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CORRELATION BETWEEN TWO SETS OF DATA PRESENTED AS RANGE-MEAN-PA--ETC(U)
JUL 81 P J HOWARD
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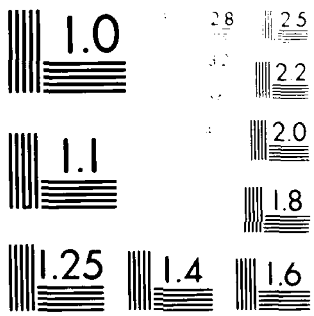
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DEPARTMENT OF DEFENCE

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AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

STRUCTURES NOTE 477

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P. J. HOWARD

Approved for Public Release.

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CORRELATION BETWEEN TWO SETS OF DATA PRESENTED AS RANGE-MEAN-PAIR COUNTS

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SUMMARY

One beneficial attribute of the Aircraft Fatigue Data Analysis System (AFDAS) now being seriously considered by RAAF as an alternative to Fatigue Meters, is a capacity to self monitor through interchannel comparisons. This note describes a systematic approach to interchannel correlations when data are presented in the form of range-mean-pair counts.

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16. *ABSTRACT*

This note describes a systematic approach to interchannel correlation for an instrument which records data in the form of range-mean-pair counts.

CONTENTS

1. INTRODUCTION

The Aircraft Fatigue Data Analysis System (AFDAS) is an electronic device which pairs turning points in time histories of strain or acceleration, obtained from up to eight sources, according to a range-mean-pair counting algorithm and stores the count in a 105 cell array. It has an inbuilt potential for self-checking provided that data from two or more channels correlate. To exploit this potential a rationale must be developed to quantify the inter-channel correlation. This note discusses a number of ways in which the data may be manipulated to effect such a correlation.

2. BRIEF DESCRIPTION OF AFDAS

The instrument and the counting algorithm have been described previously (1, 2), but a brief recapitulation is necessary for the present discussion. In essence the system has four components, namely a set of eight sensors, the strain range pair counter (SRPC) fitted in the aircraft, the interrogator, display and recording unit (IDRU) which transfers data from the SRPC memories to a cassette, and a computer which analyses the data when fed from the cassette.

The SRPC functions by splitting the total available recording range (user-selected to optimise the usefulness of the data) into 16 sub-ranges separated by 15 counting thresholds (Table 1). Each time a signal crosses a threshold and returns without crossing the adjacent threshold a turning point is registered in a temporary store. When a second turning point is registered, and specified criteria are met, the pair are cancelled in the temporary store and one more count is registered in the appropriate cell of the permanent memory.

In the instrument all sub-ranges except for the boundary sub-ranges 0 and 15, which extend to $-\infty$ and $+\infty$ respectively, are of equal width. Data are amplitude filtered by rejecting ranges crossing less than two thresholds.

The process is illustrated on the imaginary time history shown in Figure 1*a*, the resultant set of range-mean-pairs being shown in Figure 2*a*, where self-crossings have been retained.

For simplicity the data have been grouped into only 6 levels. The effects of grouping on the data are to impose an uncertainty of one sub-range on each turning point occurring in levels 1–4, while turning points in levels 0 and 5 are unbounded on one side. However a minimum (maximum) value can be placed on all peaks (troughs).

Figures 1*b* and 1*c* show, respectively, the effects of changing the offset (by half of a sub-range) and the gain (by 25%) on the range pair counting process, the resultant range pair matrices being shown in Figures 2*b* and 2*c*. If we now imagine that Figures 2*a* and 2*c* represent data from two sources our task is to determine from such data an unknown gain and offset which will transform one to the other, with an additional hazard that the 1 to 1 relation between turning points in the parent sequences, as shown in Figures 1*a* and 1*c*, rarely occurs in practice.

3. ANALYSIS OF DATA

At this point a longer sequence of turning points could have been generated, and known gain and offset imposed. This course has been rejected in favour of an attempt to deal with real data, in the belief that this better illustrates the real problems to be overcome, as well as presenting such advantages as may accrue from regularities of the physical system.

The data, which were obtained from the first two trial flights flown in May 1980 when the first production SRPC was fitted to Mirage A3-33, are shown in Figure 3 and relate to the strain at wing main spar station 1·4T and to the normal acceleration. The gauge is sited on the inner, forward surface of the main spar tension flange 439 mm outboard of the fixing pins, and the accelerometer is fitted close to the aircraft centre of gravity. The calculated values of the threshold strains and load factors are given in Table 1.

It is immediately obvious that any comparision will hinge on matching the frequency distributions for the two data sources, since this is all the information we have, and that we may have to deal with sparse data. Four possible methods are examined below.

3.1 Comparison of Amplitude Distributions

The range-mean-pair array is oriented to the values of peak and trough of each pair. However for the purpose of fatigue damage estimation two derived quantities, the mean strain = ½ (peak + trough) and strain amplitude = ½ (peak — trough), are more convenient. It can be seen (Fig. 2) that events of equal amplitudes lie on the array diagonals, parallel to the leading diagonal, whereas events of equal means lie on diagonals perpendicular to it. Thus summing along diagonals results in two distributions, of amplitude and means. Unfortunately the groupings overlap, for example the leading diagonal Figure 3 contains amplitudes from ½ to 1½ sub-ranges, and the next diagonal contains amplitudes from 1 to 2 sub-ranges i.e. both contain amplitudes 1 to 1½ sub-ranges. The reason for this overlap may be seen in Figures 1*a* and 2*a*, where for example turning point sets (8, 9) and (10, 11) each give rise to a count in cell (1, 3), whereas set (6, 7), representing an intermediate amplitude, gives rise to a count in cell (1, 2) which represents a smaller amplitude. What can positively be said is that the amplitudes in the leading diagonal are greater than ½ sub-range, or in general the amplitude in the cell defined by a peak in row i and a trough in column j (cell (j, i)) is greater than $\{(i - j) - 1\}/2$. It is thus natural to consider exceedances of amplitudes as a quantity for comparison. In the ensuing discussion we must also bear in mind that upper bounds can also be placed on amplitudes, provided that neither of the turning points sits in row 15 or column 0.

The exceedances of load factor and of strain are given in Tables 2 and 3, along with the bounding amplitudes. At this point we have to recall that some of the occurrences in any group in fact relate to an amplitude greater than the minimum for the next larger group (Columns 1 and 2 of Table 2). The proportion of such occurrences was estimated by regressing the log of the raw exceedances against amplitude of load factor (n_z) and of strain (ϵ), after it had been noticed that a reasonably linear plot between these quantities existed (Fig. 4).

If N_1, N_2 and N_3 represent the exceedances at successive thresholds of strain or acceleration, x_1, x_2 and x_3 then $(N_2 - N_3)/(N_1 - N_3)$ represents the proportion of the counts in the double interval, (x_1, x_3) which are greater than x_2. Substituting from the regression $\log N = A - Bx$ this proportion is $(e^{A-Bx_2} - e^{A-Bx_3})/(e^{A-Bx_1} - e^{A-Bx_3})$ or, if Δx is the average interval between thresholds, $(e^{A-Bx_2} - e^{A-B(x_2+\Delta x)})/(e^{A-B(x_2-\Delta x)} - e^{A-B(x_2+\Delta x)})$ i.e. $(1 - e^{-B\Delta x})/(e^{B\Delta x} - e^{-B\Delta x}) = 0{\cdot}4$ when values for B and Δx are inserted. Had the plot been less regular a piecewise correction would have been necessary.

The effect of this correction is shown in Tables 2 and 3, and the modified exceedances are plotted in Figure 4. A second regression provided the slopes $-0{\cdot}474$ for n_z and $-0{\cdot}001368$ for strain. The ratio of these slopes, 346 $\mu\epsilon/n_z$, gives the stretch needed to render the plotted lines parallel, and represents one estimate of the strain per unit load factor, averaged over the range of the variables experienced in the experiment. The corresponding values obtained from earlier trials (3) varied between 280 and 360 $\mu\epsilon/n_z$ depending on flight regime. We must however remain aware that, despite the similarity in value, these numbers have an entirely different significance. Analysis of flight data assumes a causal relation between acceleration (input) and strain (response). AFDAS data only provides a number which, given an acceleration, allows us to calculate the size of strain for which the number of exceedances is equal. No causal relation is implied, and so it may be that the value of this number would vary with amplitude, or between samples of data.

In fact both air and ground loads and strains are recorded since AFDAS is switched on and off with the aircraft power. In consequence, unless the strain for a given acceleration is the same in both regimes, some bimodality will exist. For the Mirage the ground strains are small compared to flight strains and the error is minor. The situation may be quite different for transport aircraft.

The effect of amplitude can be estimated by cross plotting, from Figure 4, values of acceleration and of strain for a range of exceedances. Table 4 lists a set of such values, which are plotted in Figure 5. The crossplot uses actual values of one parameter (ϵ or n_z) and the best estimate of the second (n_z or ϵ) from the nearest adjusted data points. For convenience a linear connection between adjacent data points is assumed (e.g. in Fig. 4 lines A, B, C, D, transform 1010 $\mu\epsilon$ to 3·02 g) but this is not necessary. No assumption about the overall behaviour of the distribution is made, so that the crossplot technique can be used when the log N vs n_z or ϵ plots are non-linear. A linear regression yields a slope of 347 $\mu\epsilon/n_z$, which is reasonably close to the previous value, 346 $\mu\epsilon/n_z$.

3.2 Comparison of Distributions of Means

Summing perpendicular to the leading diagonal provides estimates of the frequency distribution of mean values, Tables 5 and 6, upon which a similar analysis may be performed. The analysis differs in detail because there exists no obvious bounds to the size of mean loads or strains, whereas negative amplitudes are meaningless. Also alternate intervals in the occurrence listing contain counts from the leading diagonal and, because counts rate rises rapidly as amplitude decreases, are thereby inflated with respect to their neighbours.

Together these circumstances prevented any analytic estimate of the form of the distributions, and a uniform distribution of means within each interval was assumed for the purpose of re-assigning counts to their proper interval for exceedance counting (cols 3 and 4, Tables 5 and 6). Exceedances were reduced to a common percentage base by multiplying by $100/(1 \cdot n)$, where n is the total counts, 121 for n_z and 96 for $\epsilon_{1\cdot 4T}$. A second listing of exceedance of n_z was derived by reducing the counts in the leading diagonal, in the approximate ratio 3 : 5, so that overall the number of counts of strain and of acceleration were equal at 96. This second listing aimed at improving the correspondence between strain and load by eliminating low amplitude load counts whose strain counterparts had already been rejected by the lower relative gain setting on the strain channel.

Exceedance data are plotted on a normal probability grid, Figure 6. It appears from this plot that acceleration and strain are unequally distributed. A cross plot of these variables by a process like that used before, Figure 7, suggests a non-linear connection between the variables, but the shape of this curve is strongly influenced by the sparse and ill-defined extremes of the distributions.

Figure 7 also supports the general validity of using 346 $\mu\epsilon/n_z$ to convert between strain and acceleration, and does not contradict too strongly the assumption that zero strain exists at zero acceleration. If these values are accepted the two strain counts at (1, 8) and (0, 15) (Fig. 3) imply accelerations less than -5 g. This is well beyond the normal range of operation of the aircraft, but could not be derived from the accelerometer data since no lower bound exists for the counts in column 0. An independent check was therefore attempted using fatigue meter data.

3.3 Comparison with Fatigue Meter Data

An independant check on the accelerometer data is possible by a comparison with fatigue meter counts. For this purpose we must estimate, from SRPC data, how many counts cross each threshold and return to, at least, 1·20 g (for peaks) this being the best estimate of the positive firing level for the Mirage fatigue meter (4). Thus all range pairs in columns 0-4, and a proportion (to be estimated) in column 5, of Figure 3 have eligible peaks. The data in Table 7 and plotted in Figure 8, which were obtained by summing rows and columns in Figure 3 for peaks and troughs respectively, suggest that in the neighbourhood of 1 g troughs are linearly distributed. If this is assumed the proportion of eligible peaks in column 5 is given by the ratio of the width of the sub-interval 0·676 to 1·20 to the total width of the interval 0·676 to 1·496, i.e. (1·20 – 0·676)/(1·496 – 0·676) = 0·64 of the total. Using this figure the exceedance Table, 8, is constructed, the data being plotted along with the fatigue meter data in Figure 9. A similar process is used to obtain the trough exceedance curve, except that in this case only the two troughs in cell (0, 5) are in doubt. One of these has been counted.

The comparison plot, Figure 9, indicates good agreement for peaks, but some difficulty is experienced in reconciling trough counts. One possibility, which would nearly remove the difficulty, is that the counts in column 0 should be excluded. Support for this view can be obtained by consideration of the strain counts. The offending counts are in cells (0, 12) and (0, 5) of the n_z array (Fig. 3) and their probable associates are in cells (0, 15), (1, 8) and (5, 8) of the ϵ array.

If the relation $\epsilon = 346\, n_z$ is assumed to hold over the whole field the excursions (0, 15) and (1, 8) represent load factors below -5 g, a most unlikely event. The trough for the remaining count lies between $-2{\cdot}52$ g and $-1{\cdot}66$ g from the strain count, and is less than $-2{\cdot}41$ g from the n_z count, i.e. must lie between $-2{\cdot}41$ g and $-2{\cdot}52$ g. Thus it is not unreasonable to imagine that this excursion failed to trigger the fatigue meter. The peak for this count lies between $0{\cdot}68$ g and $1{\cdot}50$ g (from n_z) and between $-0{\cdot}02$ g and $0{\cdot}81$ g (n_z equivalent of strain), i.e. it must lie between $0{\cdot}68$ g and $0{\cdot}81$ g. If we assume that the firing level for events < 1 g is $0{\cdot}80$ g (same displacement as the positive firing level) then this count is probably ineligible for inclusion in the SRPC analogue. It is reasonably safe to conclude that no acceleration less than $-2{\cdot}5$ g was experienced in these two flights.

3.4 Correlation of Turning Points

Another possibility is to assume that each load turning point gives rise to one and only one strain turning point, and then attempt to correlate the load and strain on the basis of equal frequencies of troughs and peaks. The data must first be adjusted by discarding load range pairs from the leading diagonal to equalise the total turning points for each channel. The only restriction on the discarding process is that 14 range pairs must be retained in the leading diagonal of the load semi-matrix. The freedom of choice can be used, within limits, to improve the regularity of the data.

Exceedance spectra of peaks and troughs are obtained by summing rows and columns respectively in the resultant semi-matrices (Table 9, 10, Fig. 10). Cross plotting strains and accelerations of equal frequency (Table 11, Fig. 11) leads to the required correlation. One point, marked G in Figure 11, is well away from the general trend. However the acceleration troughs which gave rise to this point are all in the range $-2{\cdot}41$ g to [illegible] g, and so some or all may correspond to the $-1735\,\mu\epsilon$ or less strain apparently seen by the strain gauge, and so it is not possible to reject this point by internal comparison. By extrapolation this strain is equivalent to about -5 g, which can be rejected by comparison with general experience and with the fatigue meter counts.

The peaks and troughs in Figure 11 appear to lie on slightly different lines. Various regression lines are given in the figure. The overall linear regression using all points except G is

$$\epsilon = 2 + 340 n_z$$

which is in reasonable agreement with the earlier relation $\epsilon = 346 n_z$.

4. SUMMARY AND CONCLUSION

Four varieties of comparison to verify range pair counter data are explored. Three of these, relating to interchannel comparisons, are comparisons of amplitudes, ranges, and peaks and troughs. Each of these methods gives similar values for the strain per unit load factor, provided all valid data are used. Separate consideration of peaks and troughs results in some confusion.

This confusion may arise because, in the Mirage, the strain resulting from a given acceleration depends on the aircraft mass and mass distribution, the airspeed and altitude, the roll rate and elevon deflection and whether the aircraft is aloft or on the ground. The quoted strain sensitivities reflect an averaging of these effects. The general agreement between these estimates of strain sensitivity and values measured by continuous time history recording suggests that overall the data are reliable. However internal comparisons cannot validate individual turning points, particularly if they arise in levels 0 or 15 which are unbounded on one side.

The fourth comparison between range pairs of acceleration and the fatigue meter data is capable of assessing the validity of the extreme data points and can be used as an indicator of the general quality of the SRPC data. An absolute agreement between the two instruments is probably not possible since each imposes some uncertainties on the data it produces. No guidance can be given as to the best method of analysis. The simplest is to use the peaks and troughs, since no uncertainty exists as to the classification of the turning points. This yields simultaneous estimates of gain and relative offset. The most satisfying method is the comparison of amplitudes, since these have a definite smallest magnitude which aids interpretation, but this method yields no measure of offset.

All internal comparisons must be supplemented by reference to some external data if all error sources are to be checked.

REFERENCES

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2.	R. C. Fraser	A One-pass Method for Counting Range Mean Pair Cycles for Fatigue Analysis—ARL Structures Note 454, June 1979.
3.	P. J. Howard and G. P. Bruce	Mirage Stage 1 Fatigue Investigation. Part 9—Flight Loads in Pitching Manoeuvres—ARL Note SM357, Jan. 1971.
4.	B. E. Anderson, P. J. Howard and J. G. Sparrow	Setting and Firing Levels of Two Mirage Fatigue Meters. ARL Structures Note 418, Sept. 1975.

TABLE 1

Values of Transition Strains and Accelerations Calculated from SRPC Circuit Values

Level		Transition		
From	To	Volts	Accn g	Strain $\mu\epsilon$
0	1	−2·459	−2·409	−2022
1	2	−2·107	−1·635	−1735
2	3	−1·756	−0·863	−1449
3	4	−1·403	−0·087	−1161
4	5	−1·056	0·676	−878
5	6	−0·684	1·496	−575
6	7	−0·332	2·269	−288
7	8	0·013	3·029	−7
8	9	0·366	3·806	281
9	10	0·718	4·580	568
10	11	1·091	5·400	872
11	12	1·438	6·164	1155
12	13	1·792	6·942	1443
13	14	2·145	7·719	1731
14	15	2·501	8·502	2020

TABLE 2

Occurrences and Exceedances of Amplitude of Normal Acceleration in Various Bands of Load Factor

n_z (g)		Raw Data		Adjustment		
Min.	Max.	Occur.	Exceed. N	*<	Δ	Exceed. N
0·410	1·178	{39}	121	{23}		121
0·797	1·558	22	82	13	{16}	98
1·154	1·952	19	60	11	9	69
1·564	2·333	18 (2)†	41	11	8	49
1·952	2·744	8	23	5	7	30
2·362	3·125	6	15	4	3	18
2·744	3·518	3	9	2	2	11
3·182	3·899	1	6	0	1	7
3·518	4·301	2	5	1	1	6
3·899	4·676	2	3	1	1	4
4·286	∞	1 (1)	1	0	1	2
4·676				0	1	1

† Bracketed numbers are counts without an upper bound.

* Number of counts less than the minimum of the next higher group. The difference, Δ, between this number and the raw occurrences (col. 3) is assigned to the next higher group, thus {39} − {23} = {16}.

Linear regression, assuming $\log N = A + Bn_z$:

For raw data
$\log N = 2{\cdot}2910 - 0{\cdot}4669 n_z$.

For adjusted data
$\log N = 2{\cdot}3887 - 0{\cdot}4740\, n_z$.

N at $n_z = 0$ is 244 cycles
n_z at $N = 1$ is 5·04 g
} for adjusted data

TABLE 3

Occurrences and Exceedances of Amplitude of Strain at Gauge Position 1·4T in Various Bands of Strain

Strain @ 1·4T, $\mu\epsilon$		Raw Data		Adjustment		
Min.	Max.	Occur.	Exceed, N	*<	Δ	Exceed, N
144	440	25 (1)†	96	15		96
294	581	25	71	15	10	81
437	725	16	46	10	10	56
581	870	13	30	8	6	36
725	1014	6	17	4	5	22
866	1153	5 (2)	11	3	2	13
1010	1298	1	6	0	2	8
1153	1450	2 (1)	5	1	1	6
1298	∞	2 (2)	3	1	1	4
1450	∞	0	1		1	2
2021	∞	1 (1)	1		1	1

*, † as for Table 2.

Linear regression, assuming $\log N = A + B\epsilon$.

Raw data

$\log N = 2{\cdot}2167 - 0{\cdot}001325\,\epsilon$

After adjustment

$\log N = 2{\cdot}3328 - 0{\cdot}001368\,\epsilon$

N at $\epsilon = 0$ is 215 cycles

ϵ at $N = 1$ is 1705 $\mu\epsilon$.

TABLE 4

Amplitudes of Normal Acceleration and of Strain at Gauge 1·4T Giving Rise to the Same Number of Exceedances

Number of Exceedances	Amplitude of	
	n_z	$\epsilon_{1\cdot4T}$ $\mu\epsilon$
2	4·286	1450
4	3·899	1298
6	3·518	1153
8	3·02	1010
13	2·61	866
22	2·11	725
36	1·79	581
56	1·28	437
81	1·00	294
7	3·182	1085
18	2·744	940
30	2·362	780
49	1·952	630
69	1·564	460
98	1·154	355
1	>4·676	>2021

Regression assuming $\epsilon = A + Bn_z + Cn_z^2$ and
$= A + Bn_z$

$\epsilon = -61{\cdot}4 + 371\, n_z - 5{\cdot}03\, n_z^2$.

or $= -36.1 + 347\, n_z$ if the quadratic term is set $= 0$.

TABLE 5

Distribution of Mean Loads

Load Interval g	Raw Occns.§	Occurrences* > Min.		Exceed-ances, r	$\frac{100\,r}{n+1}$	Raw† Occns.§	$\frac{100\,r\dagger}{n+1}$
< −0·456	2	2		121	99·18	2	98·97
−0·456 to 0·317	0	0	0	119	97·54	0	96·91
−0·070 to 0·697	2	1	0	119	97·54	2	96·91
0·317 to 1·082	3	2	1	118	96·72	3	95·88
0·705 to 1·472	16	8	1	115	94·26	7	92·78
1·091 to 1·852	12	6	8	106	86·89	12	87·63
1·472 to 2·262	23	12	6	92	75·41	15	78·35
< 2·266	1						
1·879 to 2·650	21	11	12	74	60·66	21	63·92
2·240 to 3·038	23	12	10	51	41·80	18	45·36
2·628 to 3·448	10	5	11	29	23·77	10	25·77
3·038 to 3·835	6	3	5	13	10·66	5	11·34
3·448 to 4·220	0	0	3	5	4·10	0	3·09
3·804 to 4·602	1	1	0	2	1·64	0	1·03
4·220 to 4·984	0			1	0·82	0	1·03
4·602 to 5·370	0			1	0·82	0	1·03
4·984 to 5·761	1	1		1	0·82	1	1·03

* Occurrences greater than the minimum in the interval, assuming linear distribution within each interval.

† Number o´ range-mean-pairs of acceleration and of strain at 1·4T equalised by reducing number in leading diagonal of load.

TABLE 6

Distribution of Mean Strain

Strain Interval $\mu\epsilon$	Raw Occns.[8]	Occurrences > Min.		Exceed-ances, r	$\frac{100\,r}{n+1}$
−1015 to 727	1	1		96	98·97
−727 to −443	0	0	0	95	97·94
−443 to −147	1	1	0	95	97·94
−155 to 149	2	1	0	94	96·91
−3·5 to 292	1	1	1	93	95·88
149 to 434	4	2	0	91	93·81
281 to 577	11	6	2	89	91·75
433 to 718	7	4	5	81	83·51
577 to 862	20	10	3	72	74·23
718 to 1006	22	11	10	59	60·82
862 to 1150	17	9	11	38	39·18
1006 to 1294	9	5	8	18	18·56
1150 to 1443	0	0	4	5	5·15
1294 to 1588	0	0	0	1	1·03
> 1732	1	1	0	1	1·03

TABLE 7

Occurrences and Exceedances of Peaks and Troughs of Load Factor $\{n_z\}$ From Figure 3

Load Factor	Occurrences of		Exceedances of	
	Trough <	Peak >	Trough <	Peak >
−2·409	3		3	
−1·635	6		9	
−0·863	6		15	
−0·087	3		18	
0·676	48	2	66	121
1·496	42	15	108	119
2·269	10	30	118	104
3·029	1	25	119	74
3·806	1	21	120	49
4·580	1	13	121	28
5·400		9		15
6·164		6		6
6·942				
7·719				
8·502				

TABLE 8

Fatigue Meter and Analogous SRPC Data For Two Flights

Load Factor n_z	Fatigue Meter	SRPC	
		Occurrences	Exceedances
−2·5	0		
−2·409		2	2
−1·635		6	8
−1·5	5		
−0·863		6	14
−0·5	13		
−0·087		3	21
0·676		58	79
1·496		15	92
2·269		25	77
2·5	71		
3·029		14	52
3·5	47		
3·806		16	38
4·5	24		
4·580		8	22
5·400		9	14
6·0	5		
6·164		5	5
6·942			
7·719			
8·0	0		
8·502			

TABLE 9

Occurrences and Exceedances of Peaks and Troughs of Strain

Strain, με, Between	Troughs		Peaks		Exceed %	
	Occur.	Exceed[1]	Occur.	Exceed[2]	Troughs	Peaks
−∞ and −2022	1	1			1·0	
−2022 and −1735	1	2			2·1	
−1735 and −1449	0	2			2·1	
−1449 and −1161	0	2			2·1	
−1161 and − 878	0	2			2·1	
− 878 and − 575	5	7			7·2	
− 575 and − 288	8	15			15·5	
− 288 and −7	3	18			18·6	
−7 and 281	31	49	2	96	50·5	99·0
281 and 568	40	89	0	94	91·8	96·9
568 and 872	6	95	13	94	97·9	96·9
872 and 1155	0	95	16	81	97·9	83·5
1155 and 1443	0	95	33	65	97·9	67·0
1443 and 1731	1	96	11	32	99·0	33·0
1731 and 2020			14	21		21·6
2020 and ∞			7	7		7·2

[1] Exceedances of magnitude less than the maximum in the interval.

[2] Exceedances of magnitude greater than the minimum in the interval.

TABLE 10

Occurrences and Exceedances of Peaks and Troughs of Normal Acceleration

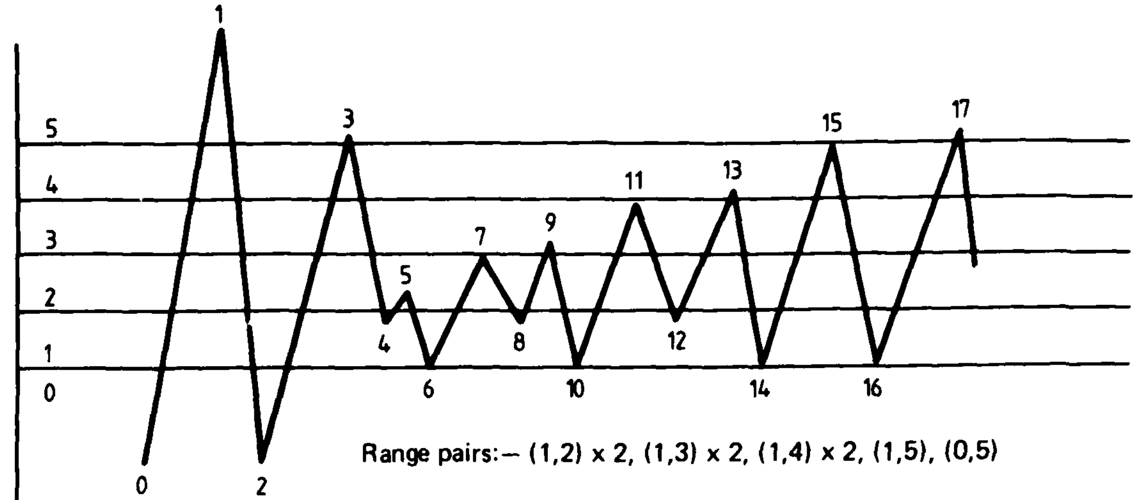
Load, g, Between	Troughs		Peaks		Exceed %	
	Occur.	Exceed.	Occur.	Exceed.	Trough	Peak
− ∞ and −2·41	3	3			3·1	
−2·41 and −1·64	6	9			9·3	
−1·64 and −0·86	6	15			15·5	
−0·86 and −0·09	3	18			18·6	
−0·09 and 0·68	33	51			52·6	
0·68 and 1·50	34	85	2	96	87·6	99·0
1·50 and 2·27	10	95	0	94	97·9	96·9
2·27 and 3·03	0	95	22	94	97·9	96·9
3·03 and 3·81	0	95	25	72	97·9	74·2
3·81 and 4·58	1	96	20	47	99·0	48·5
4·58 and 5·40			12	27		27·8
5·40 and 6·16			9	15		15·5
6·16 and 6·94			6	6		6·2

TABLE 11

Estimate of Corresponding Values of Acceleration and Strain for Equal Exceedance Frequency

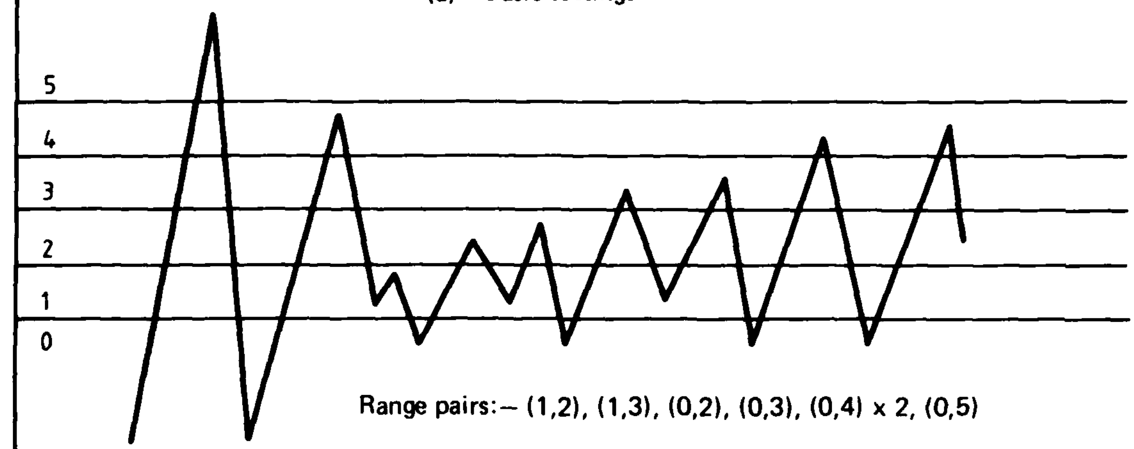
Frequency %	Trough		Peak	
	Acceleration g	Strain $\mu\epsilon$	Acceleration g	Strain $\mu\epsilon$
2	−2·5*	−1750	—	—
5	−2·05	−675	6·32*	2075*
10	−1·55	−450	5·77	1930
20	0·02	+5	5·04	1760
30	+0·21	105	4·46	1520
40	0·42	190	4·11	1370
50	0·60	280	3·78	1290
60	0·81	330	3·46	1220
70	1·01	390	3·14	1110
80	1·25	450	2·88	930
90	1·49	540	2·61	760
95	1·89	690	2·38	630
98	3·85	1450	1·16	160
99	4·58	1731	0·68	−7

* Slight extrapolation.



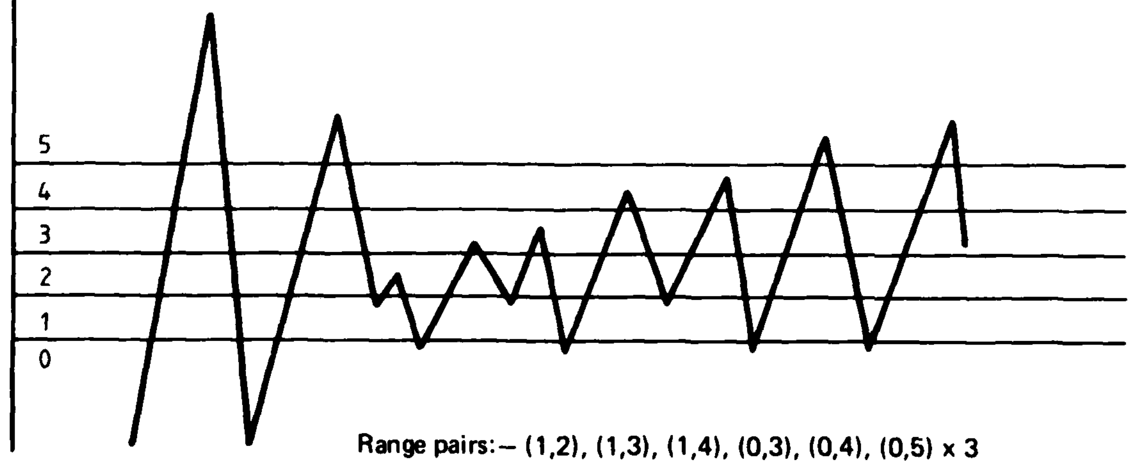
Range pairs:— (1,2) x 2, (1,3) x 2, (1,4) x 2, (1,5), (0,5)

(a) Basic settings



Range pairs:— (1,2), (1,3), (0,2), (0,3), (0,4) x 2, (0,5)

(b) Offset increased by half a sub-range



Range pairs:— (1,2), (1,3), (1,4), (0,3), (0,4), (0,5) x 3

(c) Gain increased by 25%, threshold (1,2) constant

FIG. 1 EFFECT OF CHANGES IN OFFSET AND GAIN ON RANGE–MEAN–PAIR COUNTS

Lower level

Upper level	0	1	2	3	4
1		x	x	x	x
2		2	x	x	x
3		2		x	x
4		2			x
5	1	1			

(a) Basic setting

Lower level

Upper level	0	1	2	3	4
1		x	x	x	x
2	1	1	x	x	x
3	1	1		x	x
4	2				x
5	1				

(b) Half sub-range offset

Lower level

Upper level	0	1	2	3	4
1		x	x	x	x
2		1	x	x	x
3	1	1		x	x
4	1	1			x
5	3				

(c) 25% gain increase

FIG. 2 ARRAYS OF RANGE–MEAN–PAIR COUNTS
FROM FIG. 1

n_z															
-2 409		0													
-1.635	2		1												
-0.863	3			2											
-0.087	4				3										
0.676	5	2				4									
1.496	6					15	5								
2.269	7		2	3		11	14	6							
3.029	8			1	1	5	10	8	7						
3.806	9				1	7	12		1	8					
4.580	10			1	1	3	5	2		1	9				
5.400	11		2	1		5	1					10			
6.164	12	1	2			2				1			11		
6.942	13													12	
7.719	14														13
8.502	15														

Normal acceleration n_z

$\epsilon_{1.4T}$															
-2022		0													
-1735	2		1												
-1449	3			2											
-1161	4				3										
-878	5					4									
-575	6						5								
-288	7							6							
-7	8		1				1		7						
281	9									8					
568	10						1	1		11	9				
872	11							4		3	9	10			
1155	12								2	8	19	4	11		
1443	13							1		1	7	2		12	
1731	14						1	1	1	6	5				13
2020	15	1					2	1		2					1

Strain at gauge 1.4T, $\epsilon_{1.4T}$

FIG. 3 RANGE–MEAN–PAIR COUNTS OF ACCELERATION (n_z) AND STRAIN ($\epsilon_{1.4T}$) FOR TWO FLIGHTS

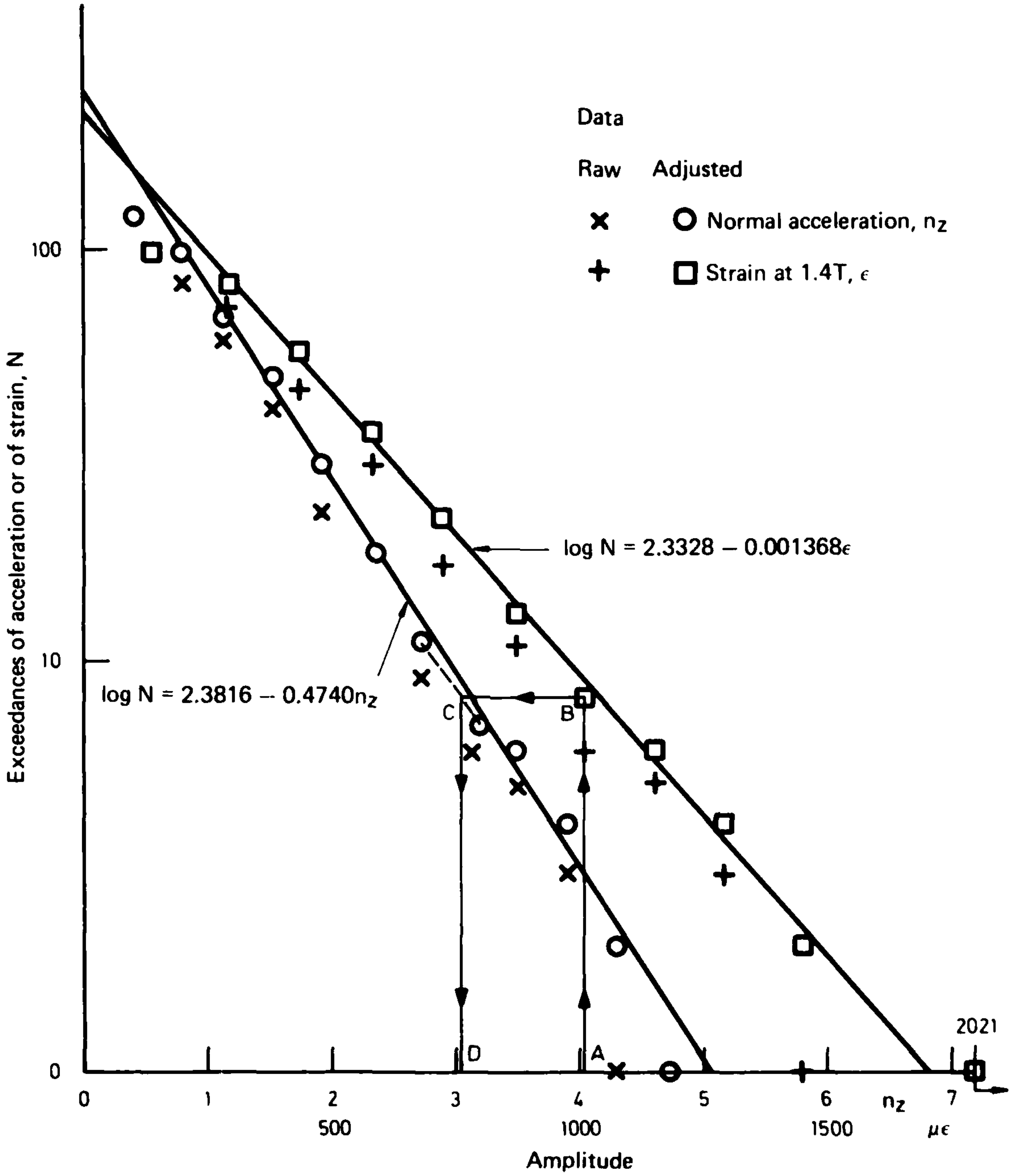


FIG. 4 AMPLITUDE–EXCEEDANCE RELATIONS FOR RAW AND ADJUSTED DATA

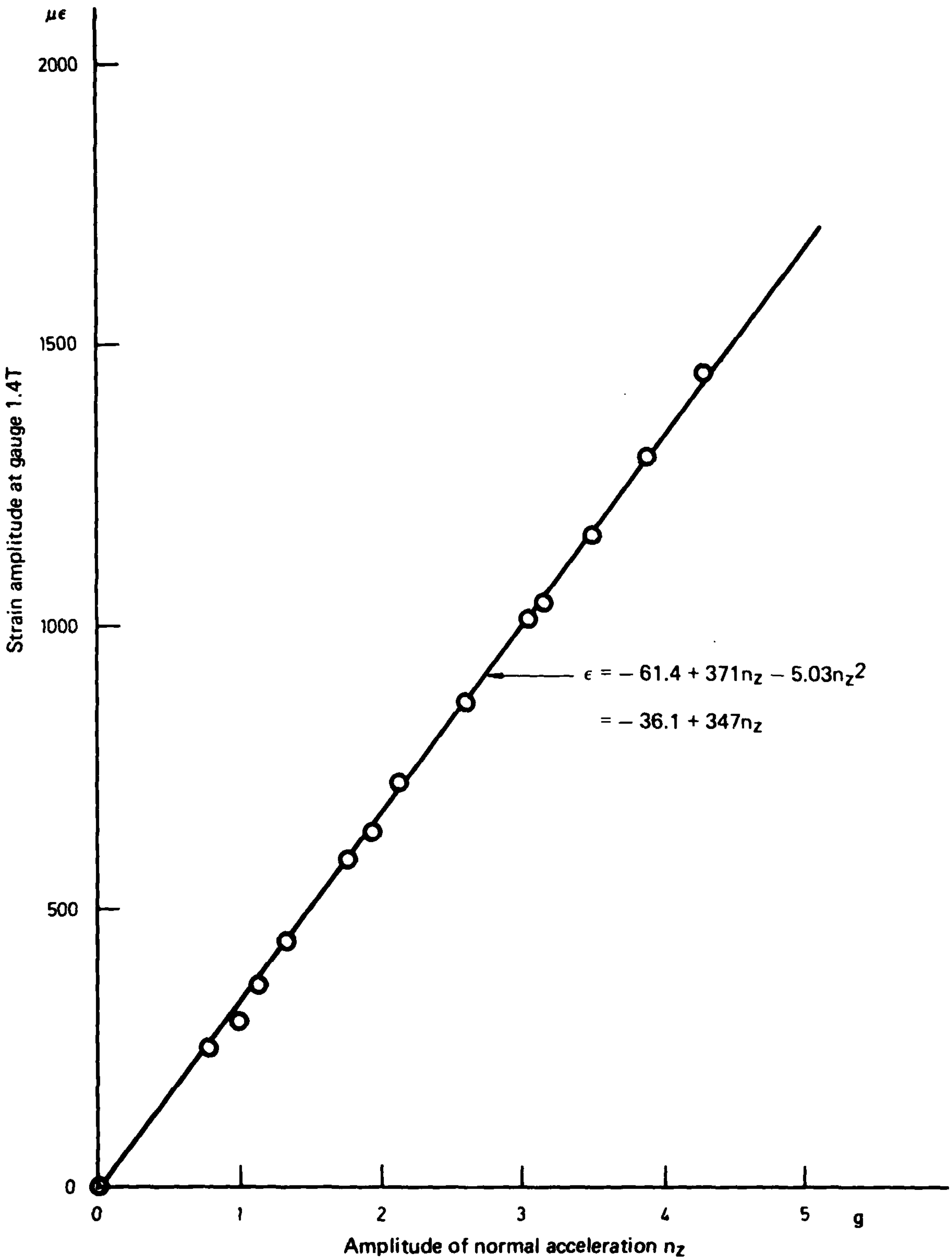


FIG. 5 VALUES OF AMPLITUDE OF NORMAL ACCELERATION AND STRAIN AT 1.4T HAVING SAME EXCEEDANCE FREQUENCY

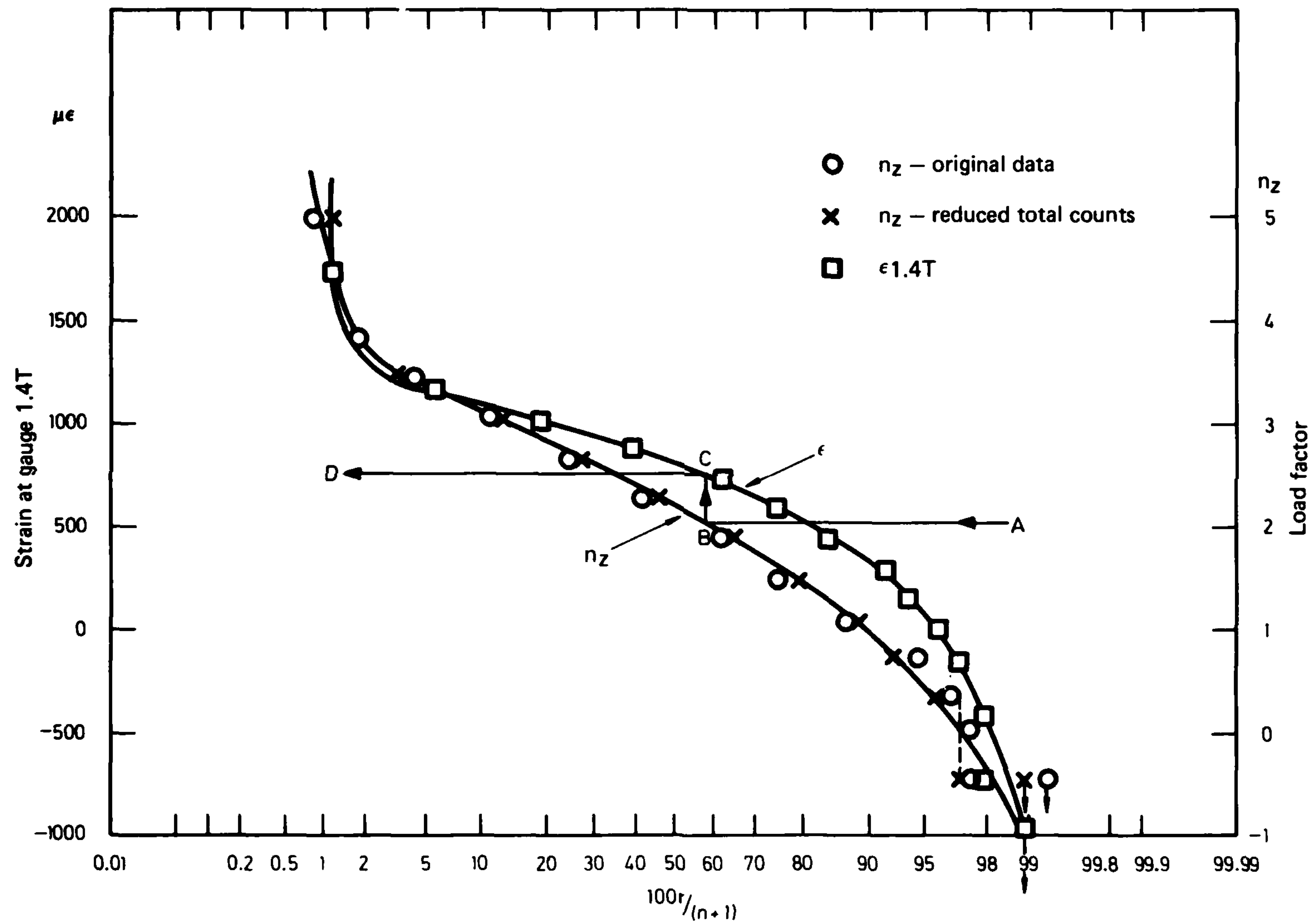


FIG. 6 CUMULATIVE DISTRIBUTION OF MEANS GREATER THAN THE LOWER BOUND OF CLASS INTERVAL

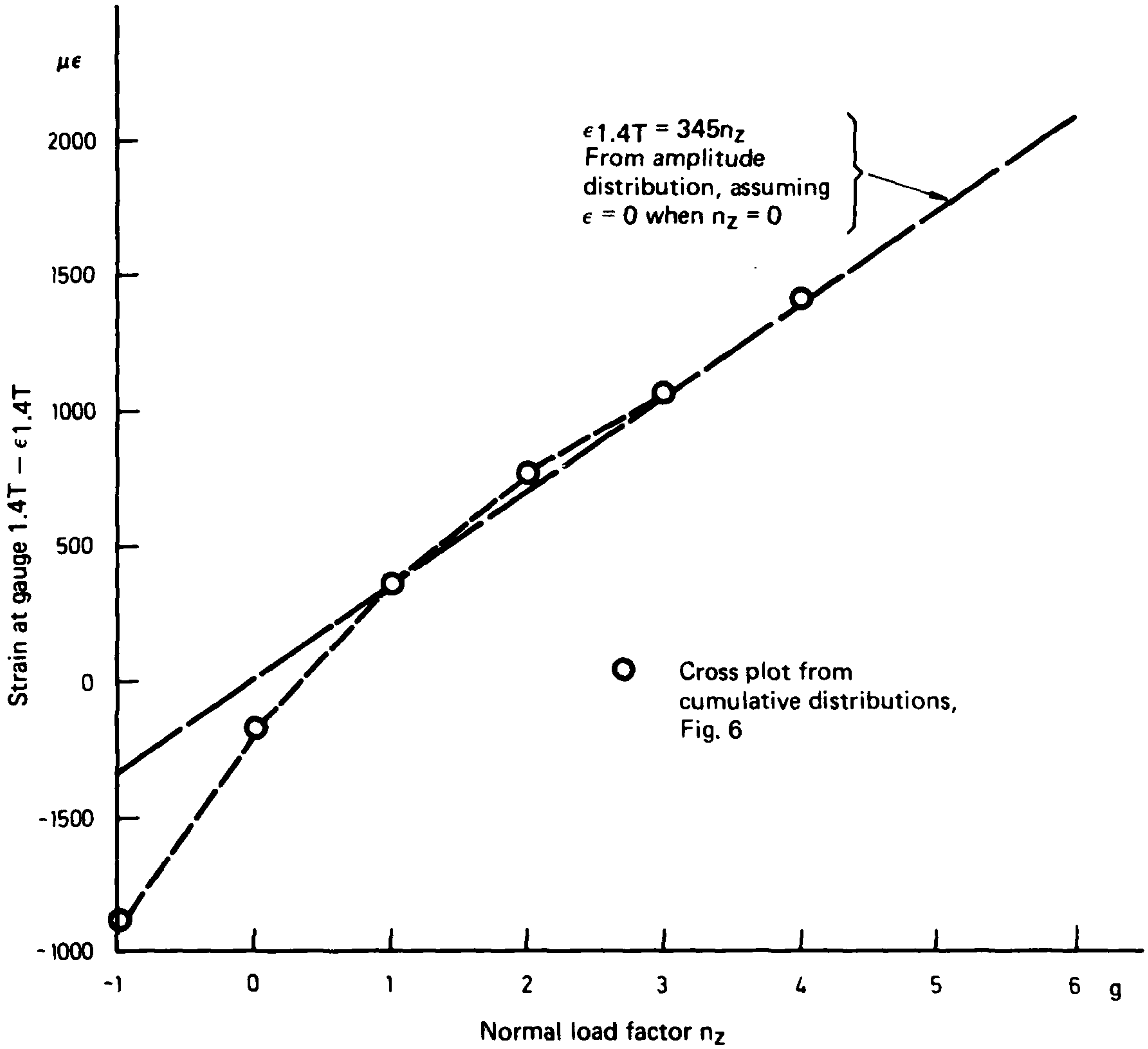


FIG. 7 POINTS OF EQUAL FREQUENCY, CROSSPLOT FROM FIG. 6

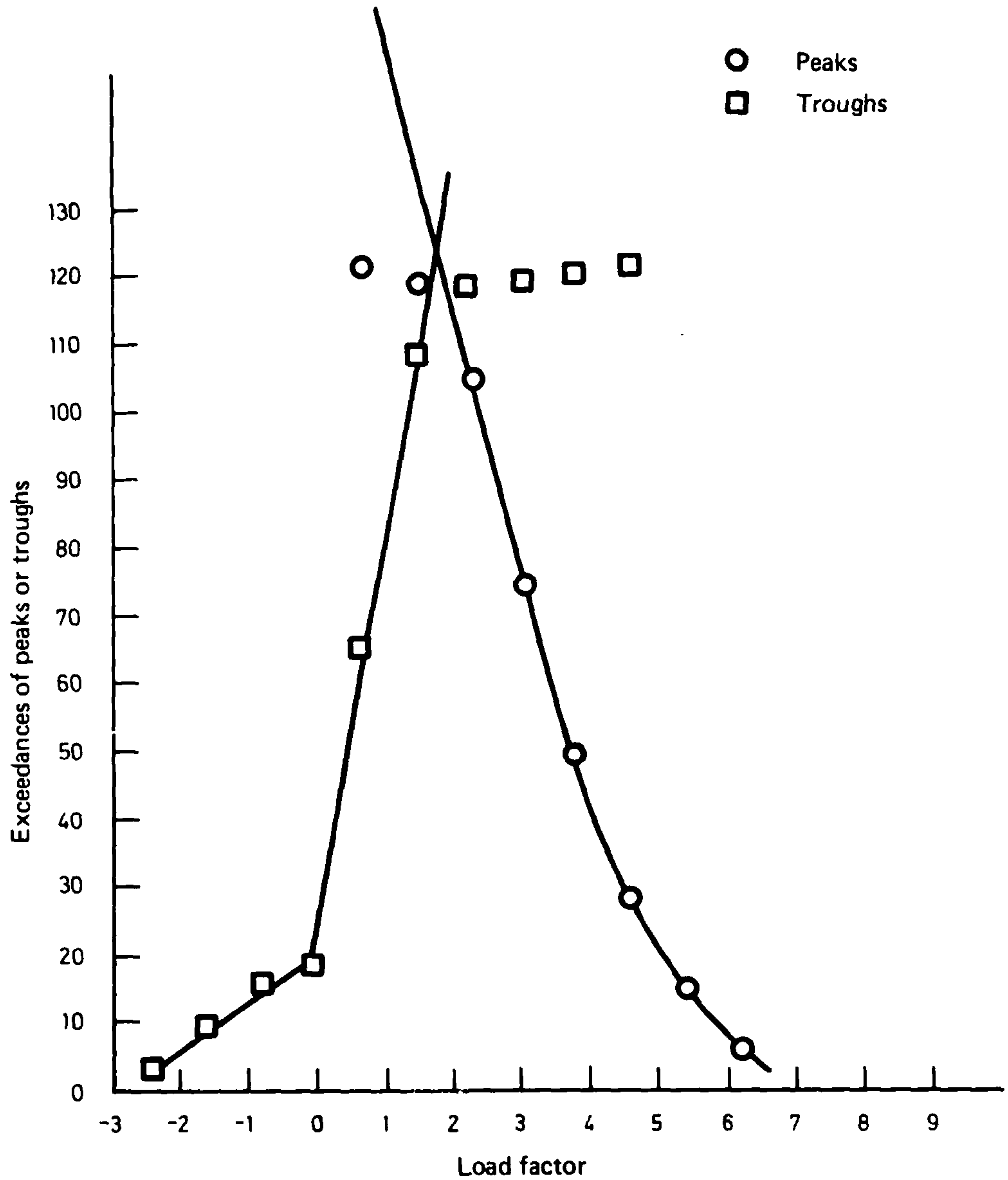


FIG. 8 EXCEEDANCES OF LOAD FACTOR PEAKS AND TROUGHS

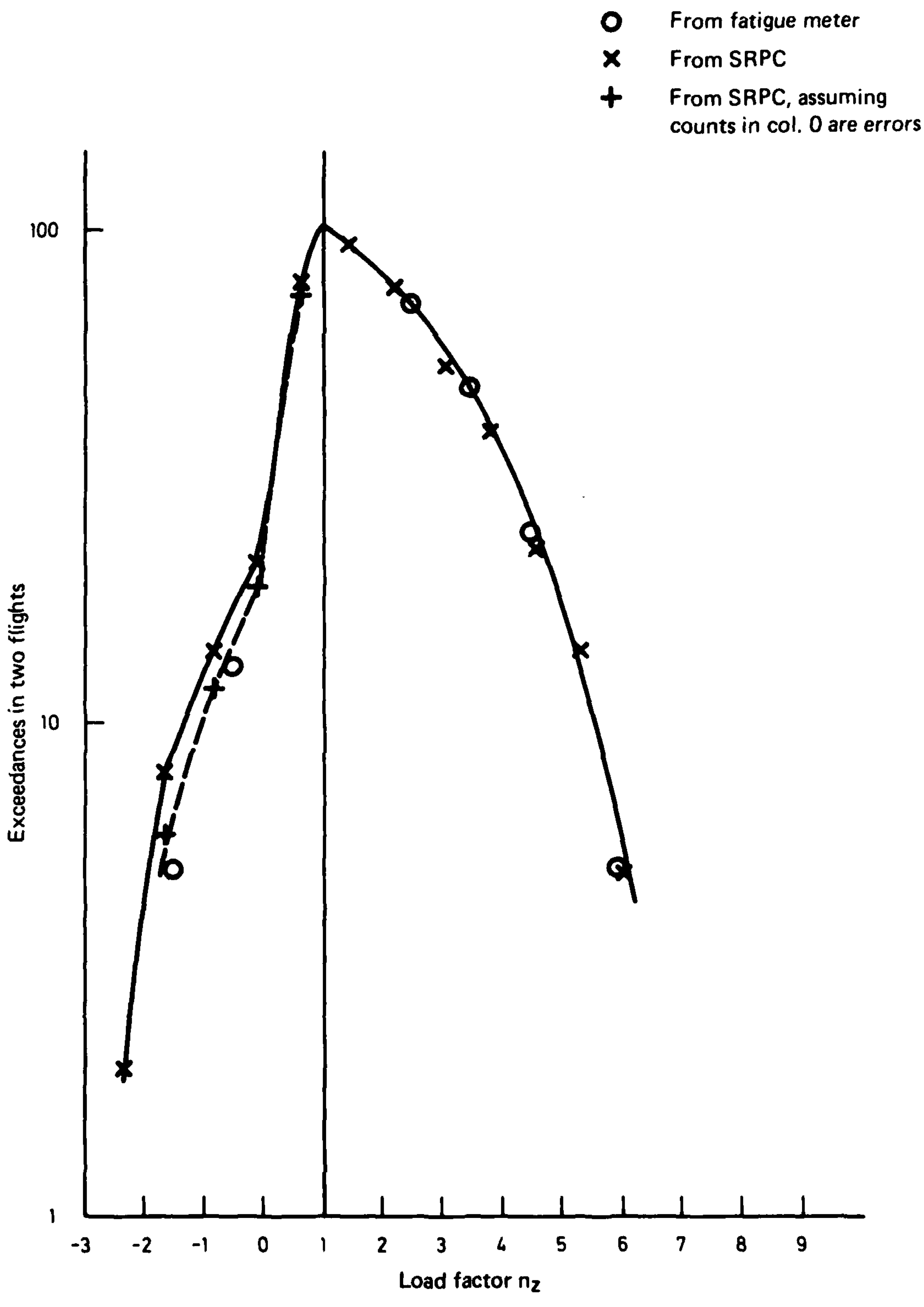


FIG. 9 COMPARISON OF SRPC AND FATIGUE METER DATA

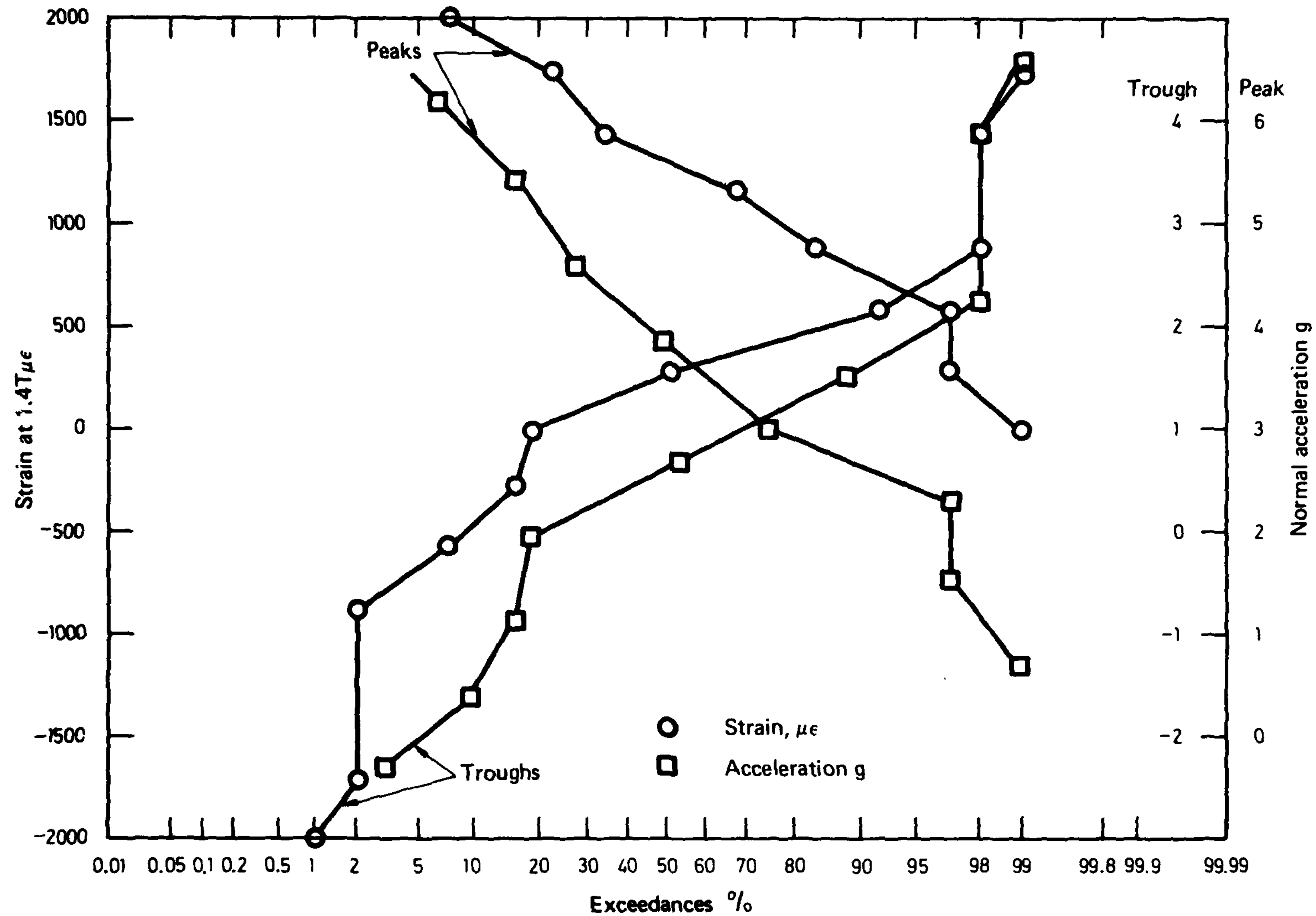


FIG. 10 EXCEEDANCES OF PEAKS AND TROUGHS OF STRAIN AND ACCELERATION

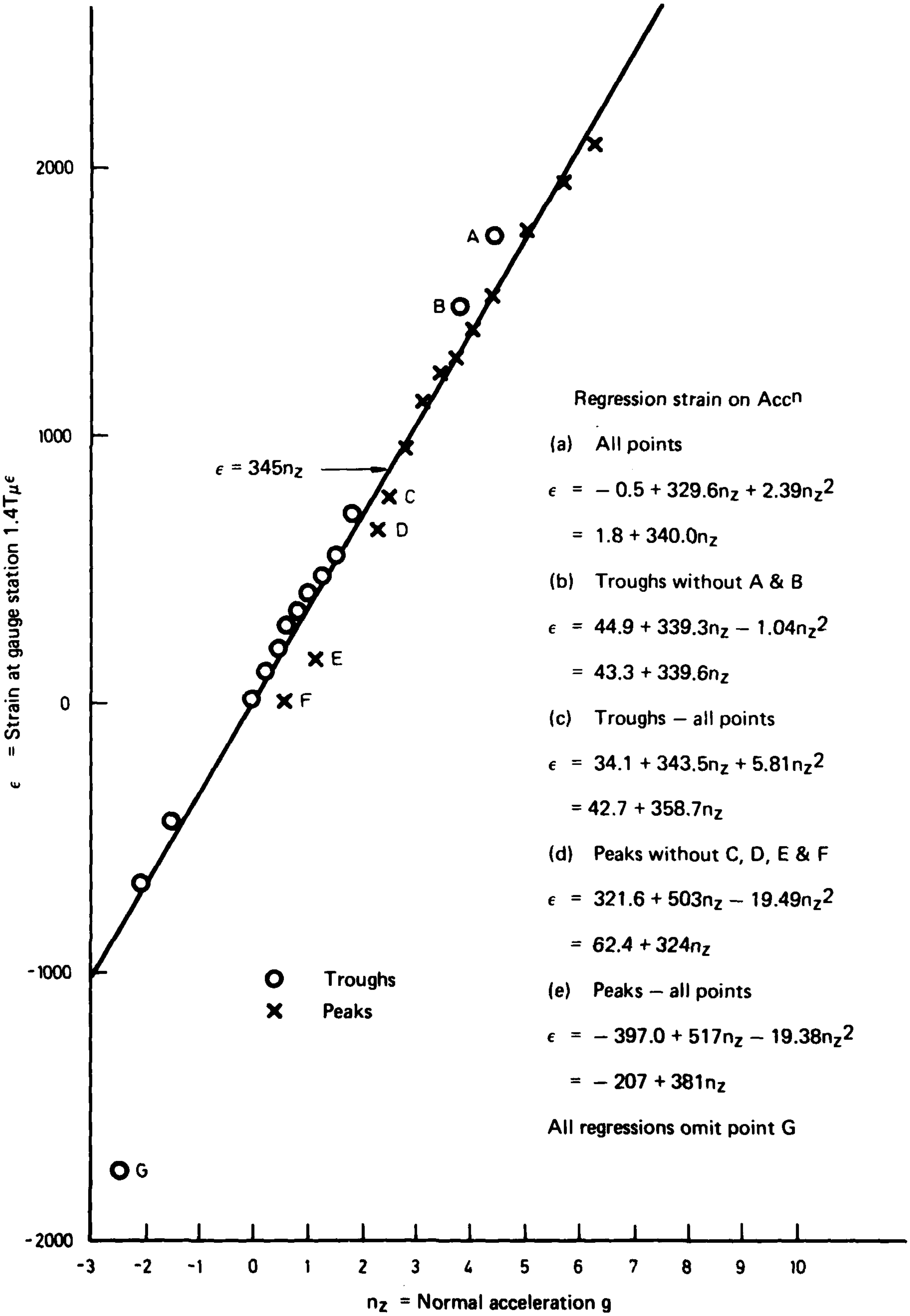


FIG. 11 STRAIN VS NORMAL ACCELERATION FOR EQUAL FREQUENCY OF EXCEEDANCE OF PEAKS AND TROUGHS

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