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An Independent Check of the Performance of Two M2208 Fatigue Meters

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ABSTRACT

Aircraft Structural Integrity section of Directorate General Technical Airworthiness (ASI-DGTA) has concerns about the current accuracy of the ageing M2208 electro-mechanical fatigue meters fitted to RAAF P-3C and C-130H aircraft. An examination of relevant documentation was undertaken and tests performed on two meters, one deemed unservicable and the other fresh from an overhaul. The results of this investergation are presented and implications discussed.

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Executive Summary

The M2208 fatigue meter records the number of exceedances of a small number of pre-described "*g*" levels that the aircraft experiences during a certain period of flight. This data can then be used to estimate the amount of structural fatigue consumed during that same period of flight.

Over the past few years, the post-flight analysis routinely performed on M2208 fatigue meter readings has indicated there may be some reasons to doubt their accuracy. This doubt originated partly from a test, suggested by the manufacturer, where the ratio of readings on two of the counters (G4/G3 ratio) should fall within certain bounds and partly from comparison with data from recently installed electronic Structural Data Recording Set (SDRS) recorders (only fitted to a limited number of aircraft). These observations caused ASI-DGTA to instigate an investigation into M2208 meter performance and management. ASI-DGTA supplied two M2208 meters to DSTO for testing. One meter was designated as "unserviceable" and was to be "overhauled". The second meter had recently been "overhauled" and was soon to be installed on an operational aircraft. This report summarises some findings in characterising the performance of each meter and discusses the implications of this investigation.

The testing performed on the two M2208 meters indicated that both these meters would produce readings of questionable accuracy due to errors not easily detected using current operational testing procedures, i.e. monitoring the G4/G3 ratio. A basic analysis suggested that if the readings from the overhauled meter were employed as the sole source of fatigue life data, then the errors observed in this study may lead to an underestimation of aircraft life consumption by about 40%. Currently, operational readings from these M2208 meters are not used for executive airframe life analysis, but are only used in a "confidence building" capacity by comparing Nz exceedances measured to the Nz exceedance spectrums used in the executive life analysis. However the limited testing performed here, and the "wear and tear" expected with these types of electro-mechanical meters, would suggest that the meters are of limited value as a "confidence builder" since the exceedances measured will be erroneous. At this stage it is not clear that suitable performance could be obtained if a more systematic study of the performance of all meters was undertaken, and a revised robust calibration procedure was implemented.

Thus, although this study has indicated that the observed performance of the overhauled meter differed significantly from the original specifications, the impact of this discrepancy on the executive airframe life analysis is minimal given the current manner in which the data from these meters are used.

The limited testing performed has indicated that data from the meters cannot be relied on for any direct or indirect lifing requirements, without further significant effort. If, however, it were decided that a more accurate "confidence building" device was required, then an updated system option of installing a low cost acceleration monitor to the existing M2208 meters is recommended. If on the other hand that the life estimation procedures were to be modified to account for more accurate operational exceedance data, then the more expensive option of a total system refit would be recommended.

Contents

1. Introduction

There is a strong perception within the RAAF that the M2208 fatigue meters fitted to P-3C and C-130H aircraft are not performing as expected. To explore these perceived performance issues ASI-DGTA have instigated investigations into the logistical management, maintenance procedures and current performance of these meters. ASI-DGTA requested DSTO to provide S&T support for the fatigue meter performance investigations[1].

The M2208 fatigue meter itself is an ageing electro-mechanical device with a spring mass style accelerometer coupled via a fine chain to a commutator (rotary switch); this is used to control a set of flip flops[2] that in turn drive electro-mechanical counters. A preliminary investigation into the M2208 fatigue meter was undertaken in [1], and provided a review of the associated documentation, a proposed testing program on the performance of a limited number of meters and outlined some interim recommendations. This Technical Note presents the results of the testing program outlined in [1].

2. Definitions and terminology

The documentation pertaining to the M2208 meter employs the convention of referring to the meter when held upright and stationary as experiencing 1 *g*. Thus when the aircraft is experiencing a "POSITIVE" *g* situation, the activity is recorded on the counters with a threshold greater than 1 *g*. When experiencing a "NEGATIVE" *g* situation the threshold of interest will be less than 1 *g* (although not necessarily a negative number).

Each counter has two threshold levels associated with it. The "LOCK" threshold is the nominal exceedance level being recorded. The "RELEASE" threshold is the value through which the *g* level must return before another lock level exceedance can be counted.

3. Role of the fatigue meter

One component of airframe life is traditionally related to dynamic stresses induced from accelerations in the vertical direction. In days gone it was often expedient, to infer stress from a small number of binned measurements of vertical acceleration, as it was found practical to manufacture, install, service and operate summing binned accelerometers. This has led to the introduction of fatigue meter (or also known as "Nz meter"). Unfortunately stress is also a function of load weight and fuel load, particularly in a transport aircraft. Thus a set of forms are often employed to record flight conditions. Hence the accuracy of the estimate of life

[1] In relation to action on ASI3 outlined in reference [8], Sect 2, Chap 9, Pg 14, Par 72, Item h

[2] Two state logic devices, used as a one bit memory

consumption is dependent on many factors including reliability of manual data entry and management, and applicability of bin interpretation to actual service conditions.

In recent times MEMS accelerometers and solid state integrated circuitry, interpretation and recording techniques have become available making a drop in replacement possible with higher accuracy and lower maintenance requirements. Such a device however would still share many of the existing limitations.

If the problem were addressed with a clean slate in modern times, it is likely more direct data could be gathered, including for example, turning point data of relevant strains. A major issue here is that to gain maximum value from such data the interpretation and reporting mechanisms (and contracts) would require a major overhaul. The process would also involve considerable risk as electronic data recording devices are already fitted to some of the fleet and the amount of information obtained is far less than may reasonably be expected. This experience would indicate much care was required in both the selection and design of such a system.

4. The nature of the concern

Various discussions and documents have given the indication there may be a performance issue with the M2208 fatigue meters. The observations supporting this suspicion appear to include:

- Lack of tight correlation between data from M2208 and the data from more modern instruments[3] fitted to some aircraft
- Broader than expected spread of G4/G3 ratio. This is the ratio of exceedances recorded by the G3 counter (employing a nominal 0.75 *g* threshold) and those recorded by the G4 counter (employing a nominal 1.25 *g* threshold). This test (i.e. the G4/G3 ratio) is the prime basic functionality test recommended by the manufacturer.
    - Uncertainty as to cause of a perceived change in the rate of exceedances[4].

For example, section 3.1.10.2 of the RAAF P-3 Annual Fatigue Assessment, 1 February 2007 to 31 January 2008 states "…a review of the duality of the period exceedances data recorded by the P-3 fatigue meters is prudent" [4]. Also later in the same reference section 3.1.10.17 stated the follow recommendation "It is recommended a program to improve the quality of current fatigue meter data is implemented".

Since significant resources are consumed collecting and analysing the data from these meters, and given the data is intended as an input to airframe life consumption calculations, it may be

[3] E.g. SDRS system on a few selected P-3C

[4] Anecdotal trends noticed by ASI–DGTA and reported verbally to DSTO

expected that poor data quality is a serious problem. However the perception of poor data quality has prevailed for a long time and procedures have evolved to effectively reduce the role of M2208 data to a minor secondary confidence-building role, consequently the perceived "poor data quality" from the M2208 has very little real effect on the fatigue assessment. It is highly probable that it is uneconomic and of little technical merit to revise the airframe life management procedures at this late date to include fatigue meter data, even if any of the perceived issues were rectified.

5. Anatomy and operation of a M2208

Shortly after metal fatigue became a high profile issue, aircraft manufacturers and operators began fitting aircraft with instruments to measure the load cycles. The M2208 meter as shown in Figure 1 is a tried and true veteran of these attempts. Detailed schematics and specifications of the meter, taken from [2], are shown in Appendix A.

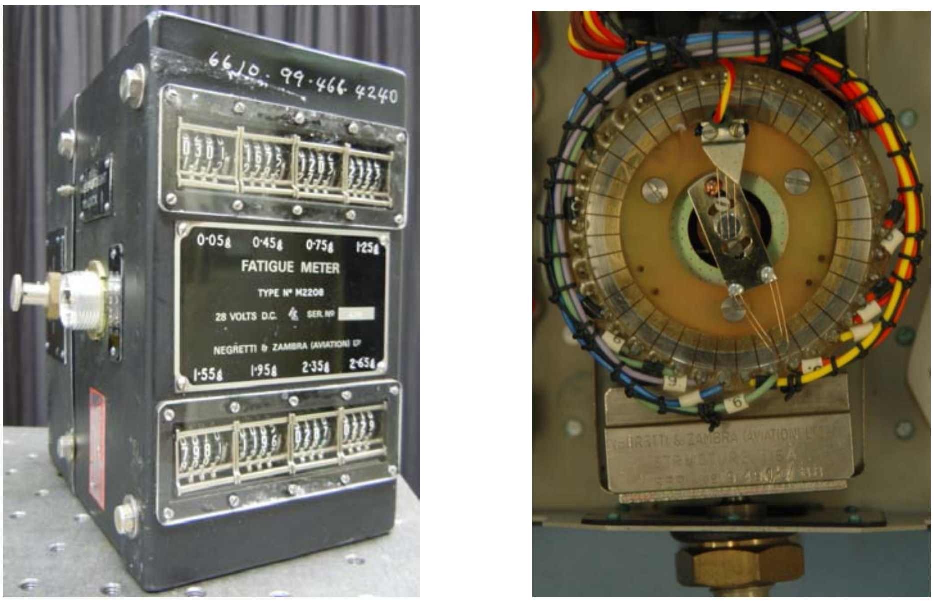


Figure 1 Photo of one of the M2208 meters tested (left), and type 15A accelerometer (right)

It contains a large mass suspended on springs, a mechanism to turn linear motion to rotary motion, a rotary damper, and a commutator[5] driving several flip flops in turn driving eight electro-mechanical counters. The commutator has several segments each corresponding to nominally 0.1 *g* of linear acceleration [2]. Selected segments of the commutator are wired to each counters flip flop to give it the required threshold levels.

The notional operation of the meter occurs when the "LOCK" threshold associated with a given counter is exceeded, the flip flop associated with that counter is set; when the

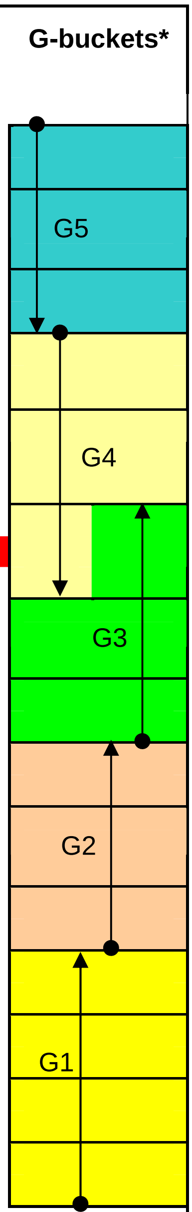
[5] Rotary switch

acceleration returns to below the “RELEASE” level for that counter, its associated flip flop is reset and the counter is incremented one count. The release threshold is selected to ensure the acceleration has significantly returned, and thus prevent rapid counting of very small changes in the region of the lock threshold. The “LOCK” and “RELEASE” levels for the first five buckets or bins are shown graphically in Figure 2.

As the intent is to measure accelerations associated with flight loads, it is common practice to apply power to the meter only when undercarriage is retracted, thus the meter only records counts when the aircraft is flying. After each flight the meter readings are recorded on an EE 360 form, these forms are sent to the contractor for collation and analysis.

A normal starting point for a device performance investigation would be the published specification. Unfortunately a definitive statement of the specified tolerance expected to be maintained between overhauls was not able to be located. The closest that could be obtained was an obsolete set of maintenance release limits discussed in the following section.

G-buckets	Lock *g*	Release *g*		Relative *g* level
G5	1.55	1.55		**+0.55**
	1.45	1.45		+0.45
	1.35	1.35		+0.35
G4	1.25	1.25	**G5**	**+0.25**
	1.15	1.15		+0.15
	1.05	1.05	**G3**	**+0.05**
	0.95	0.95	**G4**	**-0.05**
	0.85	0.85		-0.15
G3	0.75	0.75	**G2**	**-0.25**
	0.65	0.65		-0.35
	0.55	0.55		-0.45
G2	0.45	0.45	**G1**	**-0.55**
	0.35	0.35		-0.65
	0.25	0.25		-0.75
	0.15	0.15		-0.85
G1	0.05	0.05		-0.95



** each cell represents a 0.1 g segment of the commutator and the arrow represents the direction of the Nz count where the circle indicates the g-level at which the mechanism is locked (cocked) and the arrow is the g-level at which the mechanism is released (fired).*

Figure 2 A graphical representation of M2208 fatigue meter's lower lock/release bands (same colours refer to lock/release in a G-bucket and red indicates the nominal "zero" position)

6. Management of the M2208 meters

6.1 Maintenance regime

The manual suggests a storage life in a temperate climate of 2 years provided the unit is stored in sealed container with ¾ lb of silica gel[6]. Assuming the Z107 modification is fitted (as was the case with the sample meters) and the storage requirements were complied with, the manual[7] gives the meters overhaul period as 30 000 counts on any one counter or 2 years elapsed time, whichever occurs first. Recent data indicates that about 10 000 G4 exceedances occur every 1 000 flight hours, and on average a P-3C operates about 500 flight hours per year (based on a 3 months period, as shown in Table B.1 of reference [3]), thus it would be expected that the time clause (2 years) would be the most common trigger for scheduled maintenance.

6.2 In-service validation of functionality

The key in-service indicator of accuracy appears to be a check on the ratio between exceedances counted by the first positive (G4) and those counted by the first negative (G3) bins. The G4/G3 ratio may be influenced by mission type and climatic conditions but is the primary in-service method of monitoring meter integrity. For a given set of conditions, it is assumed that this ratio, and a related tolerance, can be reasonably estimated. When a meter is found having readings outside this tolerance[8], it is withdrawn for overhaul. The definition of the numeric values of these limits appears to be a matter of continuing discussion.

This criterion appears to have a high sensitivity to shift in the effective "zero" setting of the accelerometer, but will not necessarily highlight linearity or hysteresis issues.

It is interesting to note on the plots of G3 per AFHR vs G4 per AFHR (Figure A.3 Pg 6 of reference [3] and Figure 3.10 Pg 42 of reference [4]) that the readings from fatigue meters that fall outside the upper and lower G4/G3 limit, appear to have a greater number of records in the G3 bin than the G4 bin. This may reflect the calibration process, which stipulates G4 (i.e. first positive *g* bin) checks, employing a process that may introduce an effective systematic bias, but leaves G3 (i.e. first negative *g* bin) untested.

6.3 Workshop maintenance acceptance

The major workshop testing procedure appears to be mounting the unit on a centrifuge to produce pre-determined acceleration levels and monitoring the output of the commutator to observe accelerometer response. This type of test raises a few questions:

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[6] Reference [2], Sect 2, 31-10-1, Pg 15, Jan.16/74, Par 4 A and B

[7] Reference [2], Sect 2, 31-10-1, Pg 68, Apr.01/85, Par 14

[8] Current tolerance of the G4/G3 ratio appears to be 1.0 to 5.5 according to reference [4], Pg 41, Par 3.1.9.5

- Rate of change of acceleration

It is reasonable to assume that the loading rate achieved during this type of test is substantially lower than that nominally experienced in flight situations. This effect was previously observed by Nilson [5] when testing a different model fatigue meter (Appendix B refers to Figure 2 from reference [5]).

- Temperature

There appears to be a lack of measurements confirming meter precision over the range of temperatures that may be experienced in-service.

- Orientation

During workshop testing the meter is mounted on its side, thus its internal components are exposed to a non representative 1 *g* loading in a direction at right angles to the axis of interest; any effect this has on operation is neither measured nor accounted for.

- Hysteresis

The pass/fail criteria appear to consist of two clauses:

a. A limit on the scalar aggregate of low-to-high, and high-to-low threshold crossings for all positive thresholds.

b. A limit on the measured hysteresis of each positive threshold detector.

In-service it would be reasonable to assume, for positive *g* thresholds, the low-to-high threshold transitions were the only ones influencing the count values. However the calibration check appears to focus on the mean (low-to-high and high-to-low equally weighted) therefore for finite positive hysteresis values (by far the most probable situation) a systematic effective offset is introduced.

Table 1 in reference [6] illustrates a hysteresis limit (column "e") of 0.2 *g* for the M2208 unit. This would imply if the hysteresis was on the limit, the low-to-high threshold would be about 0.1 *g* high. This would equate to a 40% (relative to the straight and level 1 *g* value) offset in the G4 threshold.

The same reference gives a +/- 0.4 *g* limit for the sum of the positive and negative going threshold crossing measurements for the five positive *g* thresholds (1.25, 1.55, 1.95, 2.35 and 2.65). If the 1 *g* point was exact and the linearity was perfect, this would ensure a fairly tight uncertainty band, however it is difficult to guarantee either of these conditions.

It is interesting to note an earlier version of the manual [7] shown in Figure 3.

This appears to be much tighter than the current test limits. However it should be noted that this data refers to the 2208 fatigue meter fitted with a type M1840 accelerometer. Current documentation[9] states that the post Mod Z200[10] M2208 is equipped with a type 15-1026 accelerometer, of the basic type M2221. Visual inspection of meter with serial number A144 revealed it was equipped with a Type 15A accelerometer.

AAP 7053.002-1

d. MK 18 Type 2208 Fatigue Meter - Type M1840 Accelerometer

Threshold 'g'	Tolerance
-0.05	± 0.3 Segment = ± 0.03g
0.45	± 0.2 Segment = ± 0.02g
0.75	± 0.1 Segment = ± 0.01g
1.25	± 0.1 Segment = ± 0.01g
1.55	± 0.2 Segment = ± 0.02g
1.95	± 0.3 Segment = ± 0.03g
2.35	± 0.4 Segment = ± 0.04g
2.65	± 0.5 Segment = ± 0.05g

Figure 3 Hysteresis limit of 2208 meter from an earlier version [7]

7. Testing method

7.1 Test sample

Tests were performed on two meters

a. A nominally unserviceable meter, serial number: A144

b. A recently overhauled meter, serial number: AN 476

7.2 DSTO test method

Dynamic testing was performed on the complete instrument, mounted in a vertical orientation. The excitation applied was arranged to exercise all thresholds, however only the case of crossing the threshold in the direction of relevance to normal operation was considered in analysis.

[9] Reference [2], Sect 2, 31-30-36, Pg 1, Mar.31/88

[10] Same reference claims pre Mod Z200 were equipped with a type S2208-27 accelerometer

Some elements that the meter would be expected to experience in service are:

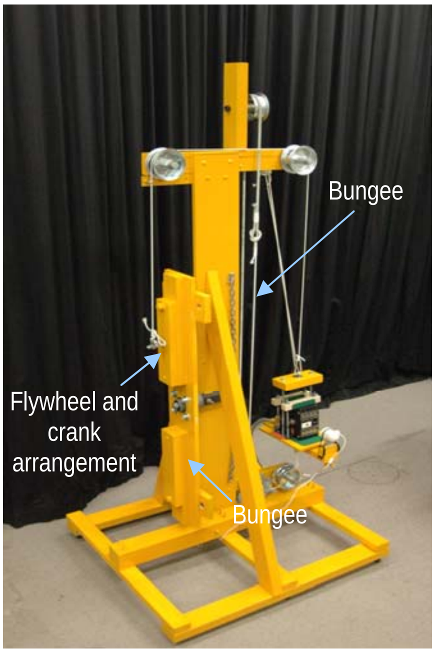
- Linear and rotary accelerations in various directions
- Variations in temperature
- Variations in power supply
- Variations in loading rates
- Variations in humidity

Resource limitations constrained testing to single axis, single temperature (room temperature, 23 °C), clean regulated electrical supply (25 V) and limited acceleration loading rates (maximum of 45 *g*/s). Each counter has two associated thresholds "LOCK" and "RELEASE"; the former being the nominal threshold of the counter, the latter being a value in the 1 *g* direction through which the acceleration must pass before the counter may be rearmed ready for the next count. Due to difficulties with observability in a closed box test, only the "LOCK" threshold was measured.

Thus the tests may be expected to have a broader coverage of factors influencing operation than test procedures outlined in the maintenance manual, but the coverage was still very limited.

The manual indicates testing should be limited to avoid unnecessary wear on the mechanism. Therefore an attempt was made to develop testing and analysis procedures, to obtain the required amount of data with minimal wear on the meter.

The initial thought was to test the meter using an electromagnetic shaker, however the stroke needed to produce the required accelerations (*g*-levels), within the specified rate of change of *g* constraint proved difficult to achieve with the available devices. Thus initially, for the lower *g*-levels a servo-hydraulic test machine was employed to provide the appropriate motion. This had the benefit of being rapid to set up and use, but still had insufficient stroke to obtain the higher *g*-levels. Thus a special "Long Stroke" rig was constructed to achieve both high and low *g* loading, with appropriate stroke in the one rig, so the meter did not need to be moved between rigs.



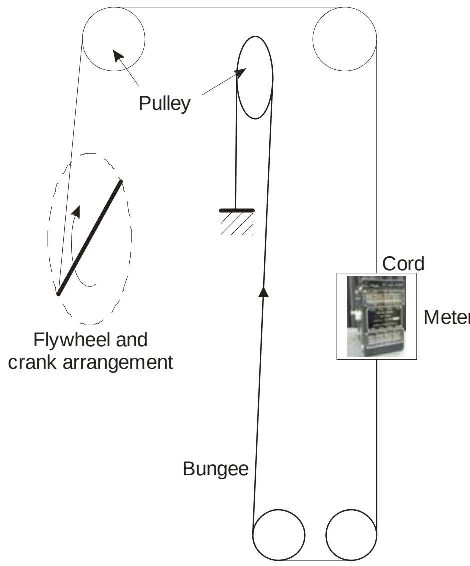


Figure 4 Photograph (left) and schematic (right) of the experimental Long Stroke test rig used (<<7 Hz, >2.65 g, <45 g/s)

The specially designed and manufactured Long Stroke rig, employing a large rotary inertia mechanism to limit rate of change of acceleration and a long vertical linear travel to achieve the maximum desired acceleration while accommodating the maximum permitted rate of change of acceleration. An image and a schematic of the mechanism of the rig in Figure 4 shows the effective flywheel and crank on the left of each image, with a system of pulleys and cords to translate rotary to linear motion, and the return bungy is to the right of the centre column. A series of runs were performed with the crank at various initial angles producing a set of semi random excitation levels.

The actual acceleration experienced by the meter was recorded on an independent accelerometer and images were recorded of the counters on three occasions for each run, viz., before the run with the meter powered up and, then after the run with the meter powered up and with the power removed. The final picture, with the power removed, is used to determine whether the counters were armed at the end of the run. The count was taken with the power removed because if the Lock threshold had been exceeded without the release being subsequently exceeded then the meter will remain in the armed state and the meter will not record the event until power is removed.

7.3 Implications of DSTO test method on experimental results

The maintenance manual test procedure carefully measures the hysteresis, and then takes the mean as the working value. In service the meter always operates on the same edge of a given threshold detector. Thus, half the hysteresis value is a potential systematic calibration aberration. To avoid this issue the DSTO test method only employed transition crossings in the active direction.

As previously mentioned the test method prescribed in the maintenance manual employs very low rate of change of acceleration, whereas the DSTO testing employed significant rates of change (still well within the maximum rate of change in the meter specifications). It is possible that damping[11] and friction effects will thus influence readings.

During testing at DSTO the device was mounted in a vertical orientation, whilst the centrifuge test requires the meter to be rotated 90°. As the meter contains several fine mechanical components, it is possible that this has a subtle influence on performance.

8. Test results and their interpretation

8.1 Test results

Figure 5 shows a typical acceleration trace produced by the Long Stroke rig and Figure 6 shows the rate of change of acceleration is well within the 45 *g*/s instrument specification.

Both meters appeared to be free from external damage and superficially operating in the correct manner. The measured threshold values are tabulated in Table 1 and displayed graphically in Figure 7. When calculating the deviation (or error) in Table 1, two values were calculated (1) absolute deviation relative to 0 *g* and (2) the relative deviation where the straight and level flight (1 *g*) condition was taken as the reference condition. Thus the percentage deviation was calculated and displayed graphically in Figure 8, which illustrates the symmetry in the G3 and G4 deviations.

[11] Reference [2], Sect 2, 31-30-36, Pg 710, Mar.31/88 suggests a drag cup style, magnetic eddy current damper is employed, and as the instrument predates the common availability of rare earth magnets it is possible the (intentionally induced component of) damping may change with age.

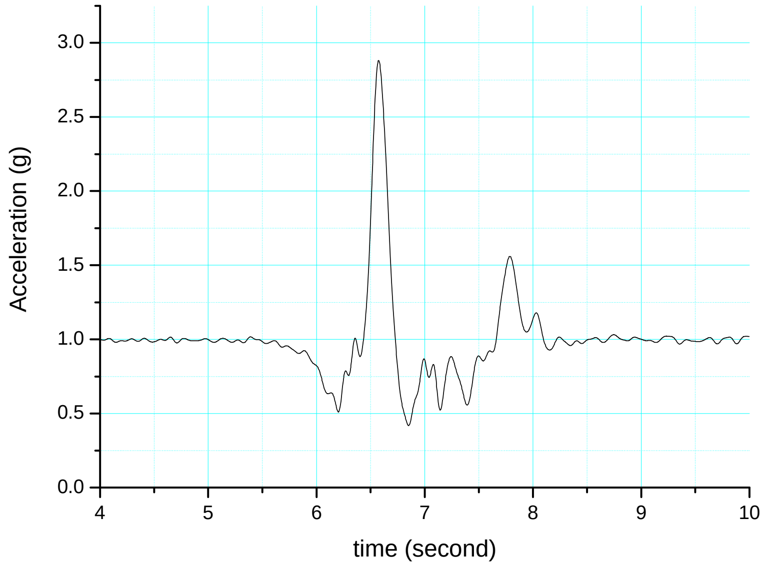


Figure 5 Typical trace of g produced by Long Stroke rig

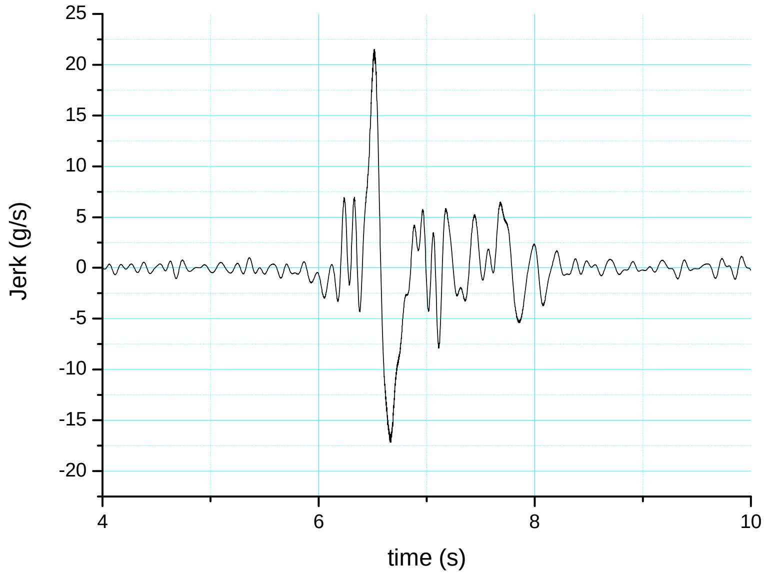


Figure 6 Typical trace of g/s produced by Long Stroke rig

It is interesting to note that this method of testing indicated the recently overhauled instrument had a larger discrepancy from the nominal threshold values for all counters. However, as the deviation on the G3 and G4 counters was of a similar magnitude for the overhauled instrument, it may be expected to perform considerably better on a G4/G3 test than the nominally unserviceable meter where G4 was high but G3 was fairly close to ideal value.

Table 1 Measured Lock thresholds

M2208 FATIGUE METER						
	S/N:A144 (Unserviceable)			S/N: 476 (Overhauled)		
	Measured lock G	% Deviation relative to 1 *g*[12]	% Deviation relative to 0 *g*[13]	Measured lock G	% Deviation relative to 1 *g*	% Deviation relative to 0 *g*
G1 (Lock:0.05 / Release:0.45)	0.03	2	**-40**	-0.22	28	**-540**
G2 (Lock:0.45 / Release:0.75)	0.45	0	**0**	0.31	26	**-31**
G3 (Lock:0.75 / Release:1.05)	0.72	11	**-4**	0.62	51	**-17**
G4 (Lock:1.25 / Release:0.95)	1.36	45	**9**	1.40	61	**12**
G5 (Lock:1.55 / Release:1.25)	1.66	20	**7**	1.70	27	**10**
G6 (Lock:1.95 / Release:1.45)	2.09	15	**7**	2.10	15	**8**
G7 (Lock:2.35 / Release:1.55)	2.52	13	**7**	2.57	16	**9**
G8 (Lock:2.65 / Release:1.85)	2.71	4	**2**	3.02	22	**14**

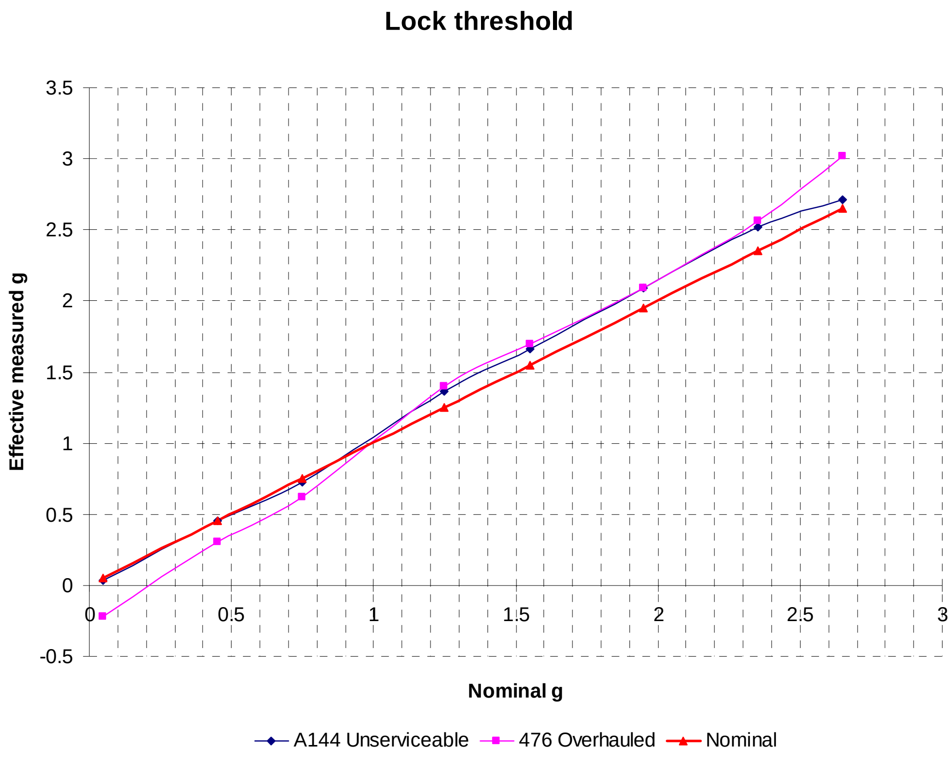


Figure 7 Measured lock threshold levels

[12] [[(Lock g threshold$_{measured}$ – 1 *g*) - (Lock g threshold$_{specified}$ – 1 *g*)] / (Lock g threshold$_{specified}$ – 1 *g*)] x 100
[13] [(Lock g threshold$_{measured}$ – Lock g threshold$_{specified}$) / Lock g threshold$_{specified}$)] x 100

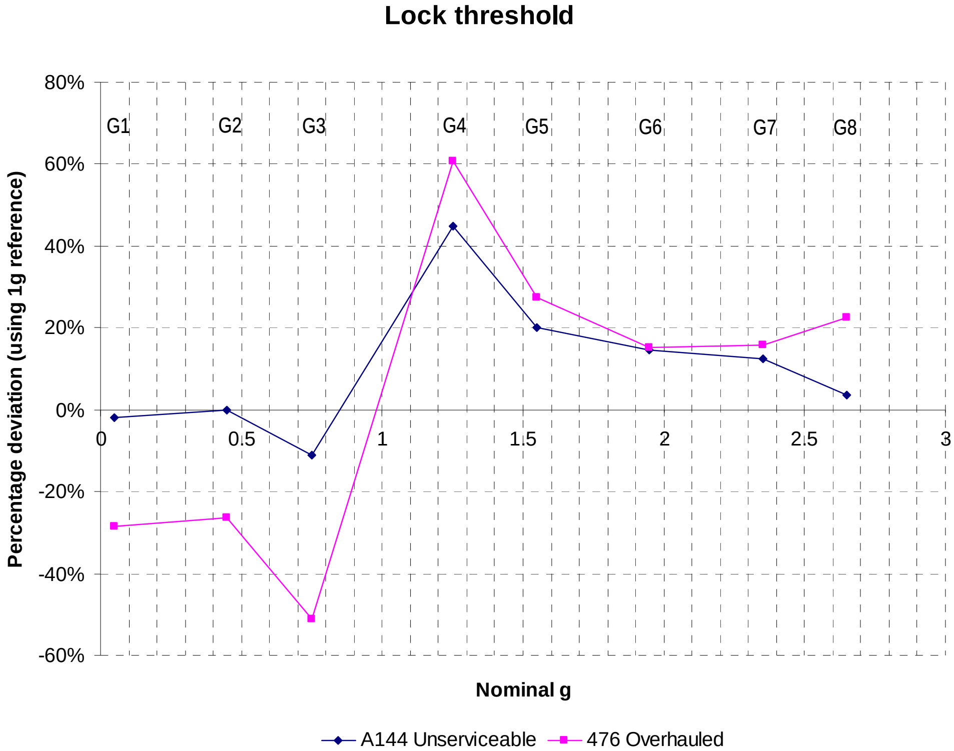


Figure 8 Percentage deviation (using 1 g as the reference)

8.2 Discussion of results

8.2.1 Correlation with operational observations

It can be seen from the measured "LOCK" thresholds, the variation in meter threshold induced contribution[14] to the G4/G3 count ratio is 3.67 for the unserviceable meter, and 1.15 for the overhauled meter. As these errors are considerable, they could be expected to consume a large amount of the allowable G4/G3[15] error ratio. As the errors for the overhauled meter almost cancel each other out, the sensitivity of the G4/G3 test, is low in this case, even though absolute error value are large. In other words, the unserviceable meter will see about the same G3 counts (G3 lock threshold decreased slightly from 0.75 *g* to 0.72 *g*) but less G4 (G4 lock threshold increased from 1.25 *g* to 1.3 6 *g*) thus tending to lowering G4/G3 ratio, whereas the overhauled meter will see less G3 counts (G3 lock threshold decreased from 0.75 *g* to 0.62 *g*) and less G4 (G4 lock threshold increased from 1.25 *g* to 1.4 *g*) thus tending to keep the G4/G3 constant.

It is interesting to speculate that employing the average of threshold crossings in both directions in the calibration process[16] could potentially introduce a systematic bias to higher

[14] G4/G3 ratio is dependent on the spectrum applied to the meter. The actual G4/G3 ratio will be a function of aircraft usage as well as meter characteristics.

[15] Current tolerance of the G4/G3 ratio appears to be 1.0 to 5.5 according to reference [4], Pg 41, Par 3.1.9.5

[16] As called for in the current maintenance procedures [6]

than desirable actual lock threshold settings (for $g > 1$, in presence of hysteresis). This would be consistent with the measurements taken on the two sample meters. It would also be consistent with the lower than expected count rates reported in a relatively recent usage summary report[17].

This hypothesis may in part also explain the comment in section 3.1.10.8 of reference [4] "In two cases… when a fatigue meter was repaired or replaced, the replacement meter was faulty as well". It is also consistent with the observation "for the flights matched to SDRS flights only recorded 35 percent of the positive Nz exceedances that the SDRS system recorded" found in section 3.2.6.3 of same reference.

8.2.2 Nature of discrepancies

As noted the test technique employed minimised the number of exceedances the meters were exposed to, and thus did not provide solid statistical information on missed counts (the limited sample size of two meters would also have precluded meaningful quantitative missed count results). However during the limited testing undertaken, there was no observed indication of counters failing to operate, it appeared that the problems were associated with bias, linearity, variability and rate dependence in the accelerometer subassembly, although no attempt was made to verify this inference.

8.2.3 Acceptability of discrepancies

As mentioned earlier, the supplied meter literature gave no definitive direct statement of expected service accuracy. The closest guidance appeared to be the post overhaul testing tolerance mentioned above and the in-service G4/G3 count ratio.

The data analysis contractor appears to have developed a tolerance of 1 to 5.5 stated in [4] in 2008 and 1 to 5.0 in [3] in 2009 for the in-service G4/G3 ratio. This may be useful, but it is only an indication of one aspect of meter performance and not a direct measure of meter accuracy. Naturally these figures are a function of accelerations experienced by the aircraft and thus, not able to be independently and directly related to a tolerance on meter threshold levels.

Thus although the test results indicate significant deviations from ideal, it is not a simple matter to declare them acceptable or unacceptable. In an attempt to throw some light on their significance, a simple indicative sensitivity check was attempted.

8.3 Potential significant of test results

Firstly and most importantly, it should be re-emphasised that the implications of the above results for the overhauled meter for P-3C aircraft life estimate outcomes are qualified by the fact that the meter readings appear not to feed directly into the life consumption estimates since Nz meter readings appear to be employed mainly as a confidence builder.

[17] Table 3.8 and Figure 3.22 of reference [4]

Secondly, in December 1966 S. I. Nilsson [5] performed a more extensive test program on a different type of fatigue meters and concluded: "The drift of actual threshold with time appears random". If this observation is correct and if it could be applied to the M2208, then over the life of a single aircraft, drifts in thresholds may be expected to cancel out to some extent, although the non linear fatigue relationship would potentially still lead to a life estimate error. This situation would naturally not apply to any systematic component fault, such as that introduced by an inappropriate calibration procedure or mechanical component wear.

Temporarily putting these considerations aside, the question of sensitivity of airframe life estimates, to an error in threshold level, has been raised; it was therefore deemed prudent to attempt to address this issue.

8.3.1 Estimate a life consumption in terms of "*g*" level exceeded

The chosen technique was to:

- Estimate a life consumption of each positive "*g*" level peak
- Estimate the distribution of positive "*g*" peaks
- Combine the two results to derive a curve of estimated damage in terms of "*g*"
- Integrate the area under the ideal to measured threshold interval, to determine significance of discrepancies in terms of "*g*"

As the aim was to obtain an indicative sensitivity relevant to current fleet utilisation, many simplifications, assumptions and limitations were employed, these include:

- Assuming relevant damage may be explained exclusively by values in top five (G4-G8) counters (Note: These counters are the ones calibrated in existing procedures)
- Ignoring all trough values
- Ignoring effects of variation in loading

The approach is naturally a massive over-simplification of aircraft lifeing, but chosen as presenting an easy to follow, workable simple approximation. In this discussion the term peak shall be used to refer to an upper (most positive) turning point (point of inflection) in a stress or acceleration waveform. The term "*g*" is used to represent acceleration in the z (vertical) direction.

High stress areas of the P-3 Orion are predominantly manufactured from 7075 (or similar) aluminum alloy [8][18]. Approximating an expression to the S-N data for this material presented by Mongru et al [9][19] gives

[18] Reference [8], Sect 2, Chap 1, Pg 1, Par 7

[19] Reference [9], Chap 5, Pg 25, Figure 17

$$S \sim 95 * N^{-0.17} \qquad (1)$$

where S is the stress in ksi and N is the number of loading cycles.

A plot of this expression is included as Figure 9.

Although Figure 9 is the conventional form, in this case it is more convenient to swap the axies, as in Figure 10, and express N in terms of ksi as below

$$N \sim (S/95)^{-5.88} \qquad (2)$$

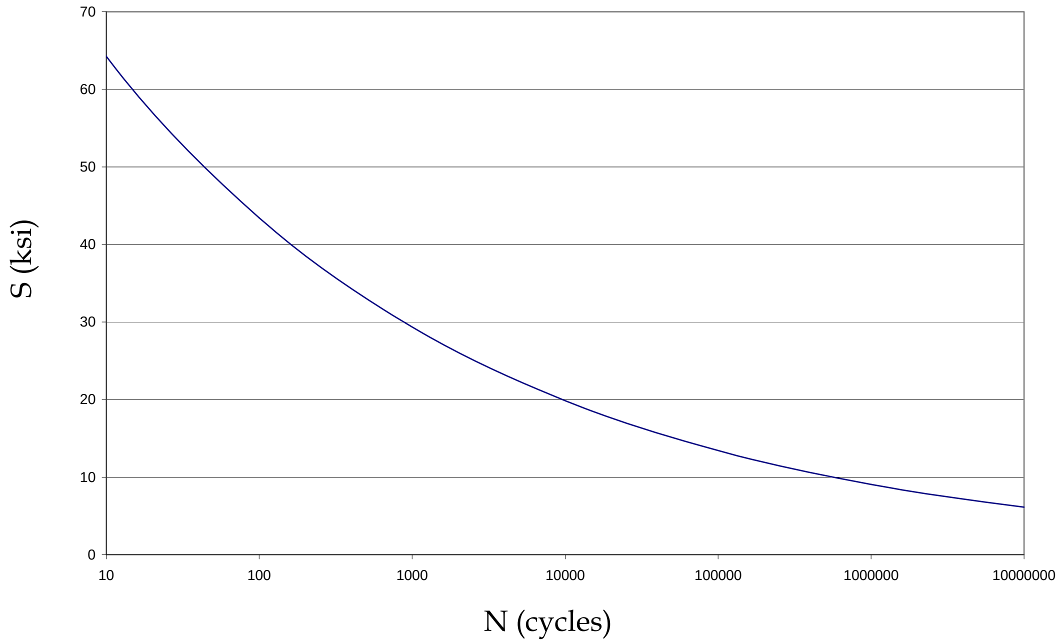


Figure 9 S-N curve for material in fatigue critical regions

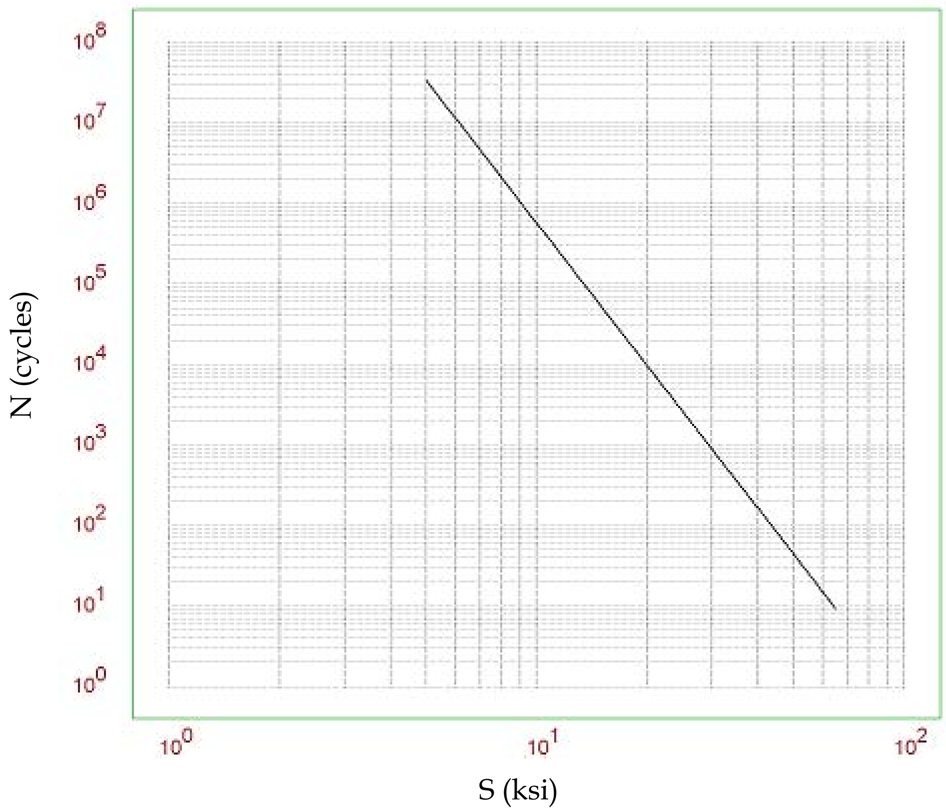


Figure 10 S-N from Figure 9 with axes swapped

Assuming a constant linear ksi/*g* ratio, finding a workable numeric value should allow the substitution of ksi with *g*[20].

Results published by Mongru et al [9][21] suggest a maximum stress in fatigue critical areas on the wing (FCA352 & FCA361) of about 20 ksi (for both RAAF AP-3C and RAAF P-3C spectrums). Using this maximum stress level and the 3 *g* positive acceleration limit indicated in [8][22], an approximate effective ksi/*g* value of 6.66 is therefore inferred. If this value is employed in the equation (2) a relationship along the lines of Figure 11 is the result.

[20] Suitable only for use across whole fleet for reasonable period of time

[21] Reference [9], Chap 3, Pg 13, Figure 5 and 6

[22] Reference [8], Sect 2, Chap 2, Pg 3 and 4, Par 20

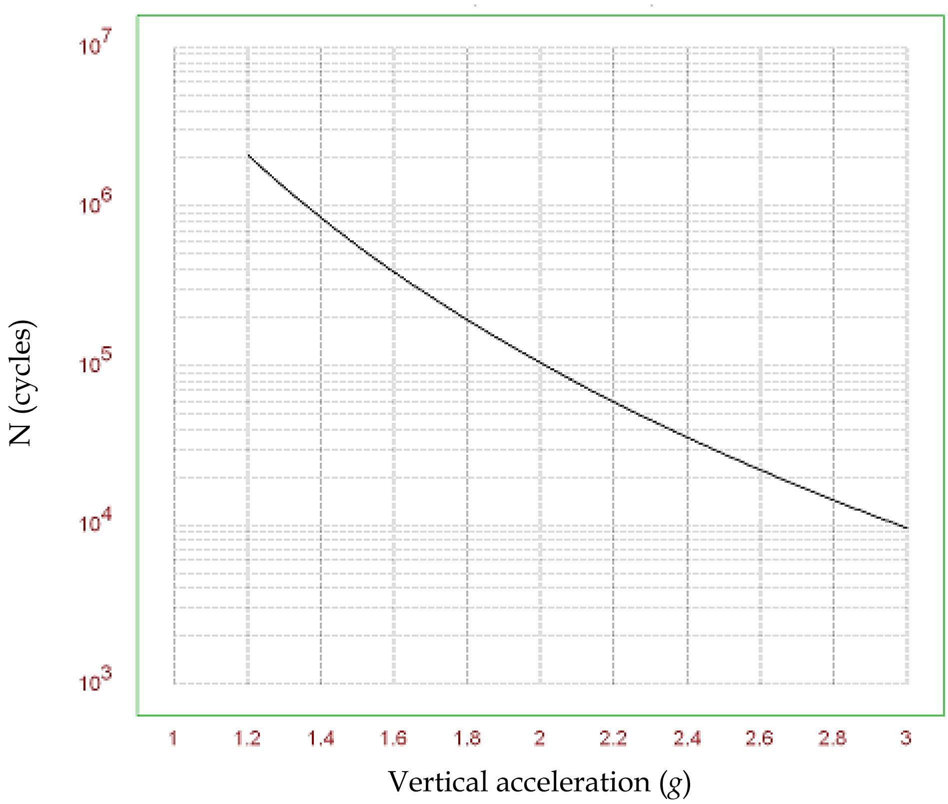


Figure 11 Cycles to failure in terms of vertical acceleration, g, using equation (2) and a stress to g value of 6.66 ksi/g

The Palmgren-Miner damage hypothesis would suggest inverting this expression would yield the fraction of life consumed by a single cycle of the given amplitude. As fatigue meters give minimal indication of the distribution or depth of "trough" points, they will be ignored for this exercise[23].

Assuming the "SLEP II Nz Exceedances per 1000 AFHRS Scaled to Period Mission Mix" as the "typical" fleet exposure, see [4][24], and the exposure to *g* over the acceleration range of interest is a simple smooth curve, then the distribution of positive exceedance values are expected to take an approximate distribution shown in Figure 12. This distribution can be expressed as

$$\text{Exceedances}/1000\text{AFHRS} = 200\,000\, g^{-11} \qquad (3)$$

The influence of release values makes it difficult to determine a precise expression (in the absence of much more detailed loading information), but this is probably a suitable working approximation.

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[23] An approximation made for convenience in estimating meter sensitivity, that would admittedly be problematic if used in a real life estimation

[24] Reference [4], Pg 111, Table B.4

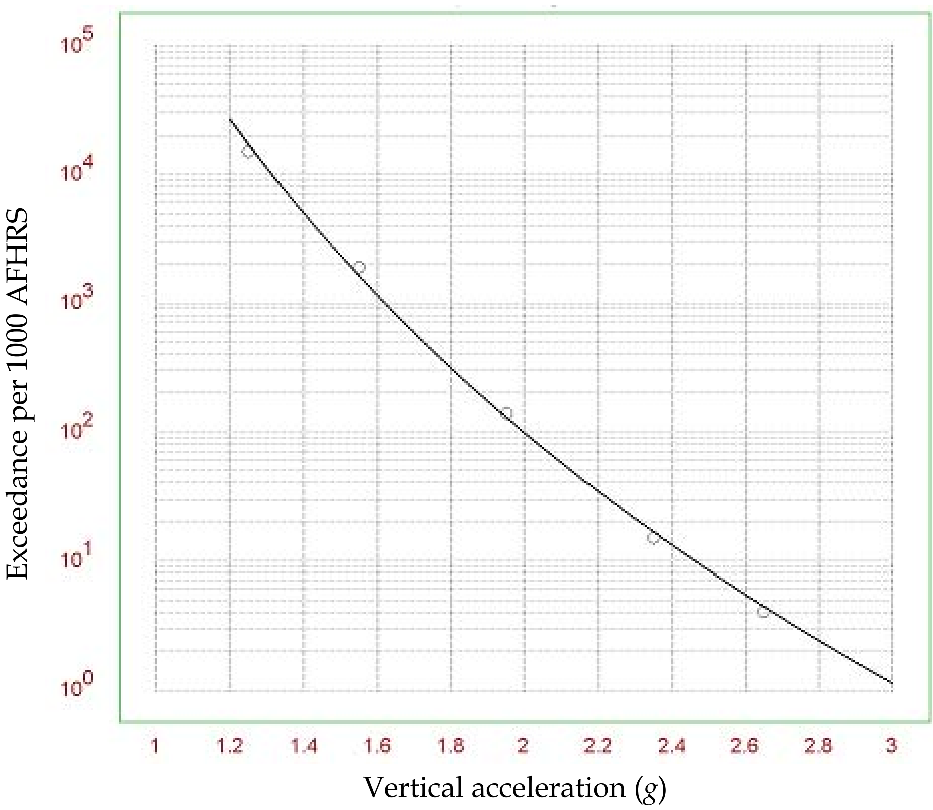

Figure 12 Reported exceedances (circles represent data points from [4]) with increasing g

As this curve is exceedances and not peaks, a point on this curve represents the sum of all the peaks to the right of it, thus the peak distribution would thus be the derivative of this curve, as shown in Figure 13.

If now the derivative of equation (3) is treated as being linearly related to a probability of peaks, and it is multiplied by the previously obtained life consumption of peaks, derived from the inverse of equation (2), and normalised, an estimate of the expected consumption in terms of "*g*" can be derived and is shown in Figure14. This figure gives an estimate of significance of life consumption between different values of *g* of the meter. For example a meter reading of 1.2 *g* is almost twice as significant as a reading of 1.35 *g*. Clearly Figure 14 indicates that errors in the lower G counters are most significant (i.e. G4 is more significant then G5, and G5 is more significant then G6 etc).

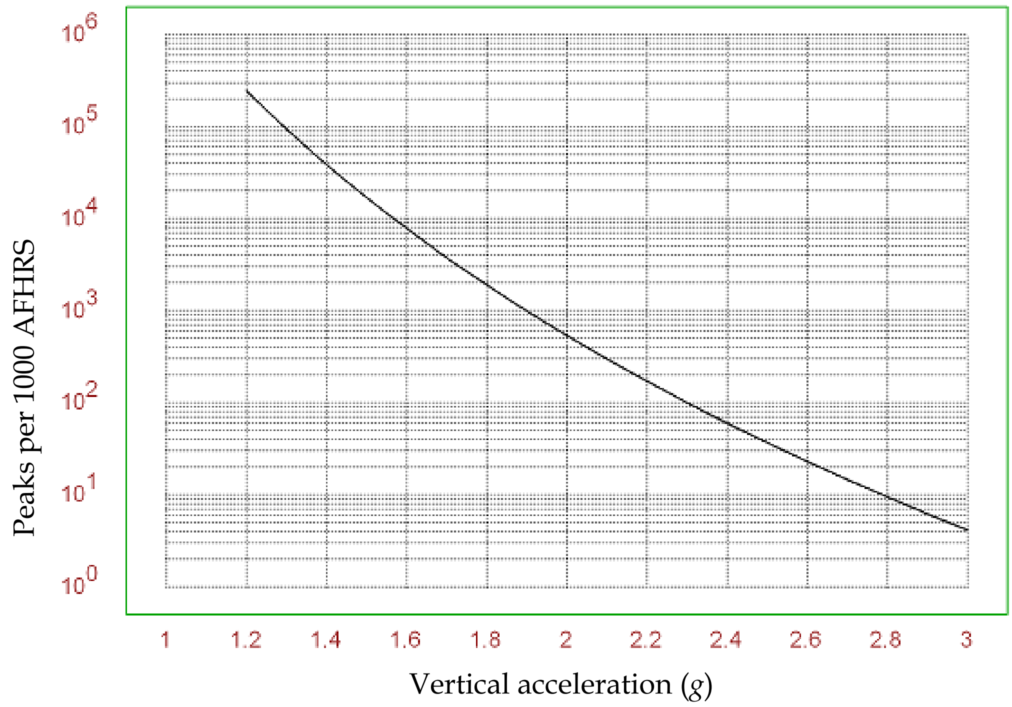

Figure 13 Estimate of distribution of loading peaks with increasing g

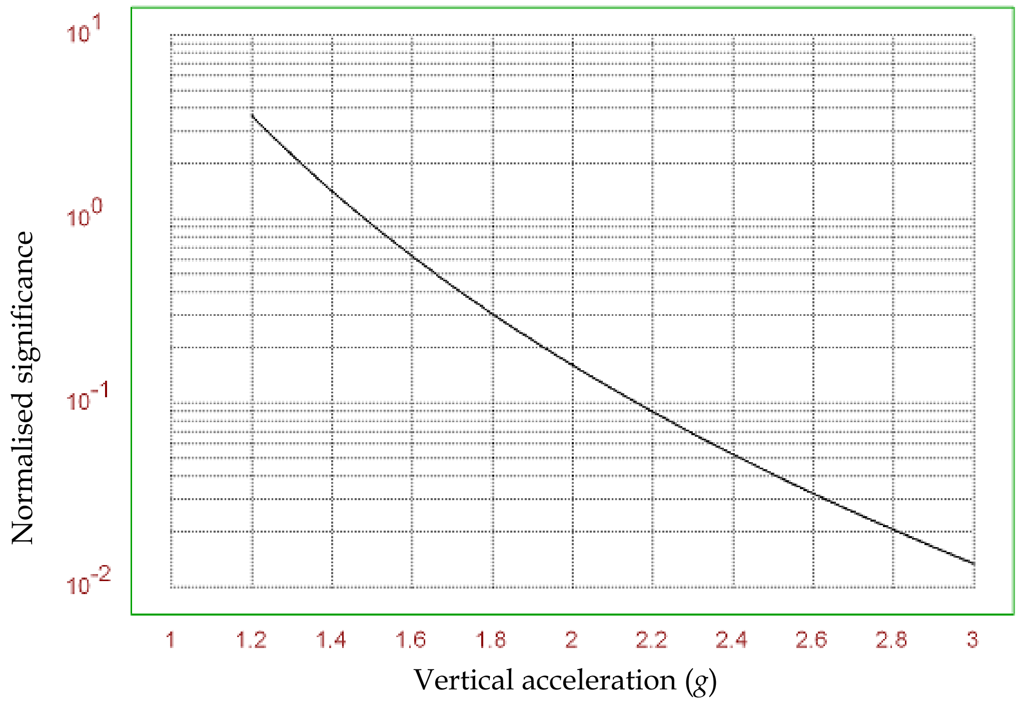

Figure 14 Normalised significance of peaks (derived from Nz exceedances curve and life consumption curves for 7075 aluminium alloy)

Comparing the ideal and measured threshold values indicates the "unserviceable" meters readings (i.e. where the meter is actually measuring 1.36 *g* compared to expected 1.25 *g*) would indicate a life consumption about 30% less then that from an ideal meter, while the recently "Overhauled" unit (i.e. where the meter is actually measuring 1.4 *g* compared to expected 1.25 *g*) would lead to a reduction of about 40% from that measured using an ideal unit. Consequently, if the meter readings were used to estimate life consumption, then the errors observed in both the unserviceable and the overhauled meters would result in an un-conservative estimate of fatigue life.

8.3.2 Reliability of influence estimation technique

The analysis undertaken above used the SLEP II Nz loading profile. If a much lower number of low threshold counts had been employed, the higher threshold levels would presumably have gained more significance. However, the general impression would remain similar.

9. Potential future actions

As noted above, the impact of meter measurement inaccuracies is minimal and insignificant, due to the fact that operational readings from these M2208 meters are not used for executive airframe life analysis, but are only used in a "confidence building" capacity by comparing Nz exceedances measured to the Nz exceedance spectrums used in the executive life analysis.

However inaccuracies were observed and a number of potential courses of action have been identified below:

9.1 Do nothing

In this case, it is difficult to imagine how accepting a fair degree of uncertainty in the M2208 readings, could have any adverse impact on safety, cost, availability, or capability.

9.2 Update existing instrument/procedures

9.2.1 Update procedures

Considering the results obtained in this study from a very limited number of meters and an understanding of the current calibration procedures from maintenance documentation [2], it is not clear that suitable performance could be obtained if a more systematic study of the performance of all meters was undertaken, and a revised robust calibration procedure was implemented.

9.2.2 Update instrument

The instrument could be modified to use a modern accelerometer that would have a high probability of maintaining its reading accuracy for long periods of time. Such a modification in a minimal implementation may simply involve incorporating a modern compact electronic device, on or in the M2208 fatigue meter, with MEMS accelerometer and electronics to record acceleration time history and G-bucket data. This would limit procedure and documentation modifications to those involving maintenance procedures only, whilst the operational procedures and documentation would remain identical. Installation could be performed during regular M2208 meter removal/replacement actions. In this case, the acceleration data collected from each aircraft would be used as a confidence building exercise, as is the current approach, when calculating life consumption estimates for each tail number.

9.3 Update total system

This option would involve a substantial contract, adding considerable cost and effort with associated long lead times for specification development, procedure development, validation and authorisation, system acquisition and installation. In this case, any improvement in information quality would be so late in the airframe life that it, could be argued, would have very limited value. It is also assumed that a program to substitute the M2208 with an updated electronic Nz meter would also require a parallel program to allow for direct input of the more accurate exceedance data into the procedure for calculating P-3C life consumption estimates.

10. Recommendations

In view of the fact that;

- most aircraft equipped with these devices have already consumed a significant component of their fatigue life, and obtaining a slightly more accurate measurement of the limited amount remaining would not have a major impact on the overall life estimate;

- more accurate readings would have absolutely no effect unless life estimating procedures were considerably modified, and this is likely to be an expensive process; and

- the aircraft would be close to retirement before useful data was obtained from a substantial refit program;

it would appear the "do nothing" option would best fit the current circumstances.

If, however, it was decided that a more accurate "confidence building" device was required as soon as possible, then the system update option of installing a low cost acceleration monitor to the M2208 meter is recommended. If the life estimation procedures were to be modified to account for more accurate operational exceedance data, then the more expensive option of a total system refit would be recommended.

Should an update be deemed appropriate, it would be prudent to thoroughly examine the effective in-service performance of the existing SDRS system, together with all factors influencing cost and workload in obtaining airframe life consumption estimates. As mentioned earlier, measuring and binning vertical acceleration was performed as a matter of expedience in the 1960s, other measurements may be more appropriate today (consequently reducing reliance on manual data recording, entry and processing).

11. Conclusion

The variable frequency closed box style testing performed in this study on two M2208 meters indicated these meters may produce readings of questionable accuracy due to errors not easily detected using current operational testing procedures of monitoring the G4/G3 ratio.

When comparing the measured lock thresholds to the nominal lock thresholds, for the positive *g* counters, using a reference value of 0 *g*, the observed discrepancy varied between about 2% to 14% of the nominal value for both meters. A basic analysis of the significance of meter readings with fatigue consumption suggested that if the positive readings from the overhauled meter were employed as the sole source of fatigue life data, then the errors observed in threshold values in this study may lead to an underestimation of aircraft life consumption by about 40%.

Currently, operational readings from these M2208 meters are not used for executive airframe life analysis, but are only used in a “confidence building” capacity by comparing Nz exceedances measured to the Nz exceedance spectrums used in the executive life analysis. Thus, although this limited study has indicated that observed performance for the overhauled meter differed significantly from the original specifications, the impact of this discrepancy is minimal given the current manner in which the data from these meters are used. The limited testing performed here, and taking into account the continual “wear and tear” expected with these types of electro-mechanical meters, would suggest that the meters are of limited value as a “confidence builder” since the exceedances measured will be erroneous. At this stage it is not clear that suitable performance could be obtained if a more systematic study of the performance of all meters was undertaken, and a revised robust calibration procedure was implemented.

The limited testing performed has indicated that data from the meters cannot be relied on for any direct or indirect lifing requirements, without further significant effort. If, however, it were decided that a more accurate “confidence building” device was required as a priority, then an updated system option of installing a low cost acceleration monitor to the M2208 meter is recommended. If on the other hand the life estimation procedures were to be modified to account for more accurate operational exceedance data, then the more expensive option of a total system refit would be recommended.

12. Acknowledgments

The authors would like to thank the staff at DGTA for their efforts in sourcing the meters for testing, and related documentation. The authors also acknowledge the efforts of Chris Rider for evaluation of shaker testing and accelerometer calibration. Thanks must also go to Leigh Conder for developing the acceleration measuring equipment.

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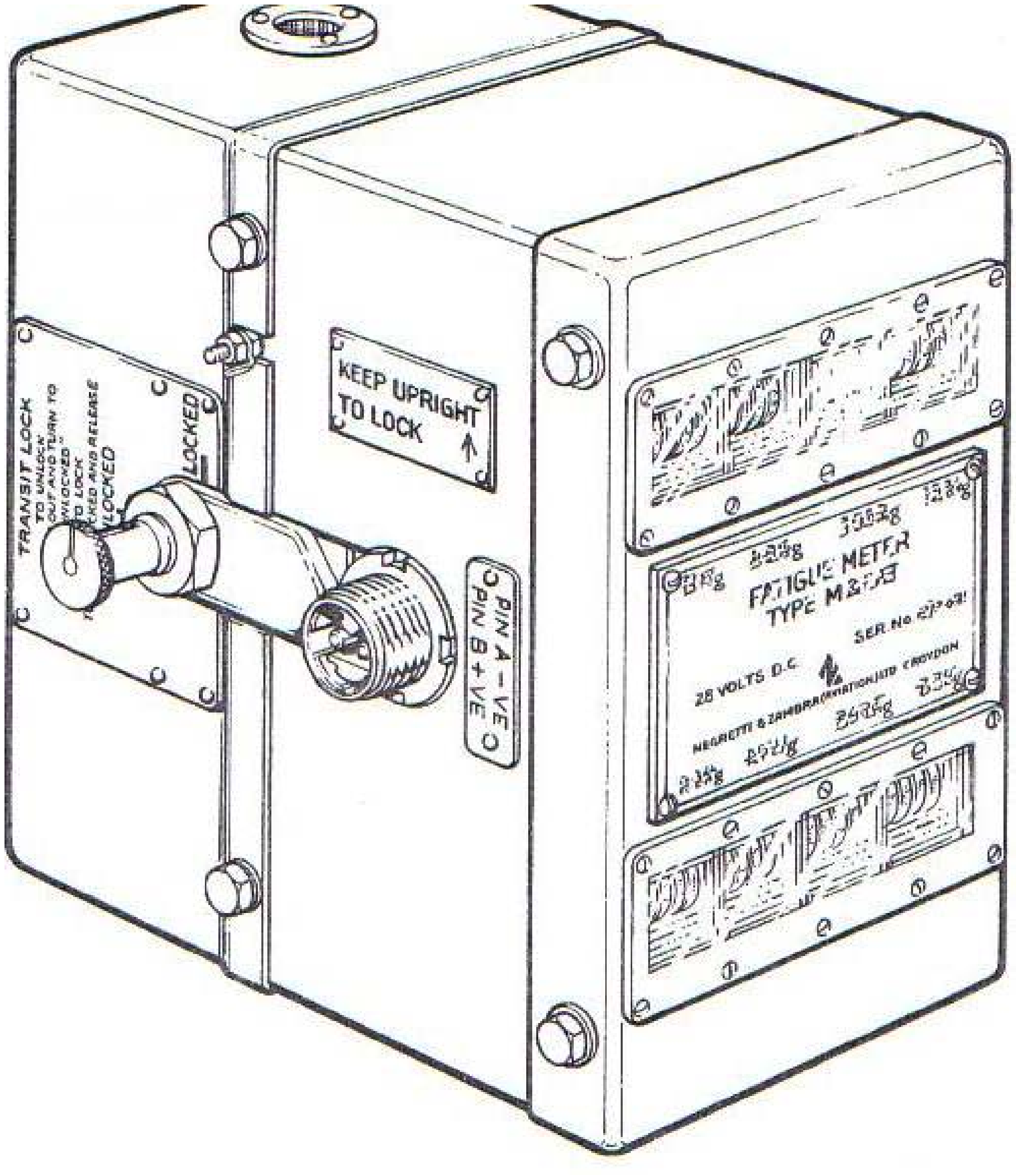
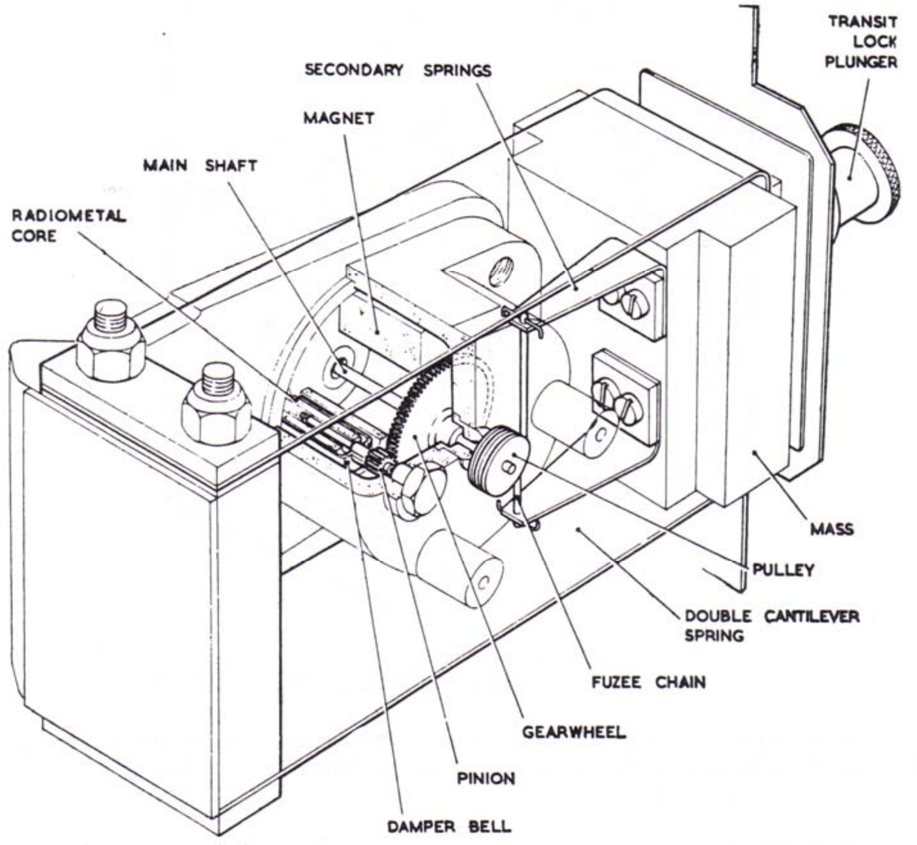
Appendix A Sketches and specifications of M2208 fatigue meter [2]

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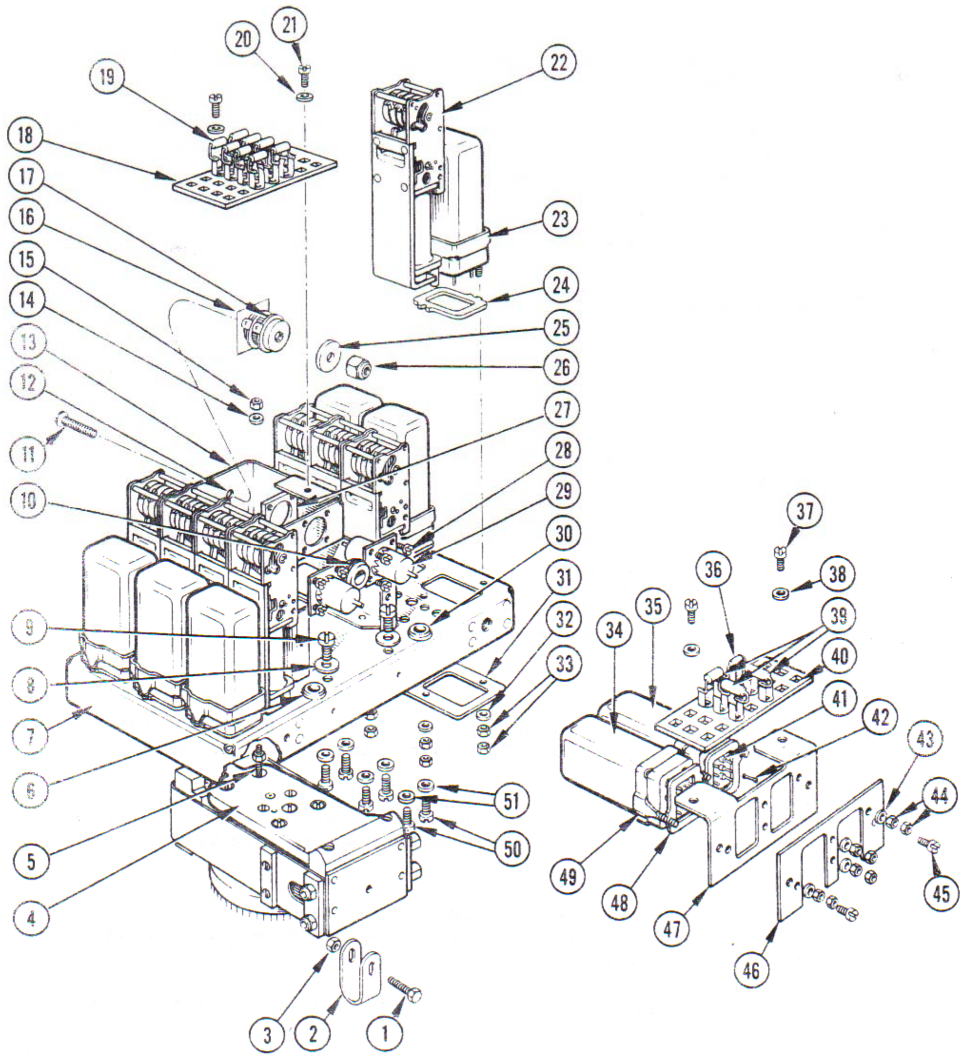
PINION
DAMPER BELL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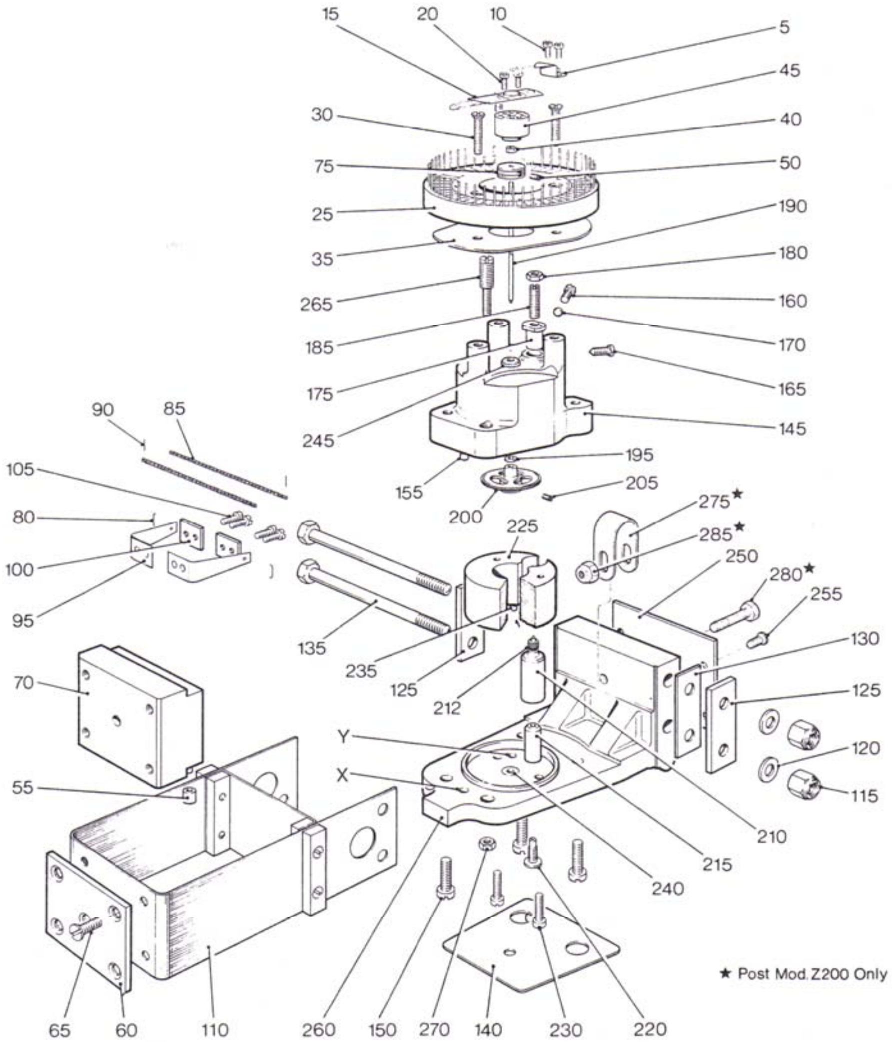
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Fatigue Meter M2208 Series

R.A.E. Structures No.	:	15
Frequency bandwidth (Hz)	:	0-11
70.7 response at (Hz)	:	11
Natural frequency (Hz)	:	7
Maximum permissible instantaneous change of applied acceleration (g)	:	1.5
Transient response time (10%-90% amplitude - ms)	:	35
Delay time (ms)	:	42
Maximum permissible rate of change of indicated acceleration (g/s)	:	45
g per commutator segment	:	0.1
Electrical connector M2208	:	Plessey Mk 4 plug 508/1/40060/320
M2208A	:	Plessey Mk 7 plug 508/1/07063/320
Electrical connections M2208	:	Pin A -ve) 21-29 V d.c. Pin B +ve)
M2208A	:	Pin A -ve) 21-29 V d.c. Pin B +ve) Pin C) Outputs to Pin D) Fatigue Consumption Pin E) Indicator.
Modifications	:	Z107, Z157, Z171, Z173, Z177
Installation details	:	Fig. 30

Acceleration thresholds (g absolute)

M2208

Lock	+0.05	+0.45	+0.75	+1.25	+1.55	+1.95	+2.35	+2.65
Release	+0.45	+0.75	+1.05	+0.95	+1.25	+1.45	+1.55	+1.85

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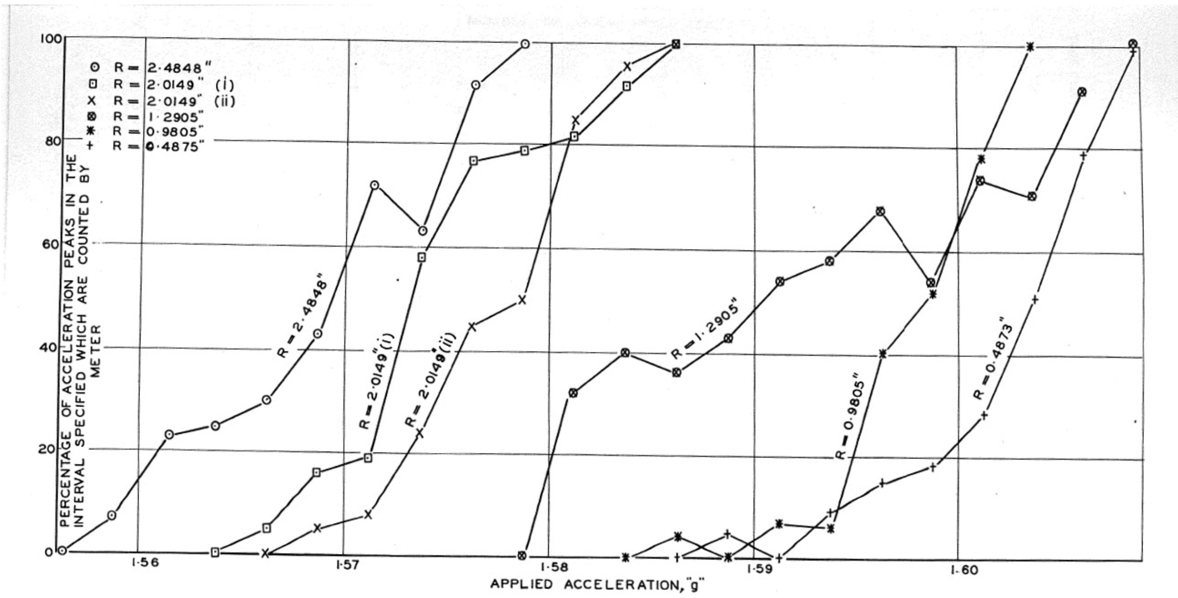
Appendix B Figure 2 from reference [5]



PROBABILITY OF A PEAK BEING REGISTERED AT THE 1.55 g LEVEL AS A FUNCTION OF ITS MAGNITUDE

Note: Calibration was achieved here by a vertical sinusoidally oscillating table driven by a crank, with radius R (in inches), and connecting rod. For a given *g* level, higher rates of *g* are achieved using a smaller R.

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Fatigue meter

19. ABSTRACT

Aircraft Structural Integrity section of Directorate General Technical Airworthiness (ASI-DGTA) has concerns about the current accuracy of the ageing M2208 electro-mechanical fatigue meters fitted to RAAF P-3C and C-130H aircraft. An examination of relevant documentation was undertaken and tests performed on two meters, one deemed unservicable and the other fresh from an overhaul. The results of this investergation are presented and implications discussed.

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