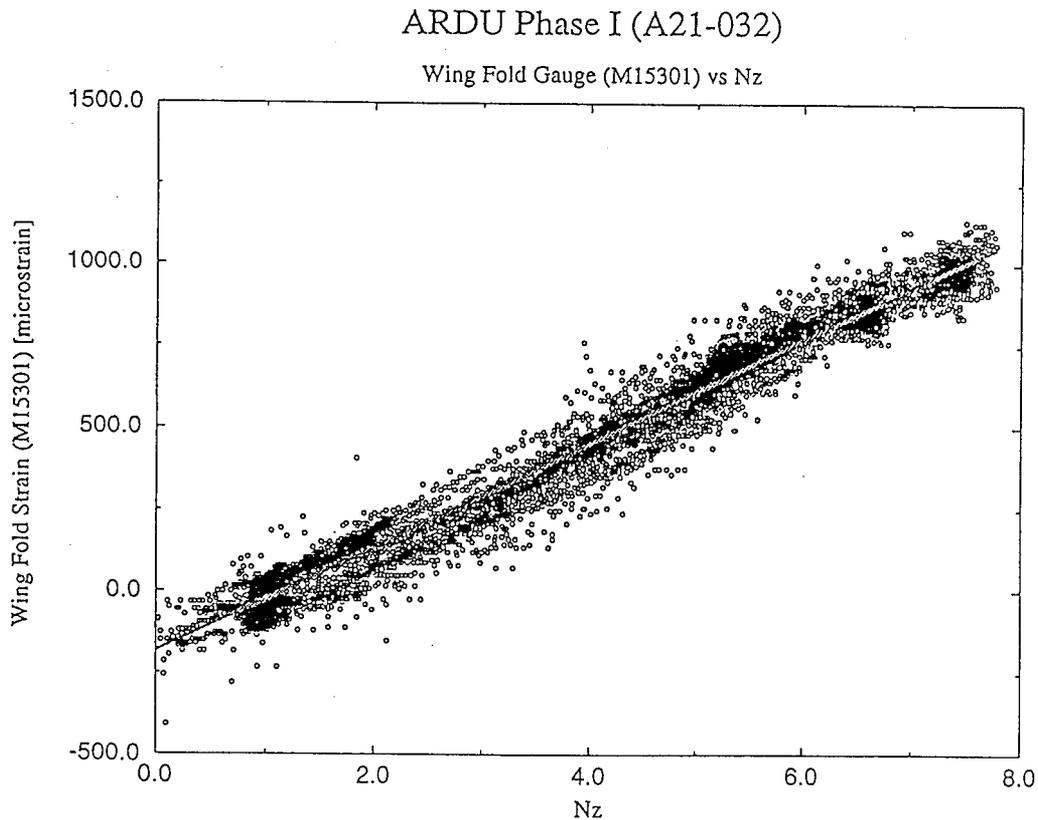


Figure 10 : M15301 vs Nz [ARDU A21-32 Expanded Conditions]

While it can be shown that these flight parameter limitations produce good linear results when applied to the ARDU flight test data, it is required that they also produce good results when applied to MSDRS operational data, for which the method was ultimately devised. This was indeed the case and an example is presented below in Figure 11, where the limitations have been applied to the corresponding MSDRS data. Results for all aircraft considered are given in Table 8.

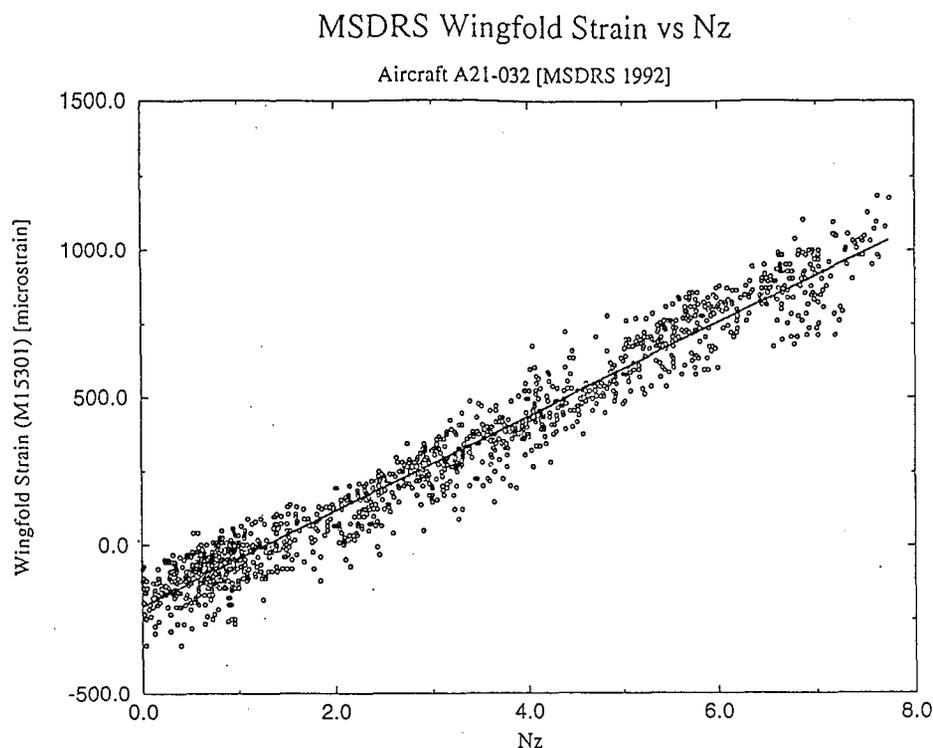


Figure 11 : M15301 vs Nz [MSDRS 1992 A21-32]

The wing fold scaling factors can be easily determined from Table 8, simply by comparing the slopes for different aircraft, the results of which are presented in the following sections. Note that scaling factor discrepancies exist between some of the periods for the same aircraft. This will also be addressed in the following sections.

At this stage it is appropriate to consider the results of a full scale fatigue test conducted by MDA, known as ST16 (see Ref [1]), this test was conducted using a (3 PITS) flight load spectrum and aircraft geometric configuration representative of RAAF F/A-18 fleet usage. As calibration of the strain gauges on this test article were carried out, it provided a valuable source for comparison with aircraft A21-32, which has also undergone static ground calibration Ref [13].

Analysis of the ST16 data using a 300 hour block, (ie Block 33 comprising test data from 9600 to 9900 hrs) revealed the following WF strain (M15301) per g (Nz) relationships, (see Figure 12 representing both PITS stated below).

$$[Mn = 0.8 @ \text{Sea Level}] : M15301[\mu\epsilon] = 161.3 * Nz - 272$$

$$[Mn = 0.95 @ 15,000 \text{ ft}]^8 : M15301[\mu\epsilon] = 159.1 * Nz - 202$$

⁸ Note that this PITS is at the extreme of the limitation envelope, but still gave a consistent value.

Table 8 : MSDRS WF Strain Response (Nz vs M15301)

| Aircraft Period | Slope of Regression | Standard Error of Reg. Slope | Regression Intercept | R ² | No of Points | No of Flights |
|-----------------|---------------------|------------------------------|----------------------|----------------|--------------|---------------|
| A21-32 | | | | | | |
| 1988/89 | 163.3 | 0.563 | -221 | 0.947 | 4759 | 154 |
| 1992 | 160.3 | 0.939 | -205 | 0.951 | 1502 | 44 |
| ARDU | 159.8 | 0.317 | -187 | 0.959 | 10976 | - |
| A21-38 | | | | | | |
| 1989/90 | 139.1 | 0.632 | -113 | 0.937 | 3252 | 101 |
| 1991 | 125.1 | 0.757 | -123 | 0.953 | 1362 | 54 |
| 1992 | 122.1 | 0.887 | -85 | 0.983 | 322 | 25 |
| 1993 | 127.4 | 0.468 | -117 | 0.968 | 2435 | 45 |
| A21-44 | | | | | | |
| 1990 | 148.6 | 1.188 | -162 | 0.951 | 815 | 53 |
| 1991 | 124.2 | 0.723 | -115 | 0.972 | 853 | 58 |
| 1992 | 126.8 | 1.380 | -107 | 0.979 | 181 | 15 |
| 1993 | 124.8 | 0.661 | -144 | 0.939 | 2314 | 36 |
| A21-107 | | | | | | |
| 1986/87 | 144.7 | 0.382 | -204 | 0.947 | 8054 | 169 |
| 1989 | 148.5 | 0.990 | -203 | 0.955 | 1051 | 17 |
| 1991 | 115.3 | 0.590 | -68 | 0.944 | 2237 | 49 |
| 1992 | 111.1 | 0.680 | -70 | 0.959 | 1135 | 48 |
| 1993* | 115.7 | 2.1 | -93 | 0.974 | 82 | 18 |

- Number of ARDU test flights do not correspond to operational flights
 * note: limited data points.

ST16

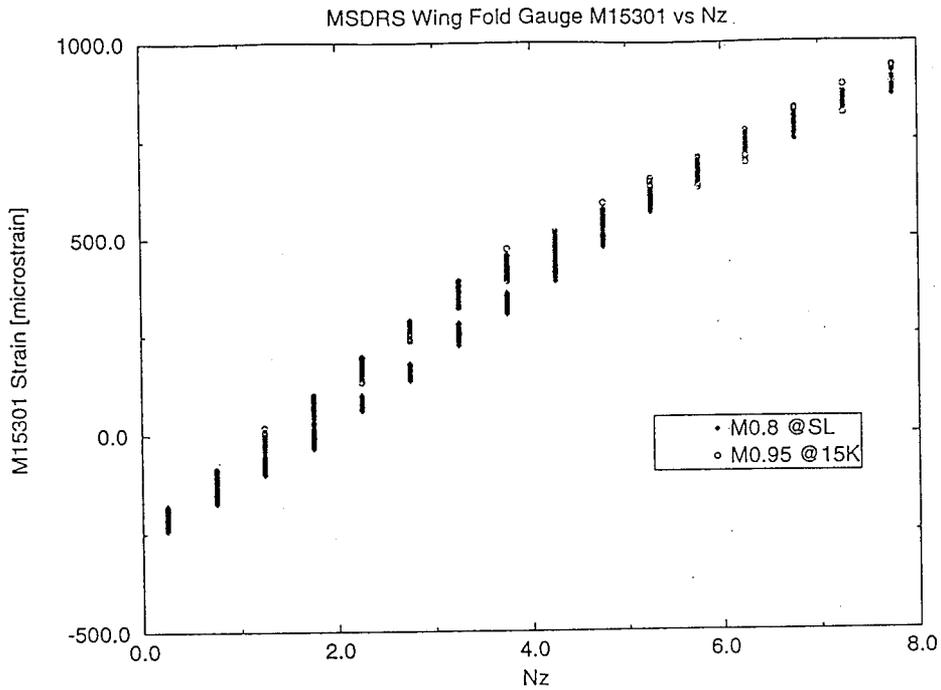


Figure 12 : M15301 vs Nz [ST16 All PITS]

The results indicated that similar strain responses exist between the two PITS, but more importantly that the ST16 test article has a WF strain response (ie strain per g) very similar to that experienced by A21-32, (see Table 8). In view of limited experimental values for operational aircraft, this result gives confidence in that obtained from the analytical technique. Note also that the third ST16 PITS (Mach 1.1 @ sea level) was investigated, but was found to respond differently to the other two, as was expected, as it falls outside of the allowable limitation envelope.

4.2.2 Parametric Equation Results

The recent development of parametric strain equations, for use at F/A-18 AFDAS strain sensor locations, mentioned previously (Ref [8]), enabled further WF analysis to be carried out, as either a separate calibration technique or as a validation of the strain versus Nz method.

Due to the unavailability of an AFDAS WF gauge during development of the parametric equations, described in Ref [8], the MSDRS WF gauge, M15301 located at the mirror location on the LHS was used as a substitute. This equation is presented below along with its allowable flight parameter ranges :

Wing Fold Parametric Equation {AoA, CG, LAil, LTef, Nz, Q, RR, W}

$$\begin{aligned} M15301^9[\mu\epsilon] = & 209648 + 83.41 \cdot AoA - 5.874 \cdot AoA^2 + 0.1289 \cdot AoA^3 - 9.34E-4 \cdot AoA^4 - \\ & 38144 \cdot CG + 2561.3 \cdot CG^2 - 76.13 \cdot CG^3 + 0.8449 \cdot CG^4 + \\ & 3.138 \cdot LAil + 0.248 \cdot LAil^2 + 0.01593 \cdot LAil^3 - \\ & 31.7 \cdot LTef + 4.125 \cdot LTef^2 - 0.291 \cdot LTef^3 + 0.00755 \cdot LTef^4 + \\ & 88.69 \cdot Nz + 14.348 \cdot Nz^2 - 1.079 \cdot Nz^3 - \\ & 118.44 \cdot Q + 13.18 \cdot Q^2 - 0.6526 \cdot Q^3 + 0.01106 \cdot Q^4 - \\ & 0.646 \cdot RR - 0.0044 \cdot RR^2 + 2.347E-6 \cdot RR^3 + \\ & 0.4135 \cdot W - 2.25E-5 \cdot W^2 + 5.263E-10 \cdot W^3 - 4.454E-15 \cdot W^4 \end{aligned}$$

Valid Parameter Ranges :

$$\{0 < Q < 22\}, \{1.2 < AoA < 35\}, \{-230 < RR < 235\}, \{27320 < W < 43320\}, \\ \{18 < CG < 24.76\}, \{2 < Nz < 7.98\}, \{-17.6 < LAil < 18.4\}, \{-6 < LTef < 17.7\},$$

For the purpose of using this equation to calibrate WF gauges on fleet aircraft, an initial parameter sensitivity investigation was carried out looking specifically at the independent contributions to strain response from each parameter. This was achieved by plotting the strain contributions for each parameter over the normalised parameter ranges considered, see Figure 13, (Note the W and CG parameters had minimal contributions and are not presented here).

⁹ This equation is valid for positive Nz. See Ref [8] for validation details for this equation.

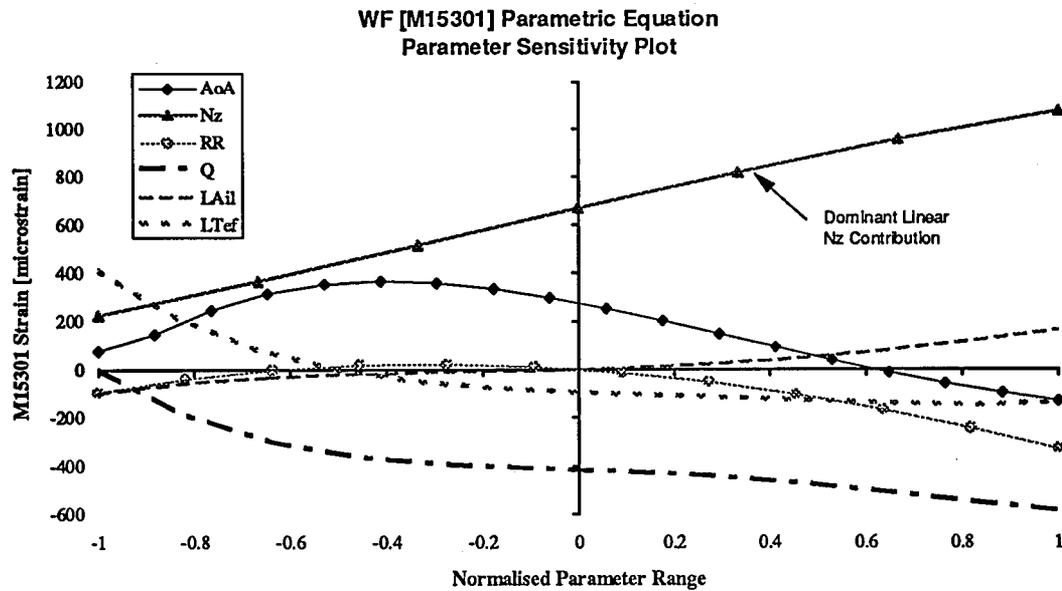


Figure 13 : Wing Fold Sensitivity Plot

The results of this plot indicate that the dominant flight parameters inducing WF strain are the Nz, Q and AoA parameters. Note also the linear response relating WF strain and Nz, previously exploited to obtain a WF calibration technique. The fact that the (0.2 Hz sampled) control surface deflection parameters have only a minor contribution to the WF strain means that the equation should produce a good result even with the inadequate interpolation of these parameters. Note also that the CG parameter is not available on the MSDRS system and must be obtained from a table "look up" routine taking into account the aircraft stores configuration and weight. For the purposes of this report an assumption has been made that due to the relative insignificance of the CG on the WF strain response (as noted in Ref [8]), the parameter will be set at a default value of 21 % Mean Aerodynamic Chord (MAC).

The basis of this parametric equation calibration technique relies upon the fact that the equation was derived using ARDU flight test data from aircraft A21-32. Therefore applying data from a different aircraft to this equation, and plotting the resulting (ie A21-32 equivalent) strain against actual strain, results in a slope which was considered here as the scaling factor between these aircraft.

In order to perform this calculation, the required flight parameters were extracted from the MSDRS FDS files using the EXTRACT program, Ref [5]. These parameters were then entered into the M15301 equation and the results plotted against the actual strain values. An example is shown in Figure 14.

Calculated strain using data from A : Model [$\mu\epsilon$] = C * Actual [$\mu\epsilon$] + Const

Where the scaling factor for aircraft A is : 1/C (ie using the model (A21-32) as the baseline aircraft).

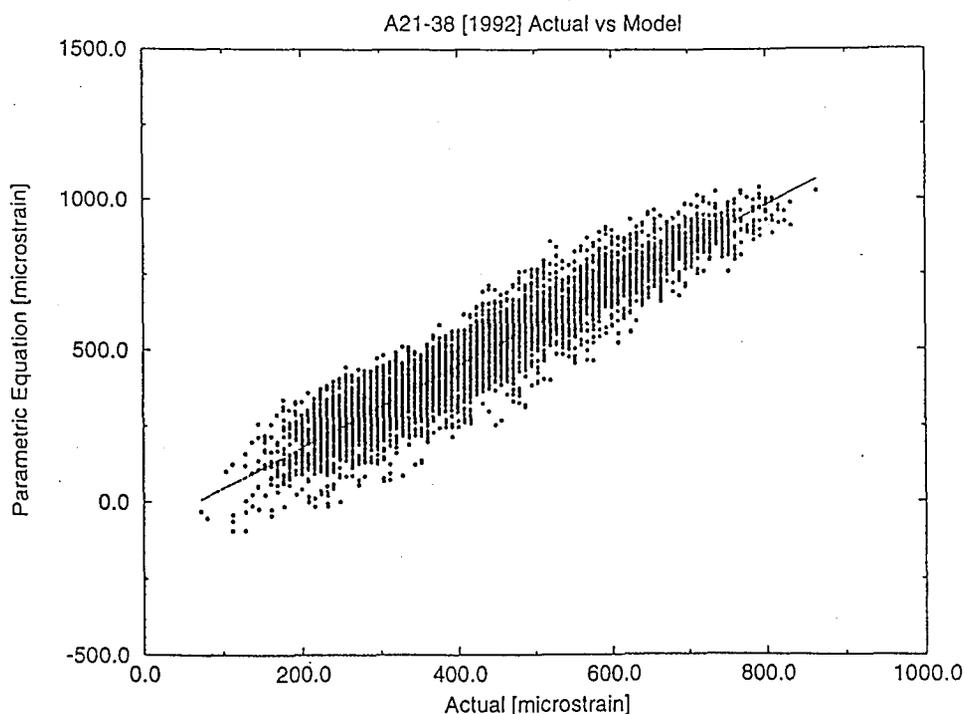


Figure 14 : MSDRS Wing Fold Calibration

This analysis was performed for all of the candidate aircraft, using MSDRS operational data, with the results presented in Table 9.

Table 9 : MSDRS Parametric Equation Wing Fold Strain Scaling Factors

| Aircraft | MSDRS Period | Num Points | Scale Factor $1/C^B$ | R ² | σ [$\mu\epsilon$] |
|----------|--------------|------------|----------------------|----------------|----------------------------|
| A21-32 | 1988/89 | 9006 | 1.05* | 0.84 | 86 |
| " | 1991 | 143 | 1.04 | 0.72 | 18 |
| " | 1992 | 4634 | 1.02 | 0.84 | 108 |
| A21-38 | 1989/90 | 16965 | 0.91 | 0.80 | 101 |
| " | 1991 | 4533 | 0.77 | 0.83 | 86 |
| " | 1992 | 5715 | 0.75 | 0.89 | 72 |
| " | 1993 | 8812 | 0.73 | 0.87 | 92 |
| A21-44 | 1990 | 6709 | 0.90 | 0.79 | 100 |
| " | 1991 | 4796 | 0.77 | 0.89 | 80 |
| " | 1992 | 1984 | 0.77 | 0.89 | 75 |
| " | 1993 | 7664 | 0.74 | 0.85 | 103 |
| A21-107 | 1986/87 | 7190 | 0.89 | 0.73 | 106 |
| " | 1989 | 3233 | 0.88 | 0.84 | 91 |
| " | 1991 | 6666 | 0.71 | 0.85 | 84 |
| " | 1992 | 5094 | 0.72 | 0.79 | 111 |
| " | 1993 | 4348 | 0.73 | 0.83 | 84 |

* The scaling factor here represents the error in the method.

^B Where $1/C$ is equal to: $\frac{\text{Actual}}{\text{Model [A21 - 32]}}$ microstrain.

It should be noted that the calculated scaling factor for aircraft A21-32 was between 1.02 and 1.05. As the parametric equation was developed using data from this aircraft, the variation from the expected value of 1.0 represents the induced error, (ie $\pm 5\%$).

One of the advantages of this method is that the parameter limitations are generous, in that as the equation was developed to predict strain response under operational flying conditions, it is valid over a large portion of the flight envelope, (PITS). Therefore a large number of data points are available for calibration, using a limited data set, (ie a standard quarter of data can be used). Note that scaling factor discrepancies exist between some of the periods for the same aircraft. This will be addressed in the following section.

It should be noted that the desired commonality with the WR data limitations was not achieved for either method considered.

4.2.3 Wing Fold Scaling Factors

Summarising those strain response and scaling factor results presented in sections 4.2.1 and 4.2.2 respectively, and comparing the WF scaling factor results for the two methods, shows that good agreement was achieved, see Table 10. Note that the scaling factors derived using the parametric equation method are essentially using A21-32 (ARDU) data as the base or denominator. Therefore for reasons of consistency the correlations presented for the (M15301 vs Nz) method will also adopt this approach ie the slope values from Table 8 have been ratioed with respect to A21-32 ARDU data. This also allows a comparison of A21-32 ARDU data against A21-32 MSDRS operational data.

$\frac{\text{A21-32}}{\text{A21-32}_{\text{ARDU}}} = \text{Response of A21-32 data from } \textit{Period} \text{ against ARDU(1992) flight test period.}$

Table 10 : F/A-18 [MSDRS] Wing Fold Scaling Factors

| M15301 Strain ratio | MSDRS Data Period | Method .1 Scale Factor Accuracy $\pm 3\%$ | Method .2 Scale Factor Accuracy $\pm 5\%$ |
|-------------------------------|-------------------|---|---|
| <u>A21-32</u> | 1988/89 | 1.02 | 1.05 |
| <u>A21-32</u> _{ARDU} | 1991* | - | 1.04 |
| | 1992 | 1.00 | 1.02 |
| <u>A21-38</u> | 1989/90 | 0.87 | 0.91 |
| <u>A21-32</u> _{ARDU} | 1991 | 0.78 | 0.77 |
| | 1992 | 0.76 | 0.75 |
| | 1993 | 0.79 | 0.73 |
| <u>A21-44</u> | 1990 | 0.92 | 0.90 |
| <u>A21-32</u> _{ARDU} | 1991 | 0.78 | 0.77 |
| | 1992 | 0.79 | 0.77 |
| | 1993 | 0.78 | 0.74 |
| <u>A21-107</u> | 1986/87 | 0.90 | 0.89 |
| <u>A21-32</u> _{ARDU} | 1989 | 0.92 | 0.88 |
| | 1991 | 0.72 | 0.71 |
| | 1992 | 0.70 | 0.72 |
| | 1993 | 0.72 | 0.73 |

* Only 3 flights were obtained for this period, and insufficient data for use in Method 1.

Method .1 : WF strain (M15301) vs Nz

Method .2 : M15301 Parametric strain equation

Note : Aircraft service entry dates were as follows:

A21-32 : Aug 1988.

A21-38 : Oct 1988.

A21-44 : Jun 1989.

A21-107 : Dec 1985.

Note also that the results indicate large differences in strain response between aircraft, (ie as much as $\approx 30\%$).

Whilst good agreement has been achieved between the scaling factors derived using methods 1 and 2, the concern lies with the apparent "drift" or step change of strain response on some of the aircraft considered above. If a WF strain gauge (M15301) was behaving correctly we would expect to see a consistent scaling factor per aircraft per period.

Information was obtained from the RAAF concerning an operational procedure implemented in March 1990, which has been shown to relate to this drift. This concerned the removal of the AIM9 missile tail fins for all F/A-18 flight operations. The exception to this being for ferry missions, where it had been shown that better

aircraft performance was achieved with fins fitted. Further investigation in this area led to the discovery that the strain response discrepancies between different flight periods (see Tables 8, 9 and 10) did correlate with this change in missile configuration.

Subsequent investigation using ARDU Phase II data, in which flights with both AIM9 fins on and off were flown, gave the following results:

| A21-32 Aircraft Period | Slope of Regression | Standard Error of Reg. Slope | Regression Intercept | R ² | Standard Deviation | No of Points |
|---------------------------|---------------------|------------------------------|----------------------|----------------|--------------------|--------------|
| Oct 1993 AIM9 (no fins) | 119.1 | 0.52 | -94 | 0.989 | 28.5 | 586 |
| Nov 1993 AIM9 (with fins) | 163.0 | 0.67 | -200 | 0.987 | 25.1 | 1243 |

On comparison with Table 8 and 10 above it can be seen that the change in strain response at the WF location does appear to be directly attributed to the missile configuration differences, indicating that without AIM9 fins the aircraft experiences a smaller WF strain per g response. Note that the strain response calculated from operational data for aircraft A21-32 did not vary over this period due to the fact that the missile configuration was constant, (ie the flights were performed with AIM9 and fins). The noted effect is thought to be attributable to the lift provided by the missile fins.

Therefore the configuration of the AIM9 must be known before a WF scaling factor can be interpreted.

5. Canadian Aircraft

As part of the IFOSTP spectra development, characteristic Canadian Forces (CF) and RAAF usage spectra were developed. The CF spectrum consisted of a combination of flights from a number of fleet aircraft. As a further test of the scaling factor procedures developed in this report, scaling factors were derived for the Canadian aircraft and the results were compared to those previously calculated using the methods detailed in Ref [10, 11].

The Canadian aircraft considered were:

| | | | |
|----------------|----------|----------------------|----------|
| <i>PRE-LEX</i> | CF188911 | <i>POST-LEX</i> | CF188732 |
| <i>USAGE</i> | CF188913 | <i>USAGE</i> | CF188780 |
| | CF188917 | (<i>post 1987</i>) | CF188925 |
| | CF188920 | | CF188940 |

The results of this comparison are presented in Tables 11, 12 and 13 with further details presented in Appendix 2. The scaling factors in Table 11 are all scaled with respect to aircraft A21-107, ie $SF = Aircraft / A21-107$, (the reference aircraft used in Ref[10]). The scaling factors in Table 12 are all referenced with respect to aircraft A21-032, the reference aircraft used in Ref [11].

Table 11 : CF Horizontal Stabilator Scale Factor Summary

| Aircraft | [Ref 10] Method SF | | | [Strain/Q vs AoA] Method SF | | |
|----------|--------------------|------|------|-----------------------------|------|------|
| | $\frac{RHS}{LHS}$ | RHS | LHS | $\frac{RHS}{LHS}$ | RHS | LHS |
| 911 | 0.68 | 0.51 | 0.73 | 0.95 | 0.60 | 0.64 |
| 913 | 1.12 | 1.15 | 0.90 | 1.03 | 1.07 | 1.05 |
| 917 | 0.98 | 1.01 | 0.97 | 0.96 | 0.95 | 1.00 |
| 920 | 1.24 | 1.15 | 0.85 | - | - | - |
| 732 | - | - | - | - | - | - |
| 780 | 0.93 | 1.03 | 1.12 | 1.12 | 0.95 | 0.85 |
| 925 | 1.05 | 0.92 | 1.01 | - | - | - |
| 940 | 0.98 | 1.19 | 1.11 | 1.09 | 0.82 | 0.76 |

- Scale Factors not determined due to insufficient data

RHS - M33378 HS Gauge

LHS - M33377 HS Gauge

Work carried out in Ref [11] indicated that the results achieved using the Ref [10] method of HS scale factor determination were suspect, and produced far from confident results. Comparison of results in Table 11 appears to confirmed this, however the results for aircraft 911 do show the same expected trend, in that the HS strain response for the heavy configuration spindle block is considerably lower than the rest, Ref [20].

An attempt to reconstruct the Ref [11] method of scale factor determination was also conducted, see Table 12. Enhanced¹⁰ MSDRS data required for the Ref [11] technique was available for aircraft 917 and 940, but not for the remaining aircraft. Therefore the data extraction method developed in section 3.1.2 was used on RAW MSDRS data to obtain data for this.

¹⁰ See Refs 8 and 11 for a discription of the enhancement procedure.

Table 12 : CF Horizontal Stabilator Scale Factor Summary

| Canadian Aircraft | [Strain/Q vs AoA] Method SF | | | [Ref 11] Method SF | | |
|-------------------|---------------------------------|------|------|---------------------------------|------|------|
| | $\frac{\text{RHS}}{\text{LHS}}$ | RHS | LHS | $\frac{\text{RHS}}{\text{LHS}}$ | RHS | LHS |
| 911 | 0.95 | 0.65 | 0.69 | 0.94 | 0.67 | 0.75 |
| 913 ^b | 1.03 | 1.15 | 1.14 | 0.96 | 1.11 | 1.19 |
| 917 | 0.95 | 1.02 | 1.10 | 1.00 | 1.09 | 1.10 |
| 920 | - | - | - | - | - | - |
| 732 | - | - | - | - | - | - |
| 780 ^b | 1.12 | 1.02 | 0.93 | 1.00 | 1.01 | 1.02 |
| 925 | - | - | - | - | - | - |
| 940 | 1.08 | 0.86 | 0.81 | 1.07 | 0.91 | 0.86 |

^b Limited data available for these aircraft. Therefore low number of points used in the determination of scale factors.

RHS - M33378 HS Gauge

LHS - M33377 HS Gauge

On comparison of the results for the two methods presented in Table 12, the majority show that good correlations have been achieved, (in particular for aircraft 911 and 940). Note also that equally accurate results have been achieved yielding high correlation statistics (see Appendix 2, Table A1.1), using both enhanced and RAW MSDRS data, indicating that enhanced data may not necessarily be required for the Ref [11] scale factor determination method.

Analysis conducted in the determination of CF WF scale factors using the method derived in section 4.2.1, (ie WF strain per g), was also conducted, with results presented in Table 13.

Table 13 : CF Wing Fold Scale Factor Summary

| Aircraft | LEX | WF [M15301] Scale Factor [®] AIM9 (with fins) | WF [M15301] Scale Factor [®] AIM9 (no fins) |
|----------|------|---|---|
| 911 | PRE | 0.65 | 0.87 |
| 913 | PRE | 0.93 | 1.25 |
| 917 | PRE | 1.03 | 1.38 |
| 920 | PRE | 1.00 | 1.34 |
| 732 | POST | 0.81 | 1.09 |
| 780 | POST | 0.82 | 1.11 |
| 925 | POST | 0.74 | 1.00 |
| 940 | POST | 0.82 | 1.10 |

[®] Scaling factors with respect to RAAF F/A-18 A21-32, see Appendix 2 Table A1.2

$$SF [with fins] = \frac{\text{Aircraft}}{159.8}$$

$$SF [no fins] = \frac{\text{Aircraft}}{119.0}$$

Due to initial uncertainty in the missile fin configurations for the CF data, scale factors, (Table 13) were determined for both fin configurations. Comparison of strain per *g* values with those obtained for RAAF aircraft indicated which CF scale factors were considered the more likely, (ie compare CF and RAAF WF strain per *g* values in Appendix 2, Table A1.2). These have been highlighted on Table 13 as a shaded region. Note however that until the CF determine exactly which configurations the aircraft were flown with, these values remain speculative.

Recently the CF reported that they generally operate the F/A-18 without AIM9 fins. If, as in the case of the RAAF, this is a fairly recent situation, (ie 1990), we would expect to see the CF *POST-LEX* aircraft exhibiting this reduced strain response due to removal of missile fins. This was confirmed by the results in Table 13 (also Appendix 2, Table A1.2), indicating that the likely scale factors for *POST-LEX* aircraft, are those calculated using a no AIM9 fin configuration.

6. Recommendations

6.1 Horizontal Stabilator Calibration

Two separate analytical calibration techniques have been developed in this report for the HS MSDRS sensors. Although both techniques appear promising, some minor discrepancies have been noted between the two, in specific aircraft periods of flying (see section 3.1.3). As only one RAAF aircraft has been ground calibrated (ie A21-032) to date, there exist insufficient data to validate either technique, or to establish which leads to the most consistent result.

To remedy this, it is recommended that a simplified (relative to Ref [14]) ground calibration be undertaken on a limited number of fleet aircraft to determine the response of the HS MSDRS sensors to applied loading. The candidate aircraft for this purpose should be :

A21-032
A21-107
A21-038 and
A21-044.

Although A21-032 has been calibrated previously, for direct comparison purposes it is recommended that this aircraft be re-calibrated using the "simplified" technique.

Once the preferred analytical technique has been established, a fleet wide analysis of the HS MSDRS sensors should be conducted.

6.2 Wing Fold Calibration

Two separate analytical calibration techniques have been developed for the WF MSDRS sensor. The configuration of the AIM9 missile (tail fins on or off) was shown to affect the calculated scaling factors for both methods.

Both techniques appear promising, but as to date only one RAAF aircraft A21-032 has been ground calibrated, there exist insufficient data to validate the techniques.

To remedy this, it is recommended that a simplified (relative to Ref [14]) ground calibration be undertaken on a limited number of fleet aircraft to determine the response of the WF MSDRS sensors to applied loading. The candidate aircraft for this purpose should be those identified for the HS calibration. To limit the impact on aircraft operational availability, both HS and WF ground calibrations should be conducted concurrently. The option of concurrently calibrating other sensors (ie WR and vertical tail) should be considered.

Once the preferred analytical technique has been established, a fleet wide analysis of the WF MSDRS sensors should be conducted.

7. Conclusions

Two nominally independent analytical calibration techniques have been developed for each of the F/A-18 horizontal stabilator and wing fold MSDRS sensors. Repeatable and consistent results over different flying periods, with good statistical correlation values, were achieved for the candidate RAAF aircraft considered. Scaling factors were also calculated for Canadian Forces aircraft used in the IFOSTP spectra development.

These techniques will enable scale factors, defined as the ratio of the responses between two gauges positioned at nominally identical locations on different aircraft, to be calculated using operational MSDRS data. These results will allow comparisons between aircraft in terms of operational usage or against fatigue test results to be made.

8. Acknowledgments

This work was conducted under AIR Task 92/461. The authors wish to acknowledge the useful contributions and discussions held with FLTLT D. Trentin (ASIA-LC), and Messrs B. Aktepe, G. Habermann and D. Graham of AED AMRL.

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Appendix 1: Parameter Estimation from the MSDRS

Data used to calculate fleet aircraft scale factors can be extracted from the MSDRS FDS (Flight Data Set) files. Most of the required parameters are available directly from Code 46, albeit in some cases with different units to those used in this report. Some, however, need to be derived from other Code 46 parameters. The following derived parameters are required:

True angle of attack

- $AoA \text{ [deg]} = 1.131 * HUD AoA - 0.553$

Mach number

- $Mn = \frac{TAS}{[662 - 0.002423 * Altd]}$

Normalised vertical load factor

- $Nz \text{ [g]} = Nz@CG * \frac{A/c \text{ weight}}{32,357}$

: A/c weight [lb] = empty + fuel + stores

Compressible dynamic pressure

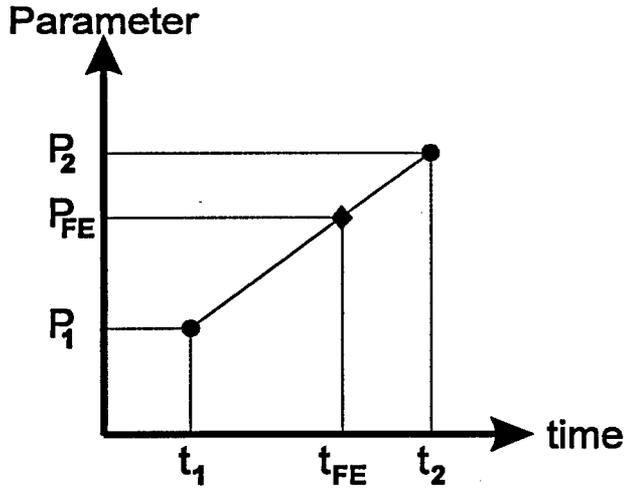
- $Q \text{ [in.Hg]} = P_{stat} * [(1 + 0.2 * Mn^2)^{3.5}] - 1] * 1.413855E-2$

: Assume ISA conditions

: $T \text{ [° K]} = 288 - 1.9812E-3 * Altd$

: $P_{stat} \text{ [lb/ft}^2\text{]} = 2116.2 * \left[\frac{T}{288} \right]^{5.63}$

All parameters are required to be time correlated. As fatigue events are triggered randomly upon encountering a peak/valley event, but Code 46 is recorded continuously, (ie at one of two frequencies, 1.0 Hz or 0.2 Hz), a form of linear interpolation is required in order to obtain an estimate of the respective Code 46 values at the triggered fatigue events. The method adopted in this report, is described by the following diagram:



Where :

- P₁ - Code 46 flight parameter.
- P₂ - Code 46 flight parameter.
- t₁ - time at P₁.
- t₂ - time at P₂.

- P_{FE} - Linearly interpolated Code 46 flight parameter
- t_{FE} - time at triggered fatigue event.

Therefore calculation of the P_{FE} value, either for a 1.0 Hz or 0.2 Hz Code 46 flight parameter can be determined, from a knowledge of the fatigue event time t_{FE}.

$$P_{FE} = (t_{FE} - t_1) * \left[\frac{P_2 - P_1}{t_2 - t_1} \right] + P_1$$

It should be noted that the EXTRACT software Ref [5] performs the above manipulations automatically.

Appendix 2 : Canadian Aircraft Scaling Factors

This appendix contains results of an analysis aimed at determining HS and WF scaling factors for the CF aircraft used in the IFOSTP spectra derivation. The scaling factors are determined using the methods derived in this report and also for comparison, from those specified in Ref [10 and 11].

Using the HS strain vs AoA calibration method presented in section 3.1.1, scaling factors were determined for all relevant CF aircraft, see Table A1.1.

- X - Slope of M33378/Q vs AoA [RHS]
- Z - Slope of M33377/Q vs AoA [LHS]
- X/32 - RHS Scaling Factor (with respect to aircraft A21-32)
- Z/32 - LHS Scaling Factor (with respect to aircraft A21-32)

Table A1.1 : CF Horizontal Stabilator Scaling Factors

| PRE-LEX : | | | | M33378 [RHS] | | M33377 [LHS] | | SCALING FACTORS | | |
|-------------------|-------|------|------|--------------|----------------|--------------|----------------|-----------------|------|------|
| Aircraft | Cfg | Flts | Pts | X (stdE) | R ² | Z (stdE) | R ² | X/Z | X/32 | Z/32 |
| 911 ¹¹ | all | 95 | 1253 | 15.5 (0.6) | 0.989 | 16.4 (0.3) | 0.997 | 0.95 | 0.65 | 0.69 |
| 911 | clean | 38 | 754 | 15.6 (0.9) | 0.971 | 15.7 (0.4) | 0.995 | 0.99 | 0.65 | 0.66 |
| 913 | all | 25 | 300 | 27.8 (2.5) | 0.958 | 27.1 (2.6) | 0.930 | 1.03 | 1.15 | 1.14 |
| 917 | all | 126 | 1391 | 24.7 (0.7) | 0.993 | 26.1 (0.8) | 0.993 | 0.95 | 1.02 | 1.10 |
| 917 | clean | 50 | 1163 | 24.7 (0.7) | 0.992 | 25.8 (0.7) | 0.993 | 0.96 | 1.02 | 1.09 |
| 920 | all | 19 | 68 | - | - | - | - | - | - | - |

POST-LEX :

| Aircraft | Cfg | Flts | Pts | X (stdE) | R ² | Z (stdE) | R ² | X/Z | X/32 | Z/32 |
|----------|-------|------|------|---------------|----------------|---------------|----------------|------|------|------|
| 732 | all | 29 | 53 | - | - | - | - | - | - | - |
| 780 | all | 79 | 670 | 24.6 (1.3) | 0.979 | 22.0 (1.2) | 0.979 | 1.12 | 1.02 | 0.93 |
| 925 | all | 17 | 77 | - | - | - | - | - | - | - |
| 940 | all | 117 | 1787 | 20.7 (0.6) | 0.994 | 19.1 (0.8) | 0.986 | 1.08 | 0.86 | 0.81 |
| 940 | clean | 35 | 984 | 21.3 (0.6) | 0.993 | 19.5 (0.8) | 0.984 | 1.09 | 0.88 | 0.82 |

RAAF ARDU [see Table 4]

| | | | | | | | | | | |
|--------|-------|----|------|------------|-------|------------|-------|------|------|------|
| A21-32 | clean | 17 | 2117 | 24.1 (0.5) | 0.992 | 23.7 (0.4) | 0.996 | 1.02 | 1.00 | 1.00 |
|--------|-------|----|------|------------|-------|------------|-------|------|------|------|

- Insufficient data

¹¹ Spindle Material different to other aircraft [HP9420 as opposed to AF1410]
MDA (Ref[20]) determined that AF1410 Scale Factor = 1.00
HP9420 Scale Factor = 0.74

Using the WF calibration method presented in section 4.2.1, scaling factors were determined for all relevant CF aircraft, see Table A1.2.

- Y - Slope of Wing Fold Strain (M15301) vs Nz (ie strain per g')
- Intercept - Regression intercept
- Y/32 - Scaling Factor with respect to aircraft A21-32 (AIM9 with fins)
- W/32 - Scaling Factor with respect to aircraft A21-32 (AIM9 no fins)

Table A1.2 : CF Wing Fold Scaling Factors

| PRE-LEX : | | | | M15301 [LHS] | | | SCALE FACTOR | |
|-----------|-------|------|------|--------------|-----------|----------------|--------------|-------|
| Aircraft | Cfg | Flts | Pts | Y(stdE) | Intercept | R ² | Y/32 | W/32 |
| 911 | all | 95* | 3599 | 103.5 (0.4) | -104 | 0.935 | 0.65 | 0.87* |
| | | | 1384 | 132.6 (1.3) | -138 | 0.900 | 0.83* | 1.11 |
| 913 | all | 25 | 379 | 148.5 (1.3) | -147 | 0.944 | 0.93 | 1.25 |
| 917 | clean | 50* | 621 | 164.7 (1.4) | -167 | 0.984 | 1.03* | 1.38 |
| | | | 800 | 119.2 (0.4) | -113 | 0.935 | 0.75 | 1.00* |
| 920 | all | 19 | 115 | 159.2 (2.2) | -157 | 0.954 | 1.00 | 1.34 |

POST-LEX :

| Aircraft | Cfg | Flts | Pts | Y(stdE) | Intercept | R ² | Y/32 | W/32 |
|----------|-------|------|-----|--------------|-----------|----------------|------|------|
| 732 | all | 29 | 176 | 129.8 (2.0) | -60 | 0.949 | 0.81 | 1.09 |
| 780 | all | 79 | 843 | 131.7 (0.74) | -150 | 0.949 | 0.82 | 1.11 |
| 925 | all | 17 | 196 | 119.0 (1.5) | -161 | 0.944 | 0.74 | 1.00 |
| 940 | clean | 35 | 522 | 131.5 (1.6) | -160 | 0.929 | 0.82 | 1.10 |

RAAF ARDU [see Table 8, also section 4.2.3]

| | | | | | |
|--------|---------------|--------------|------|-------|------|
| A21-32 | AIM9 and fins | 159.8 (0.32) | -187 | 0.959 | 1.00 |
| A21-32 | AIM9 no fins | 119.0 (0.52) | -94 | 0.989 | 0.74 |

* Data represented by two distinct bands [ie Confirmed by CF indicating AIM9 with and without fins]

* Consistent scale factor results achieved for Y/32 and W/32 AIM9 configurations.

Resulting WF scale factors indicate that the majority of flying has been conducted without AIM9 fins, with the exception of a number of flights for aircraft 911, 917 and 920.

Development of Analytical Techniques for Calibration of F/A-18 Horizontal Stabilator and
Wing Fold Strain Sensors

L. Molent, R.W. Ogden and Y. Guan Ooi

DSTO-TR-0205

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|---|-------------------------------|-----------------------------------|---|---|-----------------------------|
| DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA | | | | 1. PAGE CLASSIFICATION UNCLASSIFIED | |
| | | | | 2. PRIVACY MARKING/CAVEAT (OF DOCUMENT) | |
| 3. TITLE Development of analytical techniques for calibration of F/A-18 horizontal stabilator and wing fold strain sensors | | | 4. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (L) Title (U) Abstract (U) | | |
| 5. AUTHOR(S) L. Molent, R. Ogden and Y. Guan Ooi | | | 6. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001 | | |
| 7a. DSTO NUMBER TR-0205 | | 7b. AR NUMBER 009-333 | | 7c. TYPE OF REPORT Technical Report | |
| | | | | 8. DOCUMENT DATE August 1995 | |
| 9. FILE NUMBER M1/9/71 | 10. TASK NUMBER AIR 92/461 | 11. TASK SPONSOR RAAF - ASI-LC | 12. NO. OF PAGES 49 | | 13. NO. OF REFERENCES 20 |
| 14. DOWNGRADING/DELIMITING INSTRUCTIONS To be reviewed three years after date of publication | | | 15. RELEASE AUTHORITY Chief Airframes and Engines Division | | |
| 16. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT <p>Australian Department of Defence and Defence Force personnel and their equivalent in UK, USA, Canada and NZ may have access to this document. Others inquiring should be referred to Chief, Airframes and Engines Division, Aeronautical and Maritime Research Laboratory.</p> <p>OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE CENTRE, DIS NETWORK OFFICE, DEPT OF DEFENCE, CAMPBELL PARK OFFICES, CANBERRA ACT 2600</p> | | | | | |
| 17. DELIBERATE ANNOUNCEMENT Announcement of this report is unlimited | | | | | |
| 18. CASUAL ANNOUNCEMENT YES | | | | | |
| 19. DEFTEST DESCRIPTORS F/A-18 aircraft Folding wings Strain measurement Stabilators Detectors | | | | | |
| 20. ABSTRACT Two nominally independent analytical calibration techniques have been developed for each of the F/A-18 horizontal stabilator and wing fold "Maintenance Signal Data Recording Set" (MSDRS) sensors. Repeatable and consistent results over different flying periods, with good statistical correlation values, were achieved for the candidate RAAF aircraft considered. Scaling factors were also calculated for Canadian Forces aircraft used in the International Follow On Structural Test Program spectra development. These techniques will enable scale factors, defined as the ratio of the responses between two gauges positioned at nominally identical locations on different aircraft, to be calculated using operational MSDRS data. These results will allow comparisons to be made between aircraft in terms of operational usage or against fatigue test results. | | | | | |