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The Chance of a Rough Flight

by

N. I. Bullen, B.Sc.

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SUMMARY

The variability of the numbers of bumps experienced during flights of a typical passenger transport during normal operation is examined in order that the sequence of loads applied in the fatigue test of an aircraft structure may more nearly simulate that occurring in practice. A statistical distribution of a standard form is fitted to the observations.

It is found that the magnitude distribution of bumps within a flight is dependent on the total number of bumps in the flight, and the correlation between successive flights is found to be low.

The degree to which the results can be extended to apply to other aircraft is discussed.

It is concluded that the findings of the paper are sufficient to enable comparative tests to be done to assess the effect of variability between flights on fatigue life.

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CONTENTS

1 INTRODUCTION

In the early days of fatigue testing of aircraft structures, alternating loads of constant amplitude were usually applied, and an assessment of fatigue life made on the basis of Miner's rule.

It was soon felt that this procedure was inadequate because of the doubtful accuracy of the rule, and attempts were made to make the applied loading more realistic. For this reason programme loading tests were developed in which a range of loading cycles representing gust and manoeuvre loads in flight are interspersed between loads representing the ground-to-air cycle.

Work of this kind has shown the importance of the order in which the loads are applied on the fatigue life achieved, and it may be that the present procedure still does not simulate with sufficient accuracy the sequence of loads experienced by an aircraft during its actual operational life.

In particular, the application of a given number of loading cycles between each ground-to-air cycle is unrealistic. Some flights are calm, some are extremely turbulent, and the majority of flights range somewhere between the two extremes. It is the object of this paper to examine this variability between flights.

For the purpose of the investigation, counting accelerometer records from Viscount aircraft operated by British European Airways are examined. This is considered to be a fairly typical case, and over one thousand flights were available for analysis.

2 INSTRUMENTATION AND METHOD OF INVESTIGATION

During the flights under consideration the aircraft carried a counting accelerometer Mk.4, and this instrument recorded the numbers of times normal acceleration increments (subsequently referred to as bumps) of 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6g units were exceeded. The counter readings, altimeter and air-speed indicator were photographed automatically at given intervals of time, but for the present purpose only the total acceleration counts for each flight are considered.

In the present analysis each complete flight is classified according to the number of bumps of 0.2g, or greater, occurring during the flight, and the resulting distribution examined.

However, this is not the whole problem. When a flight is very rough, not only are more bumps experienced, but there is likely to be a higher proportion of large bumps relative to the smaller ones. It is thus necessary to know both the distribution of bumps per flight, and also for a given number of bumps in a flight the probable magnitude distribution among them.

To examine this factor, flights are grouped according to bumps per flight, and the magnitude distribution of bumps within each group is examined. The degree to which successive flights are correlated is then studied, and finally consideration is given to the application of the results to other aircraft, and for this purpose the ways in which certain parameters vary with acceleration and duration of flight are examined.

3 ANALYSIS OF DATA

The classification of flights according to the number of bumps of 0.2g, or greater, occurring during the flight is given in Table 1, and the cumulative distribution up to 120 bumps in a flight is shown in Fig.1. In both Table 1 and Fig.1 comparison is made with a theoretical distribution, the estimation of which is now described.

In previous papers[1,2] the author has examined the distribution of bumps within 10-minute intervals, and has found that the generating function of the distribution is given with reasonable accuracy by a binomial expression with negative exponent. In the present case we have additional variability because of differing lengths of flight and any long-term trends that may be present; but, nevertheless, fitting a function of this kind will provide a useful starting point (this is equivalent to fitting, in the continuous case, a Pearson Type III distribution with known origin).

Let the proportion of flights with exactly n bumps be given by the coefficient of t^n in the expansion of

$$\{(1 + p) - pt\}^{-k} . \qquad (1)$$

The mean number of bumps per flight, m, is equal to pk and the variance is pk(1 + p). As the variance is (1 + p) times the mean, the parameter p can be taken as an indication of the variability of the data, and will be referred to as the variability parameter.

Putting pk and pk(1 + p) equal to the mean and variance respectively* of the observed distribution of Table 1 gives:-

*As pointed out in the earlier papers referred to, fitting by moments is not an efficient method, but here its convenience outweighs other considerations. Fitting by maximum likelihood would be far too long, even on a computer, and fitting to mean and first term is not so good here as previously because k is not small.

$$p = 42.7460$$
$$k = 0.541,323 .$$

The distribution estimated from these parameters and multiplied by the total number of flights is given in Table 1 and shown plotted in Fig.1*.

A comparison of observed and calculated values shows that there is a discrepancy in the zero class, but over the main body of the distribution the fit is considered adequate. It is likely that the discrepancy is due to the effect of manoeuvring loads. On the majority of flights it is probable that some manoeuvres are made near the beginning or end of the flight, which, even if they are too small to register themselves, would, in combination with small gusts, often be sufficient to actuate the counters. For the purpose of fatigue testing, the discrepancy is not likely to be serious, particularly as the overall total of bumps is correct, and it is suggested that the given expression represents the actual loads with sufficient accuracy.

4 THE MAGNITUDE DISTRIBUTION OF BUMPS WITHIN FLIGHTS

Having decided upon a distribution giving the numbers of bumps of 0.2g, or greater, per flight, the next question to be examined is the way in which the magnitudes of the bumps are distributed within flights.

The result of grouping flights according to the number of bumps of 0.2g, or greater, and totalling the bumps of all magnitudes for each group, is shown in Table 5. It will be seen that, as the number of bumps per flight increases, so also does the proportion of larger bumps. The average number of bumps of different magnitudes per flight for each group is shown plotted in Fig.5 (only points based on more than ten bumps have been shown). It will be seen from Fig.5 that the distributions form a family, each intersecting the vertical axis at the same point, corresponding, in the usual terminology, to the average number of "zero crossings" per flight. The change from one distribution to another corresponds merely to a change of scale in the horizontal direction.

The experimental points do not, of course, follow this relationship exactly, and an expression representing the average shape of the curve has been derived:-

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*As the number of flights and the number of bumps can take only integral values, the observed distribution should be represented on the diagram by a series of discrete points, no meaning being attached to intermediate values. However, for convenience in plotting and reading the figure, a smooth curve has been drawn through the calculated values. The same procedure has been followed in Figs.2-4.

$$N = 130 \exp\left(-\frac{a}{0.1108r}\right) + 2530 \exp\left(-\frac{a}{0.0576r}\right), \qquad (2)$$

where 'a' is the aircraft normal acceleration in g units, i.e. magnitude of bump, N is the mean number of bumps per flight equal to or exceeding an acceleration, a, for a given number of bumps of 0.2g or greater, and 'r' is a parameter determining the scale.

When r = 1 and a = 0.2, expression (2) gives N = 100, and by varying r, the range of distributions of Fig.5 is obtained. The number of zero crossings per flight is seen to be 130 + 2530 = 2660.

5 CORRELATION BETWEEN SUCCESSIVE FLIGHTS

We have now determined the distribution of bumps between flights and the magnitude distribution within a flight. In making use of this information in a fatigue test we shall also require to know whether it is sufficient to sample the distribution for the number of bumps completely at random, or whether some correlation between successive flights should be introduced. As kinds of weather often persist for times that are long compared with the duration of a flight, it is to be expected that some correlation exists between flights. An assessment of the magnitude of this effect will be given by the serial correlations between the numbers of bumps in a series of flights. Unfortunately, apart from aircraft unserviceability, which is a part of the phenomenon being studied, gaps exist in the data due to instrument unserviceability and often when film changes are necessary. However, one film from the counting accelerometers usually covers about sixteen successive flights, and since, as will be seen later, only the first few serial correlations are significant, it has been thought sufficient to treat the whole data as a complete sequence, and assume that this is fairly typical of what occurs in practice.

When this is done it is found that

$$r_1 = 0.224$$
$$r_2 = 0.055$$
$$r_3 = 0.014$$
$$r_4 = 0.048$$
$$r_5 = 0.024$$

with standard errors of 0.033.

These values, particularly that for r_1, are surprisingly small, and only r_1 differs significantly from zero.

The correlogram is shown in Fig.6. It would appear unnecessary at this stage to introduce any refinement into the fatigue test to correlate numbers of loads in successive flights, although this is simple to do*.

6 VARIABILITY AT DIFFERENT ACCELERATION LEVELS

With the derivation of the distribution of bumps per flight, and the magnitude distribution within a flight for a given number of bumps, and the determination of the correlation between flights, the problem as regards the Viscount may be considered solved. However, if we wish to apply the results

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*Suppose that, instead of sampling at random from:

$$(1 + p - pt)^{-k} \quad (1)$$

we sample from:

$$(1 + p - pt)^{-0.2k}$$

obtaining a series of values x_1, x_2, x_3, etc.

If we now form the successive sums $x_1 + x_2 + x_3 + x_4 + x_5$, $x_5 + x_6 + x_7 + x_8 + x_9$, $x_9 + x_{10} + x_{11} + x_{12} + x_{13}$, etc., then these sums will have the distribution (1) and also have a first serial correlation of 0.2.

More generally, if we select at random from

$$(1 + p - pt)^{-k_1}$$

a series of values x_1, x_2, x_3, etc., and from

$$(1 + p - pt)^{-k_2}$$

a series of values y_1, y_2, y_3, etc.

and form the successive sums $x_1 + y_1 + x_2$, $x_2 + y_2 + x_3$, $x_3 + y_3 + x_4$, etc., then the distribution of these sums will be given by

$$(1 + p - pt)^{-2k_1 - k_2}$$

and the correlation between successive values will be $k_1/(2k_1 + k_2)$. The scheme can obviously be extended if necessary to include serial correlations with higher lags.

to other aircraft, more needs to be done. Different aircraft respond to different extents to the same gust, and a gust that produces a 0.2g bump on a Viscount aircraft will not necessarily produce the same acceleration on another aircraft.

It is thus necessary to determine how the parameters of the distribution given by (1) vary with acceleration. In order to do this, the procedure already carried out for 0.2g is repeated for 0.3g, 0.4g and 0.6g. The results are given in Tables 2-4, and shown plotted in Figs. 2-4 in order to indicate the adequacy of fitting. From these results the following short table is extracted:-

Acceleration in g units a	Mean number of bumps per flight of a or greater m	Variability parameter p
0.2	23.1394	42.7460
0.3	4.0526	16.6623
0.4	0.8781	8.1797
0.6	0.0748	1.7771

The values of m and p are shown plotted against a in Fig.7, so that for a given value of a, the values of m and p can be read off directly.

A more striking relationship to be derived from this table is, however, that between m and p. This is shown plotted on logarithmic scales in Fig.8, where it can be seen that a simple power law holds between the two variables over a wide range. Fitting to the two most significant points gives:-

$$p = 7.82\ m^{0.541} . \qquad (3)$$

So far the analysis would be sufficient to compare the results from the Viscount data with another aircraft, say aircraft B, which was operated with regard to routes, flight plan and so on, in exactly the same way as the Viscount, but which had different response characteristics. By finding the acceleration on the Viscount corresponding to 0.2g on aircraft B, the required values of m and p can be determined from Fig.7. Since it follows that the zero crossings are unchanged, the magnitude distribution can be determined from (2) as before.

If the average duration of flight for the two aircraft are not the same, difficulties arise. Consider the case in which aircraft B increases its average duration to twice that of the Viscount. It will help to simplify the argument if, for the moment, we ignore the fact that each flight has only one climb and one descent, during which time the majority of bumps are encountered.

Two extreme cases can be considered. If we choose two Viscount flights at random, and imagine them joined in time to form a longer flight, this would double the average duration. Since the two flights were selected at random, the generating function for the longer flights would be the square of expression (1), and thus, would be obtained merely by replacing k by 2k, leaving the rest of the expression unchanged.

However, this is certainly not the case in practice, since there is a high correlation between the two halves of the flight. As our second extreme case, if this correlation were unity, with the second part of the flight duplicating the first, the effect would be merely to double the numbers of bumps of all magnitudes per flight. Thus, the mean would be doubled and the variance increased by a factor of 4, so that the value of $(1 + p)$ would be doubled - for large values of p, approximately equivalent to doubling p.

Now $m = kp$, and we see that the two extreme cases correspond to increasing m by increasing k only when the parts of the flight are uncorrelated, or by increasing p only, when there is perfect correlation.

It is possible that in reality the way in which p and k contribute to changes in m depend on the kind of turbulence being considered. For turbulence due to convective activity persisting over wide areas, the mean probably depends largely on p. If, however, we restrict ourselves to a consideration of the high altitude cruise of long-range aircraft in which sporadic clear air turbulence contributes significantly, then k may become more important.

What help do the observations at present under consideration give in answering these questions?

7 INFLUENCE OF FLIGHT DURATION ON THE MEAN NUMBER OF BUMPS AND VARIABILITY

We can get some insight into the problem by taking the present data, grouping them according to duration of flight and calculating the values of m and p for each group. The disadvantage of this procedure is that for each group the variation in flight time is much smaller than for the sample as a whole. This automatically causes a reduction in the variability and decreases p accordingly. It is, therefore, to be expected that the average value of p for the grouped data will not necessarily agree with that for the data treated as a whole, and the values of p thus obtained will not be representative of normal operational flying with a wider scatter of durations. In spite of this, such a grouping should provide a useful guide to the way in which p depends on duration, and the results are given in the following table:-

Range of times minutes	Average time minutes	Bumps of 0.2g or greater per flight	Variability parameter p
0 - 59	41.2	16.63	27.41
60 - 89	76.0	22.54	32.08
90 - 119	103.8	19.99	26.14
120 - 149	135.2	20.01	38.47
150 - 179	164.5	27.45	48.20
180 - 209	194.1	29.86	41.99
210 or more	231.2	27.80	85.52

Before considering the variations of p, let us first of all examine the way in which the average number of bumps per flight varies with duration. This is illustrated by Fig.9.

There is a considerable scatter of results but, apart from this, it is immediately obvious that the two quantities are not proportional to one another. This, of course, was anticipated in the previous discussion, and is due to the fact that the majority of bumps are encountered during climb and descent, whereas increasing duration is due normally to an increase in the cruise. The full line in Fig.9 has been estimated using some figures from previous work by Heath-Smith[3]. For Viscounts operated by B.E.A. he has found that 35.76% of the time is spent in climb and descent, while 76.75% of the bumps are encountered during climb and descent. For the data under consideration here the average duration of flight is 126.5 minutes, and the average number of bumps per flight is 23.14. Dividing these in the proportions found by Heath-Smith gives 45.2 minutes per flight for climb and descent, and 81.3 minutes for cruise, while each climb and descent accounts for 17.76 bumps, and each cruise averages 5.38 bumps. Thus, the average rate of encountering bumps in the cruise is 0.0662 per minute. The relation between the mean number of bumps per flight, m, and the duration, T, in minutes, is therefore:-

$$m = 17.76 + 0.0662 (T - 45.2)$$

i.e.

$$m = 14.77 + 0.0662T \qquad (4)$$

The trend of the experimental points in Fig.9 shows good agreement with this estimate.

However, we are mainly concerned with the relationship between m and p, and Fig.10a shows their values plotted logarithmically. Apart from one point, a simple power law relationship appears to fit the facts reasonably well, and the fact that its slope is at 45° shows that m is proportional to p. Thus, the whole of the variation in m is contributed by p, indicating high correlation between conditions throughout each flight. Fig.10b shows the same values plotted to linear scales.

Even allowing for the large sampling errors, the discrepancy shown by the point representing flights of over $3\frac{1}{2}$ hours is hard to explain. This point represents 101 flights, and a closer examination reveals that of these, two were exceptionally rough and accounted for almost a quarter of the bumps and over two-thirds of the variance in this class. It is possible that in very rough weather it was necessary in these cases to make diversions, and this would account for the combination of long flights and severe conditions. Some such explanation of the large departure from the otherwise well-established relationship seems plausible.

All things considered, it seems reasonable to assume that variations in the mean number of bumps per flight due to changes in flight duration produce a corresponding change in the parameter p, and leave the value of k unaltered.

This result is not altogether unexpected but makes rather more surprising the low correlation between flights which was found earlier, and implies that for times and distances above the average flight values the correlation falls off rapidly. A good deal of caution should, therefore, be exercised in extrapolating to very long flights.

8 APPLICATION OF RESULTS TO OTHER AIRCRAFT

We have now obtained the distribution of bumps per flight, the magnitude distribution within flights and the correlation between flights for Viscount aircraft, and have examined in a general way the effect of changes in aircraft response and of average flight duration. It will, perhaps, be useful at this stage to go through the successive steps necessary to apply what we have learnt from the Viscount to another aircraft.

The first step is to derive by the best means available the distribution of the average numbers of bumps of different magnitudes per flight. In the absence of counting accelerometer or fatigue meter data, estimates based on the flight plan and existing gust data may be used. This distribution is then compared with the corresponding distribution for the Viscount given in Fig.7 of this paper. Such a comparison is illustrated in Fig.11, where the Viscount curve of Fig.7 is plotted with a similar curve for a hypothetical aircraft B.

Generally speaking, it will be found that the curves differ in two respects. Firstly, they intersect the vertical axis at different points; that is, the average numbers of zero crossings per flight differ. This corresponds to a difference in exposure to turbulence, and is the kind of change produced by changes in the average duration of flight. A vertical translation of the curve for aircraft B, so that the intersections on the axis coincide, leaves a horizontal scale difference of the kind produced by differences in response, and usually it will be found that the curves are similar in shape.

Now a change in response implies that a gust producing a 0.2g bump on aircraft B produces a different acceleration on the Viscount, and we have already examined how the parameter p varies with acceleration level for the Viscount. The value of p for the required acceleration level can therefore be read off directly from Fig.7. Alternatively, p can be calculated from the change in m and expression (3).

The vertical translation of the curve corresponds to a change in the degree of exposure to turbulence, and is allowed for by factoring the new value of p in the same ratio as the number of zero crossings.

Referring to Fig.11, the value of p is required for the point A on the curve for aircraft B. The change from A to B - that is the change in the number of zero crossings - is given by a factor corresponding to AB, i.e. 1.5. An acceleration of 0.2g on aircraft B corresponds to an acceleration of 0.182g on the Viscount, and change due to this difference of response corresponds to the change CD of the Viscount curve. Bearing in mind the power law relationship between p and m given by (3), this is found from the figure as the factor corresponding to 0.54BC, and this is 1.2.

Thus, the distribution of bumps of 0.2g or greater in a flight for aircraft B is given by (1) with m = 48.5 and p = 77.1.

The magnitude distribution of bumps within flights is given by expression (2) multiplied by a factor of 1.5 to allow for the change in the number of zero crossings, and this becomes

$$N = 195 \exp\left(-\frac{a}{0.1108r}\right) + 3795 \exp\left(-\frac{a}{0.0576r}\right)$$

the range of distributions being produced, as before, by varying r.

Little can be said regarding correlation between flights without more knowledge of the circumstances. In the case of the Viscount this correlation was seen to be small and perhaps negligible for fatigue test purposes, so that for any aircraft operating with roughly the same duration of flight or longer, it is probably safe to neglect it, certainly as a first approximation. For an aircraft flying a larger number of shorter routes per day the effect may become more significant.

9 CONCLUDING REMARKS

Existing information has made it possible to examine the distribution of numbers of bumps in a flight, the magnitude distribution of bumps within a flight, and the correlation between flights, for Viscount aircraft operated by British European Airways.

It has also been possible to make an assessment of how the parameters characterising these distributions are affected by factors such as differing aircraft response and duration of flight. Many of the conclusions, however, are of a somewhat tentative nature, and require confirmation from further work to place them on a firm basis. Nevertheless, the information given is considered adequate for comparative fatigue investigations.

Table 1

DISTRIBUTION OF NUMBER OF BUMPS OF 0.2g OR GREATER IN A FLIGHT

No. of bumps of 0.2g or greater in a flight n	Number of flights with n bumps. Observed	Number of flights with n bumps or more	
		Observed	Calculated
0	57	1083	1083.0
1	71	1026	942.9
2	68	955	868.8
3	50	887	813.0
4	41	837	766.9
5	33	796	726.9
6	37	763	691.5
7	33	726	659.5
8	33	693	630.2
9	36	660	603.3
10	30	624	578.4
11	29	594	555.1
12	23	565	533.3
13	23	542	512.8
14	22	519	493.5
15	32	497	475.3
16	22	465	458.0
17	25	443	441.6
18	19	418	426.0
19	16	399	411.2
20	22	383	397.0
21	13	361	383.5
22	7	348	370.5
23	7	341	358.2
24	9	334	346.3
25	6	325	335.0
26	14	319	324.1
27	11	305	313.7
28	10	294	303.6
29	10	284	294.0
30	8	274	284.7
31	11	266	275.8
32	10	255	267.2
33	9	245	258.9
34	6	236	250.9
35	8	230	243.2
36	5	222	235.8
37	7	217	228.7
38	3	210	221.8
39	6	207	215.1
40	11	201	208.7
41	5	190	202.5
42	7	185	196.5
43	3	178	190.7
44	7	175	185.1
45	8	168	179.6
46	2	160	174.4
47	6	158	169.3
48	4	152	164.4
49	7	148	159.6
50	3	141	155.0
51	5	138	150.6
52	4	133	146.3
53	4	129	142.1
54	5	125	138.1
55	4	120	134.1
56	6	116	130.3
57	8	110	126.7
58	4	102	123.1
59	3	98	119.6
60	2	95	116.3
61	2	93	113.0
62	2	91	109.9
63	1	89	106.8
64	2	88	103.8
65	2	86	101.0
67	2	84	95.5
68	4	82	92.8
69	4	78	90.3
70	2	74	87.8
71	2	72	85.4
72	4	70	83.1
74	3	66	78.6
75	2	63	76.4
76	1	61	74.4
78	1	60	70.4
79	2	59	68.5
80	2	57	66.6
83	3	55	61.4
88	1	52	53.6
89	2	51	52.2
90	3	49	50.8
91	1	46	49.5
92	2	45	48.1
94	2	43	45.6
95	2	41	44.4
97	2	39	42.1
98	1	37	41.0
99	1	36	39.9
100	1	35	38.9
102	2	34	36.8
103	1	32	35.9
104	3	31	34.9
106	3	28	33.1
108	1	25	31.4
111	1	24	29.0

Table 1 Continued

No. of bumps of 0.2g or greater in a flight n	Number of flights with n bumps. Observed	Number of flights with n bumps or more	
		Observed	Calculated
112	1	23	28.3
115	1	22	26.1
116	1	21	25.5
119	1	20	23.5
124	2	19	20.7
130	1	17	17.7
133	1	16	16.3
136	2	15	15.1
140	2	13	13.6
142	1	11	13.0
143	1	10	12.6
147	1	9	11.4
148	1	8	11.1
162	1	7	Not Calculated
185	1	6	
191	1	5	
245	1	4	
282	1	3	
294	1	2	
341	1	1	

Table 2

DISTRIBUTION OF NUMBER OF BUMPS OF 0.3g OR GREATER IN A FLIGHT

No. of bumps of 0.3g or greater in a flight n	Number of flights with n bumps. Observed	Number of flights with n bumps or more	
		Observed	Calculated
0	440	1083	1083.0
1	154	643	544.3
2	104	489	420.7
3	65	385	348.3
4	57	320	297.1
5	43	263	258.0
6	28	220	226.7
7	29	192	200.9
8	19	163	179.2
9	21	144	160.6
10	15	123	144.6
11	13	108	130.6
12	6	95	118.4
13	8	89	107.5
14	8	81	97.9
15	8	73	89.3
16	4	65	81.5
17	3	61	74.6
18	11	58	68.4
19	1	47	62.7
20	4	46	57.6
21	4	42	53.0
22	3	38	48.8
23	3	35	44.9
24	2	32	41.4
27	2	30	32.6
28	3	28	30.1
29	3	25	27.9
31	1	22	23.9
32	3	21	22.1
33	2	18	20.5
34	1	16	19.0
35	1	15	17.6
36	1	14	16.4
41	2	13	11.3
42	1	11	10.5
43	1	10	9.8
46	1	9	7.9
47	1	8	7.4
65	1	7	2.1
68	1	6	1.7
70	1	5	1.5
71	1	4	1.4
78	1	3	0.9
81	2	2	0.7

Table 3

DISTRIBUTION OF NUMBER OF BUMPS OF 0.4g OR GREATER IN A FLIGHT

No. of bumps of 0.4g or greater in a flight n	Number of flights with n bumps. Observed	Number of flights with n bumps or more	
		Observed	Calculated
0	801	1083	1083.0
1	133	282	229.4
2	51	149	147.7
3	30	98	107.4
4	15	68	82.2
5	7	53	64.8
6	11	46	52.0
7	4	35	42.3
8	4	31	34.8
9	4	27	28.8
10	4	23	24.0
11	3	19	20.1
12	4	16	16.9
13	1	12	14.3
14	3	11	12.1
15	2	8	10.3
16	2	6	8.8
26	1	4	2.0
30	1	3	1.1
34	1	2	0.6
41	1	1	0.2

Table 4

DISTRIBUTION OF NUMBER OF BUMPS OF 0.6g OR GREATER IN A FLIGHT

No. of bumps of 0.6g or greater in a flight n	Number of flights with n bumps. Observed	Number of flights with n bumps or more	
		Observed	Calculated
0	1036	1083	1083.0
1	31	47	45.6
2	8	16	17.6
3	4	8	8.3
4	2	4	4.3
6	1	2	1.3
8	1	1	0.4

Table 5

MAGNITUDE DISTRIBUTIONS OF BUMPS FOR DIFFERENT NUMBERS OF BUMPS OF 0.2g OR GREATER IN A FLIGHT

No. of bumps of 0.2g or greater in a flight	Number of flights	Total number of bumps equal to or greater than:-					Mean number of bumps per flight equal to or greater than:-			
		0.2g	0.3g	0.4g	0.6g	0.8g	0.2g	0.3g	0.4g	0.6g
0 to 19	702	5132	557	56	4	1	7.311	0.7934	0.07977	
20 to 39	180	5094	758	138	4	1	28.30	4.211	0.7667	
40 to 59	106	5161	890	169	9	1	48.69	8.396	1.594	
60 to 99	60	4612	862	191	19	1	76.87	14.37	3.183	0.3167
100 and over	35	5061	1322	397	45	3	144.6	37.77	11.34	1.286
Totals	1083	25060	4389	951	81	7	23.14	4.053	0.8781	0.07479

SYMBOLS

a	aircraft normal acceleration
g	acceleration due to gravity
k	a parameter in the distribution of number of bumps in a flight, - expression (1)
m	the mean number of bumps of a given acceleration or greater per flight
N	the mean number of bumps of a given acceleration or greater in a class of flights restricted by the number of bumps occurring in them, - expression (2)
n	the number of bumps of a given acceleration or greater in a flight
p	a parameter in the distribution of number of bumps in a flight - expression (1)
r	a scale parameter in expression (2)
r_1, r_2, etc.	serial correlation coefficients between numbers of bumps in a flight
T	duration of flight

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No.	Author	Title, etc.
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2	N.I. Bullen	Atmospheric turbulence in relation to aircraft. Ninth International Congress for Applied Mechanics. Brussels 1956
3	J.R. Heath-Smith	Atmospheric turbulence encountered by Viscount aircraft over Europe. A.R.C. Current Paper 463

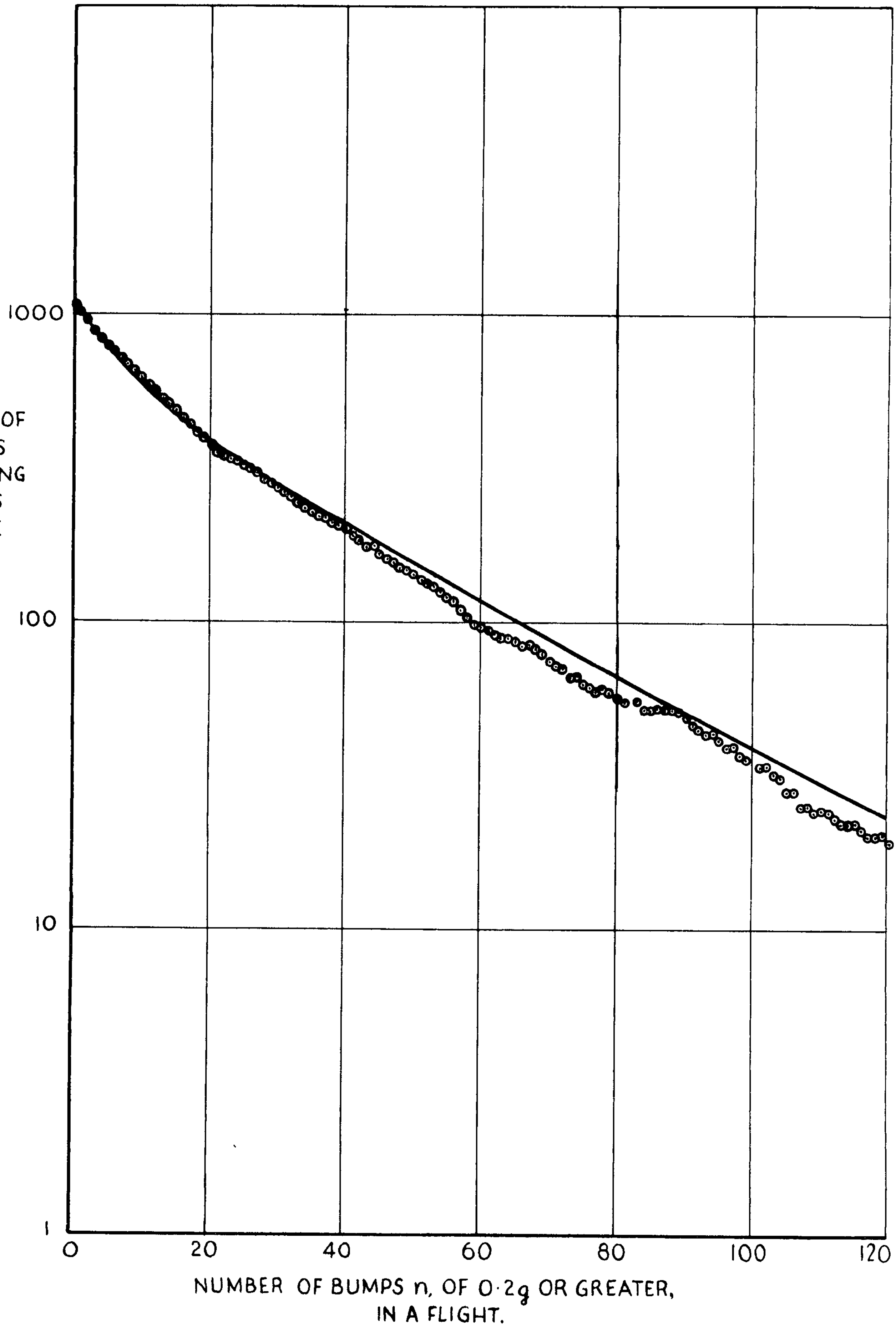


FIG. 1 DISTRIBUTION OF NUMBER OF BUMPS OF 0·2g OR GREATER IN A FLIGHT.

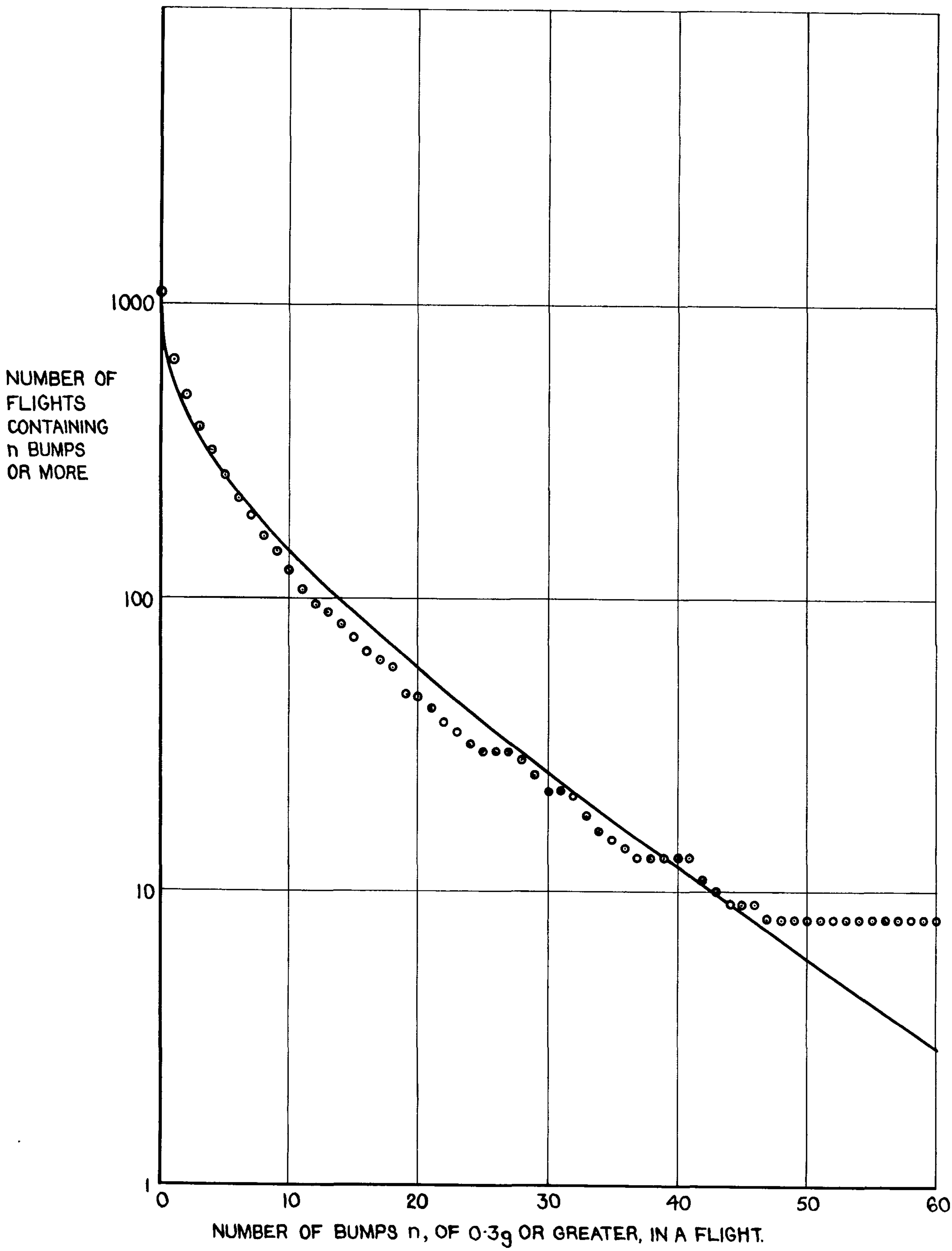


FIG. 2 DISTRIBUTION OF NUMBER OF BUMPS OF 0·3g OR GREATER IN A FLIGHT

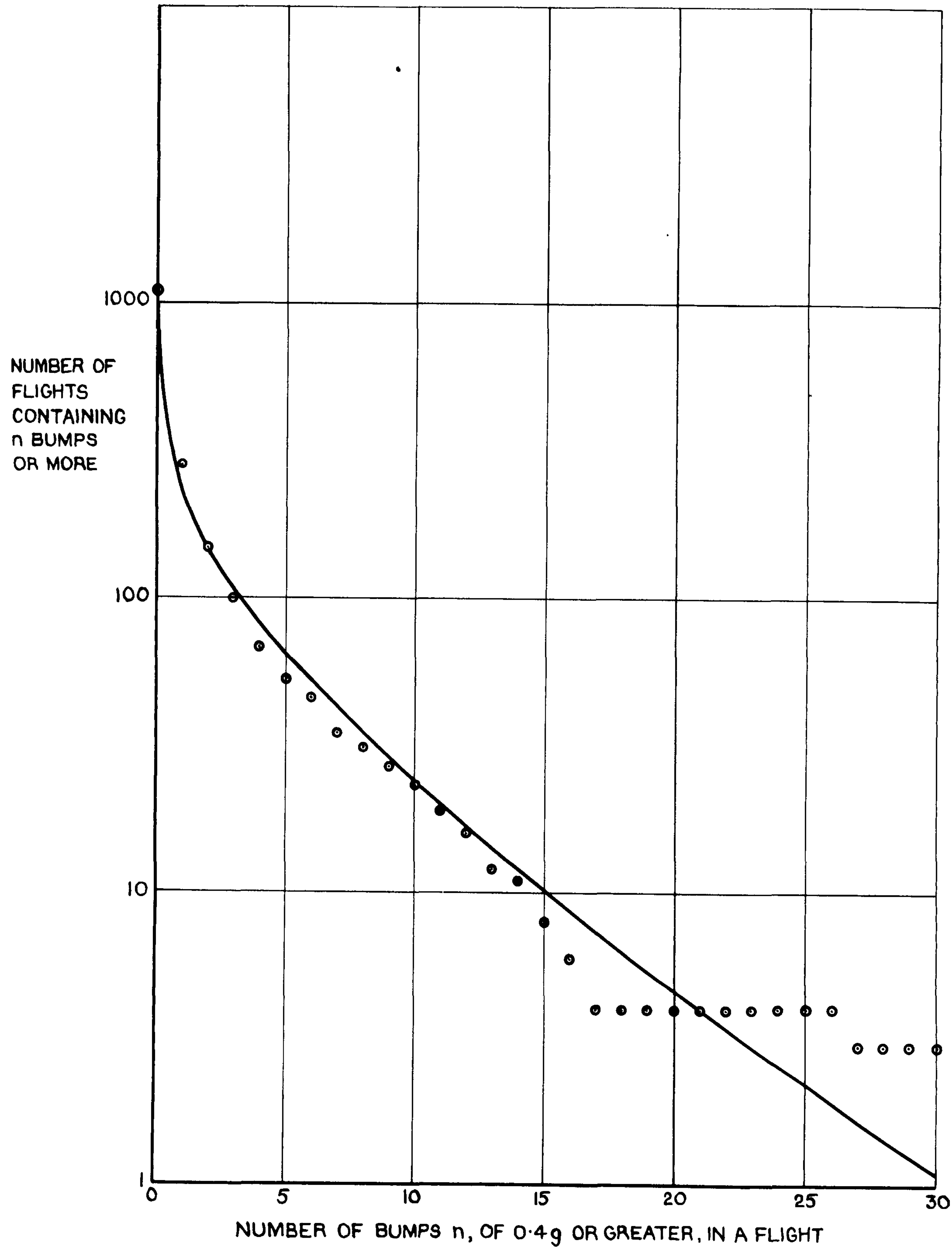


FIG. 3 DISTRIBUTION OF NUMBER OF BUMPS OF 0·4g OR GREATER IN A FLIGHT

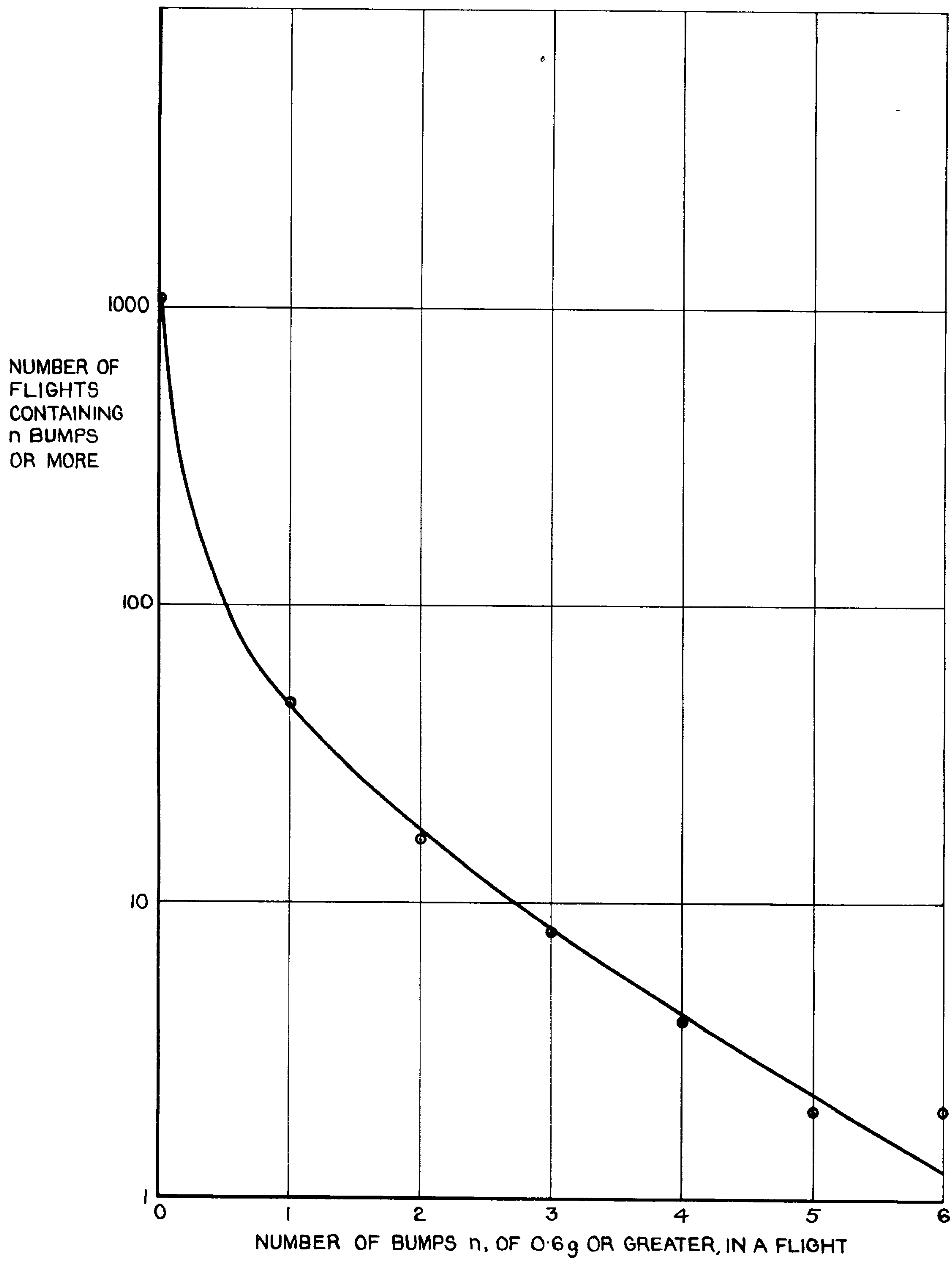


FIG. 4 DISTRIBUTION OF NUMBER OF BUMPS OF 0·6g OR GREATER IN A FLIGHT

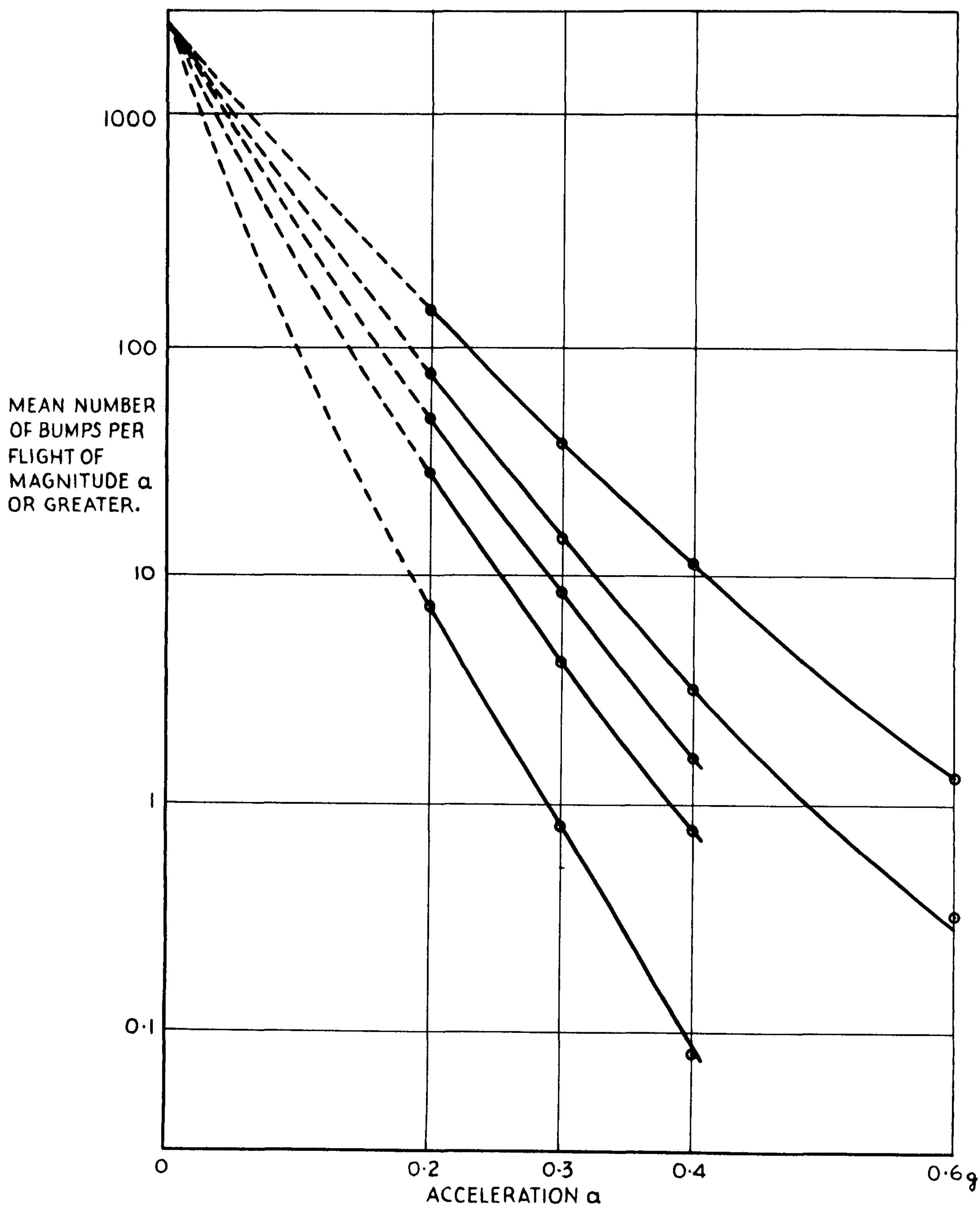


FIG. 5 MAGNITUDE DISTRIBUTIONS OF BUMPS FOR DIFFERENT NUMBERS OF BUMPS PER FLIGHT.

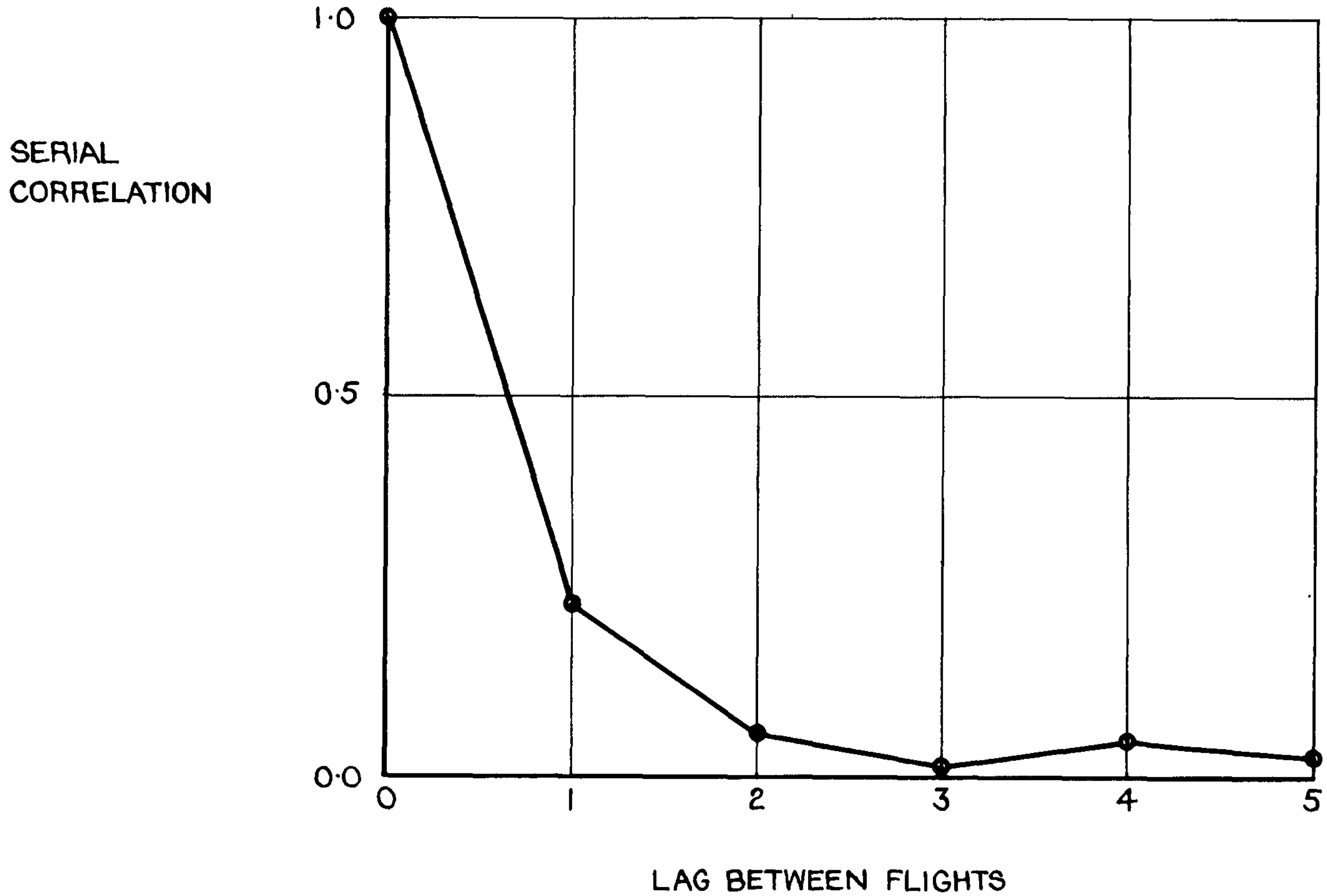


FIG. 6 CORRELOGRAM FOR NUMBERS OF BUMPS IN A FLIGHT

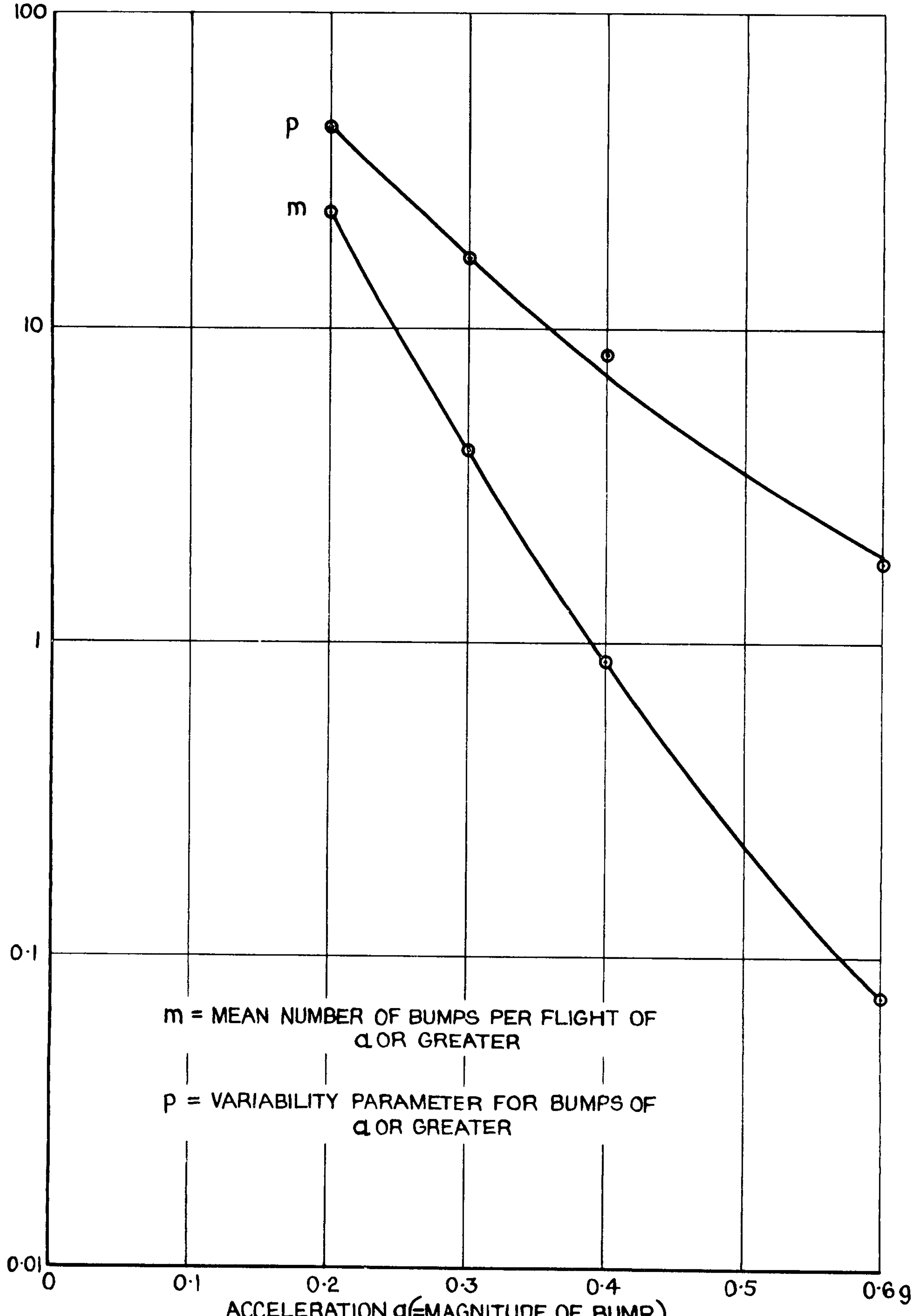


FIG. 7 VARIATION OF THE MEAN NUMBER OF BUMPS PER FLIGHT OF A GIVEN MAGNITUDE OR GREATER AND OF THE VARIABILITY PARAMETER WITH MAGNITUDE OF BUMP

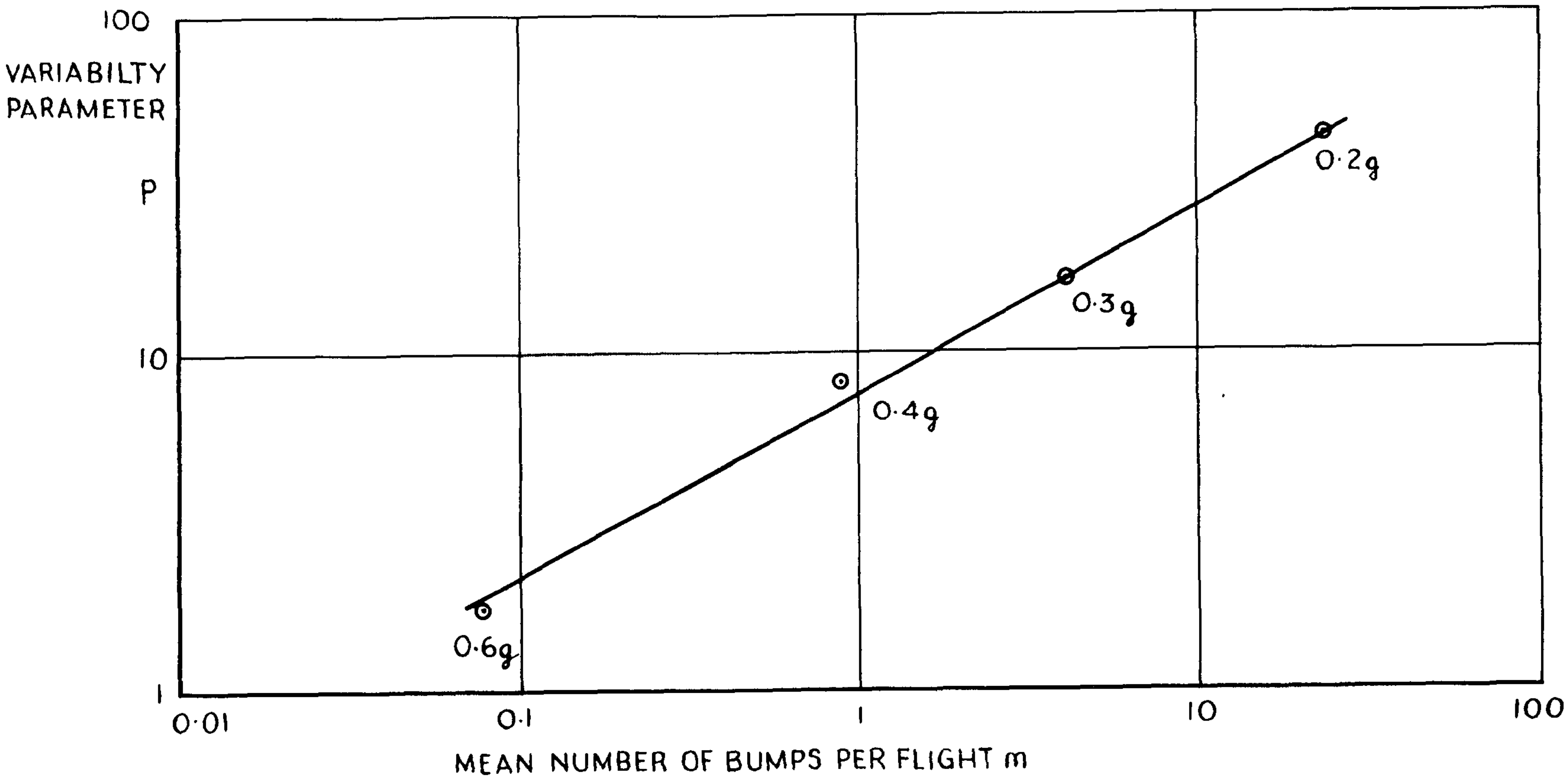


FIG. 8 RELATIONSHIP BETWEEN MEAN NUMBER OF BUMPS PER FLIGHT AND VARIABILITY PARAMETER

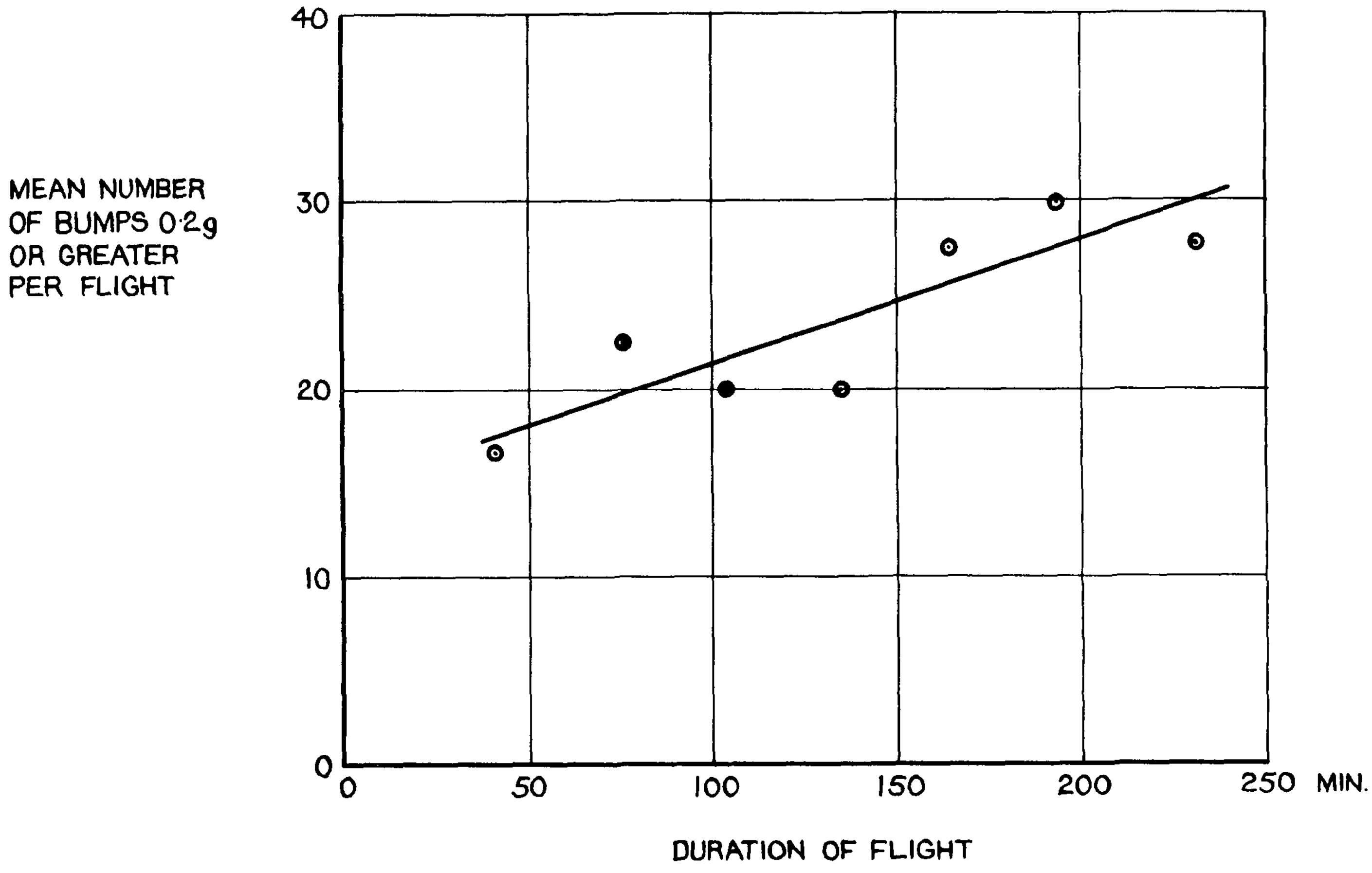
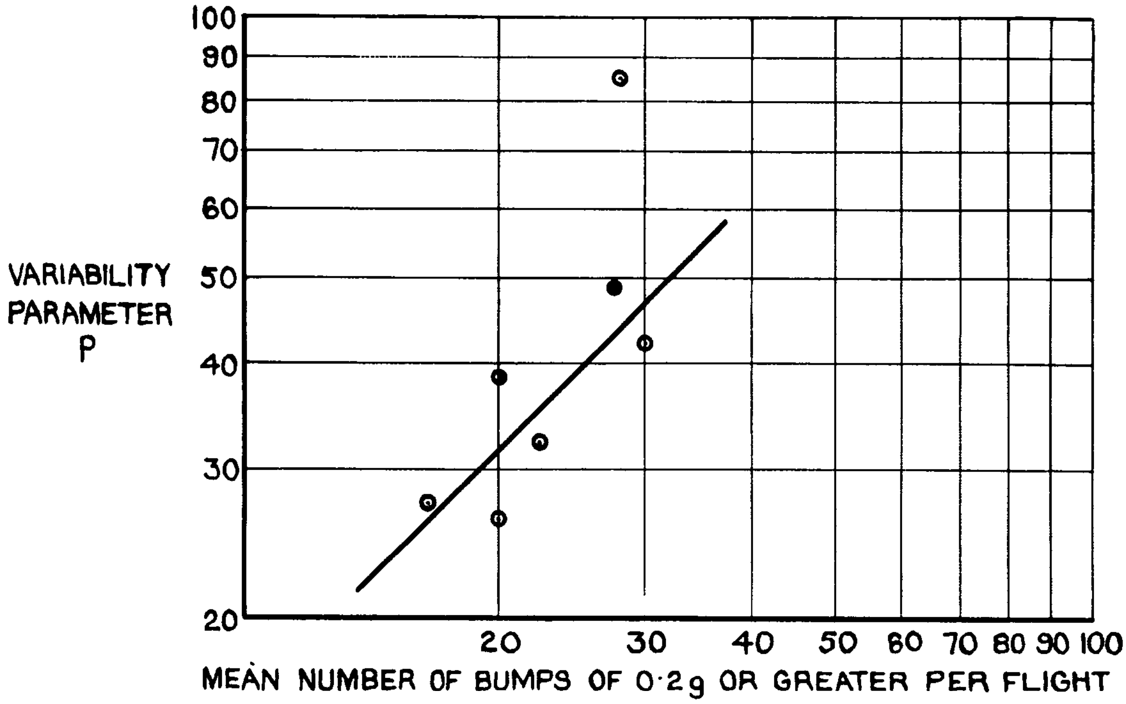
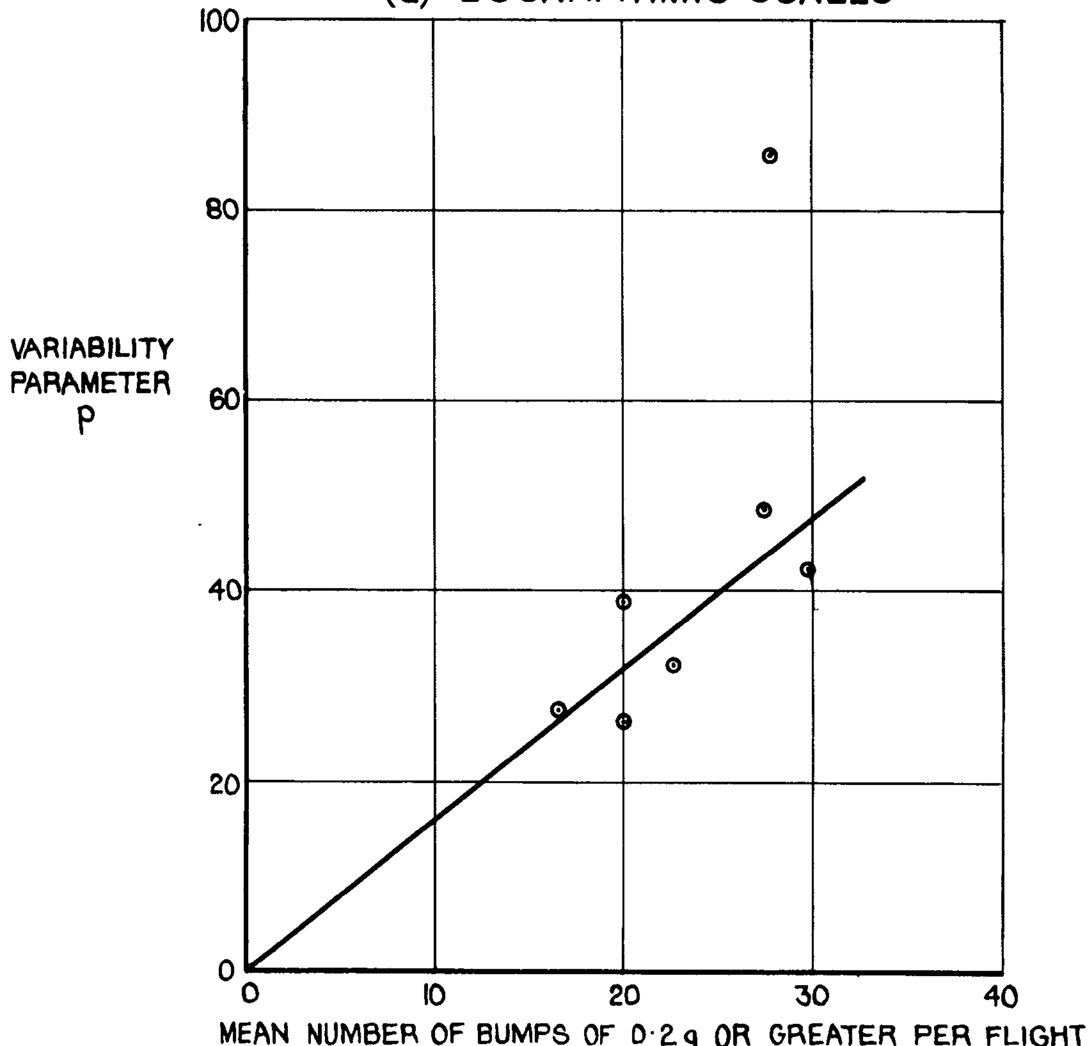


FIG. 9 VARIATION OF THE MEAN NUMBER OF BUMPS OF 0·2g OR GREATER PER FLIGHT WITH DURATION OF FLIGHT



(a) LOGARITHMIC SCALES



(b) LINEAR SCALES

FIG. 10 RELATIONSHIP BETWEEN THE MEAN NUMBER OF BUMPS OF 0·2 OR GREATER PER FLIGHT AND THE VARIABILITY PARAMETER FOR CHANGES IN FLIGHT DURATION

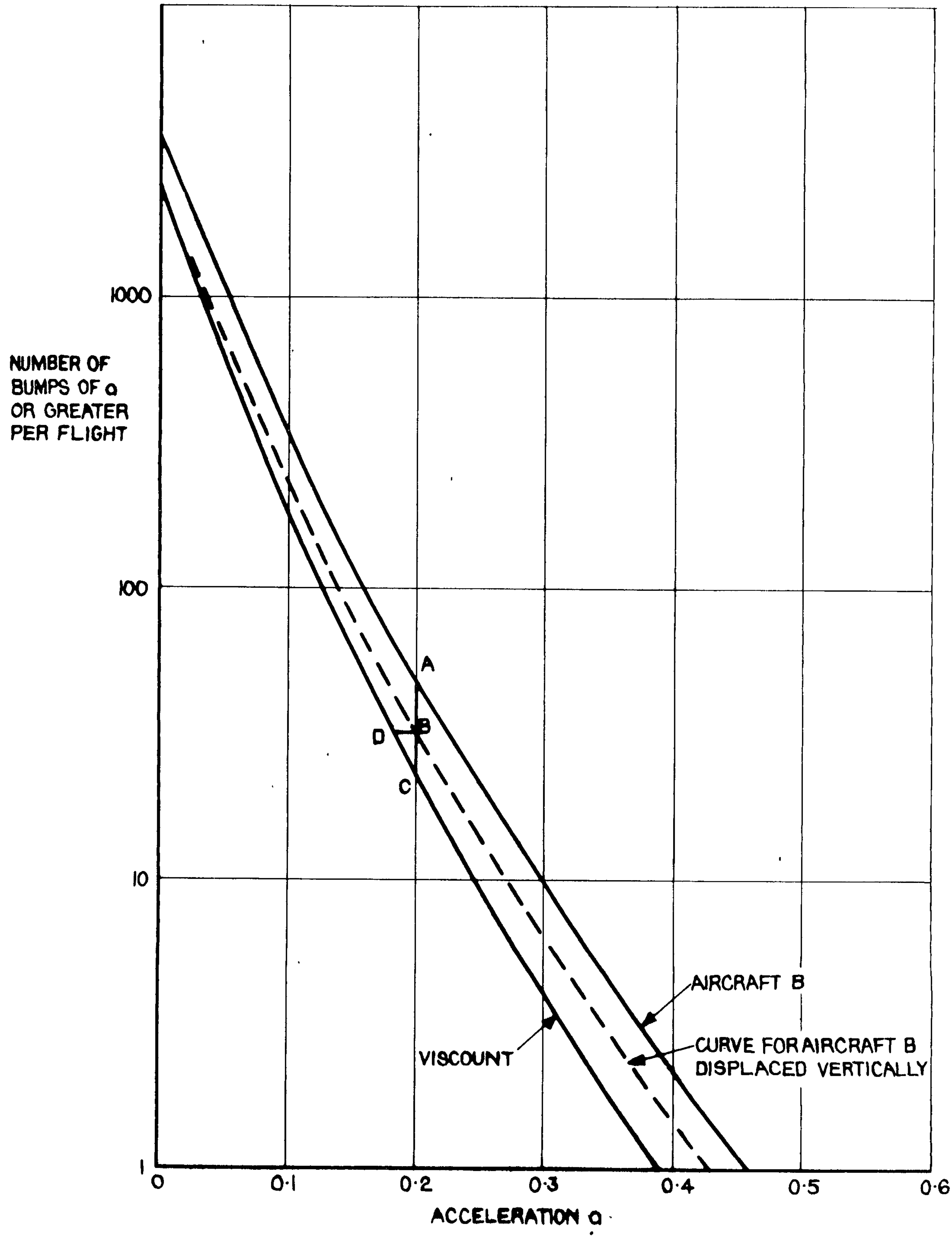


FIG.11 COMPARISON OF BUMPS PER FLIGHT EXPERIENCED BY VISCOUNT AND AIRCRAFT B

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It is found that the magnitude distribution of bumps within a flight is dependent on the total number of bumps in the flight, and the correlation between successive flights is found to be low.

The degree to which the results can be extended to apply to other aircraft is discussed.

It is concluded that the findings of the paper are sufficient to enable comparative tests to be done to assess the effect of variability between flights on fatigue life.

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