MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Vertical Acceleration in the Cockpit of a Subsonic Transport Aircraft during Take-off Measured during Airline Operation

by

C. G. B. Mitchell

Structures Dept., R.A.E., Farnborough

LONDON: HER MAJESTY'S STATIONERY OFFICE

1970

PRICE 9s 0d [45p] NET

U.D.C. 531.113 : 629.13.081 : 534.13 : 629.137.1

VERTICAL ACCELERATION IN THE COCKPIT OF A SUBSONIC TRANSPORT AIRCRAFT
DURING TAKE-OFF MEASURED DURING AIRLINE OPERATION

by

C. G. B. Mitchell

Structures Department, R.A.E., Farnborough

SUMMARY

Vertical acceleration in the cockpit of a Boeing 707-436 during take-off
has been measured for 94 take-offs from 31 airports during airline operations.
The vertical acceleration near the centre of gravity was measured during 33
take-offs. The maximum cockpit incremental acceleration was 0.75 g, and this
acceleration exceeded 0.53 g for 10% of the take-offs. At a given airport the
cockpit acceleration at a weight of 140 000 kg was about twice that at 90000 kg
but the cg acceleration did not vary with weight. The amplitude of the cockpit
acceleration varied between airports by a factor of about two at 115 000 kg.
The cockpit/cg acceleration ratio was between 0.9 and 2.3, but for more than
80% of take-offs was between 1.0 and 1.5. The vibration levels experienced
had no detectable effect on errors of rotation speed at take-off.

<u>CONTENTS</u>

1 INTRODUCTION

Some of the largest accelerations experienced by transport aircraft occur while they are taxying before take-off and after landing. These accelerations are significant in themselves, because they cause crew and passenger discomfort, and they are also significant as an indication of structural loading, at least in the vicinity of the undercarriage units and on the fuselage. There is, however, relatively little information on the vibration levels experienced in the cockpits of jet transport aircraft during taxying.

Morris[7] has measured the response of a Boeing 720 taxying on three runways at two North American international airports. The response quantities measured were the cockpit normal and lateral accelerations, and the centre of gravity normal acceleration. Power spectra of the responses were calculated, and from these transfer functions for the response of the linearised model of the aircraft could be calculated, as the runway profiles had been measured and the power spectra of the runway roughness calculated. These measurements showed that the rms normal acceleration in the cockpit exceeded that at the centre of gravity by between 45% and 110%. On the roughest runway, the maximum normal accelerations were about $0.28\,g$ near the centre of gravity and 0.50 g in the cockpit. During take-off, the lateral acceleration in the cockpit was approximately half the normal acceleration while, during landing, the lateral acceleration was about three quarters the normal. The power spectra of the normal accelerations during taxying showed peaks due to pitching of the aircraft at $\frac{3}{4}$ Hz (c/s), heaving of the aircraft at $1\frac{1}{2}$ Hz, and structural modes at frequencies of 4 Hz, $5\frac{1}{2}$ Hz, and higher frequencies.

Hall[2] has measured vibration levels in a VC 10 during take-off from runway 06/24 at Boscombe Down. Again, the quantities measured were the cockpit normal and lateral accelerations, and the centre of gravity normal acceleration. Power spectra of the measured responses were calculated and showed similar response modes to those of the Boeing 720. Hall showed that the level of vibration increased as the aircraft speed increased. The largest acceleration level in the cockpit was 0.46 g and the largest near the centre of gravity was 0.17 g. For both the Boeing 720 and the VC 10 the maximum acceleration that occurred during a take-off run was approximately four times the rms acceleration for that run.

As part of the Civil Aircraft Airworthiness Data Recording Programme (CAADRP)[3], a Boeing 707-436 four jet transport aircraft has been fitted with a

number of instruments to enable the normal accelerations at the cockpit and
centre of gravity to be measured, together with the air speed, altitude,
control positions and a number of other parameters. This Report analyses the
accelerations measured during 94 take-offs made by this aircraft during
commercial operations in December 1965 and January and February 1966. During
this time, records were made at thirty-one airports. It is complementary to
Ref.4, which contains a description of the characteristics of the cockpit normal
acceleration during twenty-five take-offs and twenty-five landings on the same
aircraft.

2   MEASUREMENT PROGRAMME

2.1   Aircraft and instrumentation

The aircraft was a Boeing 707-436 four jet passenger transport operated by
a British airline. During the period considered, the maximum weight at which a
take-off was made was 141 080 kg and the minimum take-off weight was 79950 kg.
The average weight for all 94 take-offs was 120 540 kg.

The measurements that were of interest to this particular investigation
were those of cockpit vertical acceleration, cg vertical acceleration, air
speed and elevator position; these and other parameters were recorded on
photographic paper 9 cm wide, using a SFIM* A261 recorder. This recorder runs
at a nominal paper speed of 37.5 mm/min during the take-off and landing of the
aircraft.

The air speed measurement was derived from a pressure capsule, mounted in
the recorder, and connected to the 1st officer's pitot-static system. The
elevator angle was not measured directly. A potentiometer was used to measure
the control column movement, and the actual control surface movement is
primarily a function of this control column displacement and the aircraft
speed. The vertical acceleration near the cg was measured by an R.A.E. -2 g to
+4 g accelerometer of the variable inductance, eddy current damped, type, which
directly drove a ratiometer mounted in the recorder. The vertical acceleration
in the cockpit was measured by an R.A.E. 0 g to +2 g accelerometer, the output
from which was filtered electrically, mounted on a floor beam 3 ft (0.9 m)
behind the Captain's seat. This accelerometer, without the electrical filter,
is described in Ref.5, and the -2 g to +4 g accelerometer is a modification of
the same design. The frequency response characteristics of both the accelero-
meter systems connected to the recorder are shown in Fig.1.

---

* Société de Fabrication de'Instruments de Mésure.

2.2   Airports

During the period considered, take-offs were made from thirty-one air-
ports; these are identified by numbers in this Report and were located in
Australia, Burma, Canada, Islands in the Caribbean, Germany, Hong Kong, India,
Iran, Israel, Italy, Japan, Lebanon, Malaysia, New Zealand, Islands in the
Pacific, Switzerland, Thailand, United Kingdom and the U.S.A. The airports
are believed to be representative of the operator's routes as all take-offs
that were recorded were analysed. However, the recorder was replenished at
the operator's main base and ran out of paper at some point on the route.
This may have slightly biased the sample of airports at which take-offs were
recorded. The paper supply for the recorder was sufficient to cover more than
one trip from the main base along the route and back. The runway used and the
wind conditions are only known for twenty-five of the ninety-four take-offs.

2.3   Analysis of the records

A typical record is shown in Fig.2. The cockpit vibration can be seen to
occur at $\frac{3}{4}$ Hz, which is due to pitching of the aircraft, $1\frac{1}{4}$ Hz due to heaving
and at higher frequencies due to structural vibration. Because of the low
paper speed through the recorder it has not been possible to determine the
frequency of the vibration if this was greater than about 2 Hz. It can also
be seen that interference occurs between the speed trace and the two accelera-
tion traces.

Records were analysed visually by marking the original record with lines
to represent levels at 0.1 g increments. The number of peaks exceeding each
level was counted, only one peak being counted for each crossing of the 1.0 g
datum. In addition, the number of peaks above intermediate levels (0.15 g,
0.25 g, etc.) were counted. The acceleration exceedences were found, keeping
positive and negative exceedences separate, and then these two sums totalled
to give the number of acceleration amplitude exceedence counts. These counts
were plotted against the acceleration amplitude and examples of this are shown
in Fig.3. A smooth curve was fitted through counts at the various acceleration
levels and the severity of the vibration for that particular take-off defined
as the acceleration level which occurs at the 10 count level on the smooth
curve. This quantity is called Δn_{10}. The largest acceleration that occurs
during a single take-off is given the symbol Δn_1. Both Δn_{10} and Δn_1 are
incremental accelerations about the 1.0 g datum.

Analysis of unpublished calculated and measured take-off acceleration histories for a subsonic and a supersonic transport aircraft shows that an approximate relationship exists between Δn_{10} and the rms acceleration for the complete take-off run. For both aircraft the cockpit vertical acceleration Δn_{10} was about three times the rms acceleration. For the subsonic aircraft the cg vertical acceleration Δn_{10} was twice the rms acceleration, and for the supersonic aircraft cg acceleration this ratio was about one and a half. Such a relationship can, of course, be deduced if the probability distribution and number of zero crossings for the acceleration are known.

In addition to measuring the cockpit acceleration exceedences for the 94 take-offs described above, similar measurements of the cg vertical acceleration exceedences have been made for 33 of the 94 take-offs.

3   RESULTS

3.1   Quantitative results

The numerical results of the analysis of the cockpit acceleration records for the 94 take-offs are listed in Table 1. The results are given airport by airport, and the runway used is shown, where this is known. Also shown are the aircraft weight during the take-off run, the time of the take-off run to rotation and the air speed at rotation. The time of the take-off run is only an approximate measure as it is often difficult to define the instant at which the take-off run starts. Also shown in Table 1 are the positive and negative acceleration exceedence counts for each take-off, the measured value of Δn_1 and the deduced value of Δn_{10}. It will be seen that the majority of maximum accelerations occur in the positive direction. The speed at which the maximum acceleration Δn_1 occurs is also recorded. Where the same maximum acceleration occurs more than once during a take-off run the speed of each occurrence is recorded with an indication of whether the speed corresponds to a positive or negative acceleration, if positive and negative accelerations of equal magnitude occurred. Table 2 lists the values of Δn_1 and Δn_{10} for the cockpit and cg accelerations for the 33 take-offs, for which cg accelerations were measured. Also shown is the ratio of the cockpit/cg acceleration at the Δn_1 and Δn_{10} levels for the 33 take-offs. Table 3 lists the values of Δn_{10} that occurred on two runways during landings on two trips. These data show that the responses during the trip of 30 December to 2 January were some 35% larger than had occurred during the previous trip. Within each trip the responses are repeatable and consistent. The difference was not the result of differences of elevator usage on the two trips.

Fig.4 shows a probability density diagram for the speed at which the maximum acceleration occurs during a take-off run; this quantity is given the symbol V_{ma}. The data are grouped into speed bands 10 knots wide and presented in histogram form. It will be seen that the maximum acceleration during a take-off is likely to occur either at approximately 80 knots or at about 120 knots. Less than 10% of all the maximum accelerations occur at speeds less than 70 knots. Fig.5 shows how the value of Δn_1, the maximum acceleration during a take-off run, varies with the speed at which it occurs. It will be seen that for most take-offs Δn_1 for cockpit vertical acceleration exceeds 0.2 g on good runways and that on bad runways Δn_1 increases almost linearly with speed from 0.2 g at 35 knots to 0.7 g at 130 knots. The exceptions to this are two counts of 0.75 g at between 70 and 75 knots, both of which occurred at Airport 16.

Fig.6 shows the variation of Δn_{10} for cockpit acceleration with aircraft weight. It can be seen that Δn_{10} increases linearly with weight and that it also varies from airport to airport. For smooth runways Δn_{10} varies from about 0.1 g at 80000 kg to about 0.16 g at 140 000 kg and for rough airports the variation is from 0.14 g at 80000 kg to 0.40 g at 130 000 kg. No airport appears to be outstandingly good or outstandingly bad on a basis of Δn_{10} measurements.

Fig.7 shows the variation of Δn_1 for cockpit acceleration with aircraft weight. Again, the increase of Δn_1 with weight is clear, but there is naturally more scatter in Fig.7 than Fig.6. Airport 16 produced appreciably larger peak accelerations than any other. In Fig.8 the distribution of values of Δn_1 and Δn_{10} for cockpit acceleration are plotted on logarithmic/ probability scales. It can be seen that between the 0.95 and 0.01 probability levels both distributions are straight lines, indicating that the accelerations have a logarithmic normal probability distribution.

In Fig.9 Δn_1 is plotted against Δn_{10} for cockpit acceleration. This shows that as the severity of the vibration during a take-off increases the ratio $\Delta n_1/\Delta n_{10}$ increases from about 1.5 to about 2.0. The ratio does not vary with aircraft weight, and there is no difference between positive and negative peak accelerations. The variation that does occur may be due to the non-linear stiffnesses of the undercarriages, or perhaps to differences of the roughness distributions between relatively smooth and rough runways. Fig.10 shows the average distribution of cockpit incremental acceleration exceedences per take-off, for the 94 take-offs analysed, and of cockpit and cg acceleration exceedances of the 33 take-offs for which the cg acceleration was available.

Fig.11 shows the variation of Δn_{10} for the cg vertical acceleration with aircraft weight for 33 take-offs. It can be seen that the variation with weight is very slight. Fig.12 shows the variation of the ratio cockpit $\Delta n_{10}/\text{cg}\ \Delta n_{10}$ with aircraft weight. Variation with weight is quite marked, and, with the exception of one point at each of Airports 7 and 15, the scatter between airports is less than for the accelerations separately.

Finally, the effect of the vibration environment on the accuracy with which the aircraft is rotated for take-off is shown in Fig.13, where the error in rotation speed is plotted against Δn_{10} for the take-off. No effect can be detected.

3.2 Qualitative results

Some aspects of the records cannot easily be described quantitatively and these will be briefly described qualitatively in this section.

During a number of take-offs the control column was not moved forward until after speed had increased beyond 40 knots; this forward movement of the control column usually coincided with the start of vibration at both the cockpit and the cg. An example of this is shown in Fig.14a. The reason for this is that forward movement of the control column increases the mean vertical reaction in the nose undercarriage which increases the stiffness of the nose undercarriage oleo strut. At the higher stiffness the forces transmitted to the aircraft, as a result of passing over rough points on the runway, are greater.

On the cg acceleration traces there is very frequently a large acceleration spike of very short duration after rotation. An example of this is shown in Fig.14b. The spike appears to be the result of excitation of a fairly high frequency elastic mode; the possible causes of such an acceleration just after rotation are discussed in the next section.

On many of the records the aircraft can be seen to be pitching heavily at about 0.7 to 0.9 Hz. This is shown in Fig.14c and can also be seen in the typical record shown in Fig.2.

4 DISCUSSION

The amplitude of the vibration in the cockpit during the landing roll is greater than that during the take-off[4]. However, during the take-off the crew work-load is considerably higher than during the landing roll and the probability of needing to make decisions in the event of emergencies is greater. For this reason the take-off appears the more critical case from the point of view of crew

environment, while it is likely that landing causes greater structural loads, particularly on the fuselage and near the undercarriage units.

The aircraft of this study is very similar to the Boeing 720 used in Ref.1. Runways A and B of Ref.1 are at Airport 15 of this study. Although the characteristics of the accelerometers used in Ref.1 differ appreciably from the characteristics of the accelerometers used in this study, the cockpit/ cg acceleration ratio during take-off on Runways A and B was measured at between 1.5 and 2.1 in Ref.1, and was between 1.3 and 2.3 at Airport 15 in this study. At most other airports the cockpit/cg acceleration ratio from this study was between 1.0 and 1.5. The maximum cockpit acceleration during take-off on Runway A and taxying on Runway B (0.49 g and 0.27 g) are appreciably larger than would be predicted from Fig.7 for Airport 15 and a weight of 70000 kg.

The spikes after rotation on the cg acceleration record must be due to the excitation of a structural mode, possibly at quite a high frequency. However, they are reflected by similar but smaller spikes on the cockpit acceleration trace so they do represent a real vibration of the complete aircraft. A possible explanation of the spikes is that they are caused by the undercarriage extending fully and hitting its stops as the aircraft leaves the ground, but this should be considered to be speculative.

It is clear from the records that pushing the control column forward during the take-off role increases the vibration level at both the cockpit and the cg; there are indeed occasions when the control column has been moved aft during a particularly severe patch of vibration, probably in an attempt to reduce the vibration level or the loads on the nose undercarriage. Sensitivity of the response to the control column position makes it more difficult to compare different take-offs at the same airport.

When the aircraft has reached a speed of 80 knots it has travelled about 1500 ft along the runway and is crossing the part of the runway on which air- craft normally touch down. It is possible that the high accelerations at 80 knots, which usually occur as a result of pitching motion, are caused by long wavelength roughness of the runway in the touchdown area.

When allowance is made for control usage, and the fact that not all the runways are identified, there is fair agreement between the measured vibration histories during different take-offs at the same airport. However, there is evidence that on some occasions the aircraft did not behave in a repeatable manner. The best example of this is shown by two series of flights calling at Airports 17 and 29; these happened to be made under extremely consistent conditions. Details of the take-offs are given in Table 3, from which it can

be seen that take-off 50, 88 and 51 were made on the 12 and 13 December 1965 and take-offs 52, 87, 53, 49 and 89 were made between the 30 December 1965 and the 2 January 1966. Examination of Table 3 will show that between 13 and the 30 December 1965 something appears to have happened to the aircraft that increases its response to rough runways by approximately 35%. This conclusion is even more striking if take-offs 87 and 49 are omitted from the table; these two take-offs are non-typical in that the weight is higher and different runways were used.

Throughout this Report the measured cockpit vibration levels are high. However, there is no evidence from the records that the pilot's performance was in any way degraded by the vibration. When the acceleration exceeds about 0.3 g the control column can be seen to be being moved in sympathy with the acceleration, positive accelerations causing the column to be pushed forward. There is no record of any crew complaints, although Ref.6 quotes today's airliners as being only marginally acceptable with regard to cockpit vibration during take-off.

5   CONCLUSIONS

The cockpit vertical acceleration for a Boeing 707-436 has been measured during 94 take-offs from 31 airports during routine flying by a British airline. During 33 of these take-offs the centre of gravity vertical acceleration was also measured. The maximum cockpit incremental acceleration measured was 0.75 g and for 10% of the take-offs the maximum cockpit acceleration exceeded 0.53 g. For 10% of the take-offs more than 10 occurrences/take-off of accelerations greater than 0.32 g occurred.

The amplitude of the cockpit accelerations varied from airport to airport and with aircraft weight. The variation between airports was by about a factor of two at a weight of 115 000 kg. At a given airport, the response at a weight of 140 000 kg was about twice that at 90000 kg. The level of acceleration at the centre of gravity did not vary with aircraft weight. The cockpit/cg acceleration ratio increased with increasing weight; this ratio was between 0.9 and 2.3, but for more than 80% of the take-offs the ratio was between 1.0 and 1.5. From a repeated loading viewpoint, no airport was outstandingly bad; however, one airport caused peak accelerations appreciably larger than any other.

The level of vibration, both in the cockpit and at the centre of gravity, is significantly increased by forward movement of the control column. There is some evidence that part-way through the measurement programme the aircraft

characteristics changed temporarily to increase its response to runway rough-
ness by some 35%. Vertical vibration of up to ±0.4 g, with occasional peaks
of ±0.7 g, does not affect the accuracy of the speed at which the crew initiate
rotation for take-off.

Table 1

COCKPIT ACCELERATIONS DURING TAKE-OFF

Take-off No.	Airport	Runway	Weight kg	Time to rotation sec	Rotation speed kt	Speed at max. accel. kt	Δn_1	Δn_{10}	-0.55	-0.50	-0.45	-0.40	-0.35	-0.30	-0.25	-0.20	-0.15	-0.10	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
1	1	07L	136170	47	160	150	-0.17	0.15									4	30	34	6	2											
2	1	07L	133920	47	158	55	0.22	0.17									5	23	45	18	1											
3	1	na	124900	43	152	85	0.20	0.12									1	20	20													
4	2	na	124764	32	148	80	0.38	0.22								3	7	18	23	19	11	4	2	1								
5	2	na	92840	26	128	80	0.27	0.17									3	7	15	11	6	2										
6	3	na	116670	34	144	88	0.29	0.23								8	20	55	60	25	11	6	4									
7	3	na	108860	35	136	70	0.31	0.25							1	8	18	38	47	30	15	9	7									
8	3	na	106728	35	140	80	0.45	0.27							1	6	18			34	25	9		1								
9	3	na	95451	51	130	135	0.30	0.15								1	6	24	35	4	1	1										
10	4	na	90270	55	130	136	0.20	0.15									5	10	12	5	1											
11	5	na	118030	44	145	78,142	0.50	0.40				3	6	10	13	29	38	52	57	47	41	26	16	10	8	5	2					
12	5	na	106750	37	140	95(-),145(+)	±0.30 (?)	0.27						1	4	10	18			33	22	8	4									
13	6	na	131640	42	150	120	0.33	0.20							1	2	9	30	32	19	13	4	3					1				
14	6	na	94220	28	125	80	0.20	0.16									3	16	21	14	22	10	6									
15	6	na	91342	27	130	90	0.24	0.15									2	11	22	7	28	5	5									
16	6	na	85860	26	132	126	0.22	0.15									4	13	16	6	6	13	8	2								
17	7	na	141080	48	160	80	0.34	0.26						2	5	11	21	48	44	35	13	6	3	2								
18	7	28L	141060	47	162	125	0.38	0.29						3	7	21	26	46	58	30	22	10	3	1								
19	7	28L	137780	47	160	115	0.36	0.28						3	7	21	36	67	71	53	28	15	6	4	2	1						
20	7	na	135078	40	157	105	0.60	0.33				1	2	8	8	13	27	51	51	38	25	13	8	1								
21	7	10R	120270	39	150	110	0.47	0.20					2	2	7	7	6	22	45	14	6	4	2									
22	7	na	98650	27	132	120	0.26	0.20							8	13	16	25	28	14	8	1										
23	7	na	97960	29	135	85	0.26	0.15						1	1	2	4	17	17	7	3	1										
24	7	na	96940	28	140	145	0.26	0.18								1	2	16	11	11	6	1										
25	7	na	96330	26	140	80	0.20	0.17										12	22	14	4	1										
26	8	na	122550	44	145	140	0.25	0.18								2	5	28	35	14	5	1										
27	9	na	94820	29	132	110	0.21	0.15									1	11	34	10	2											
28	9	na	84710	29	122	125	0.18	0.12										15	15	3												
29	10	11	124650	50	145	120	0.22	0.15									3	14	35	8	2											
30	10	na	124338	50	150	115	0.27	0.16										22	33	12	3											
31	10	na	105520	41	140	95	0.15	0.13										5	18	6												
32	11	na	135690	55	165	148	0.66	0.39		1	2	2	2	10	18	24	24	40	54	37	34	21	15	6	3	3	2	2	2	1		
33	11	08	135310	51	161	150	-0.52	0.35		1	2	2	3	10	17	29	7	15	31	17	38	27	8	5	1	1						
34	11	na	124750	50	150	65	0.32	0.28						1	7	18					22	12	3	1								
35	11	na	110960	35	142	126	0.31	0.20							1	3	7	15	31	7	7	2	1									
36	12	na	122090	47	152	80	0.35	0.25							1	7	17	39	41	29	19	7	2	1								
37	13	na	121080	42	150	55	0.30	0.26							1	18	29	39		26	15	3	2									
38	14	na	90933	29	130	75(+),100(-),135(+)	±0.16	0.13									1	7	7	4												
39	14	na	79950	23	132	140	0.16	0.12										5	16	4												

Acceleration peaks exceeding listed levels, g

Table 1 (Contd)

13

Take-off No.	Airport	Runway	Weight kg	Time to rotation sec	Rotation speed kt	Speed at max. accel. kt	Δn_1	Δn_{10}	Acceleration peaks exceeding listed levels, g																							
									-0.55	-0.50	-0.45	-0.40	-0.35	-0.30	-0.25	-0.20	-0.15	-0.10	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
40	15	na	132390	41	154	120	0.54	0.34			1				6	15	42	56	34	29	16	10	3	1	1		1					1
41	15	31L	122320	34	152	115	-0.59	0.34	1	1	1	2	2	11	25	33	26	34	34	38	21	13	8	3								
42	15	na	120950	42	145	126	-0.43	0.34			2	2	3	6	13	20	33	26	30	31	15	10	6									
43	15	na	109140	36	145	130	-0.52	0.26					3	4	12	22	20	26	26	22	19	14	9	8	3	2					
44	15	na	109050	31	140	120	±0.45	0.30	1		1	2	4	4	11	23	23	33	23	15	11	7	4	1	1						
45	15	na	107890	32	135	120	0.40	0.22		1	1	1	2	1	6	16	19	19	16	7	7	4	3	1	1						
46	16	na	118610	36	150	72	-0.75	0.32						2	2	4	7	9	4	1	2	1									
47	16	na	116690	37	142	140	-0.52	0.31					3	4	9	12	24	34	34	17	8	5	3	4	3						
48	16	na	109910	38	145	75	0.75	0.29						4	9	19	23	42	42	23	18	7	6								
49	17	na	116820	50	148	80	-0.29	0.20						4	7	7	2	7	1	14		4	1	1	1	2		1	1		
50	17	29	110560	37	140	140	0.21	0.14						2	1	1	9	8	30	7	5		7								
51	17	29	109029	40	146	115	-0.20	0.14					3	4	4	23	22	23	23	22	13	16	13	3	3	3					
52	17	29	104570	34	138	90	0.32	0.19					4	4	9	20	28	23	19	14	10	10	10	4							
53	17	29	104348	37	138	105	0.30	0.19	1	2	2	2	3	5	11	31	41	28	26	16	18	16	16	1	1		1				
54	18	21R	118740	48	148	125	0.65	0.35				1			2	4	24	26	26	1		7	13	4	3	2		1		1	
55	18	na	106569	39	140	130	0.37	0.25		1		1		8	13	9	9	29	41	21	19	13	13		3		2			1	
56	18	03L	101750	40	135	95(-),130(+)	±0.30	0.21					6		1		20	40	40	35	30	19	13	2							
57	19	na	84650	28	136	140	0.17	0.10								4		6	1	1											
58	20	na	127900	39	154	128	0.40	0.30					1	2	11	22	36	36	34	22	22	14	4	4							
59	20	na	115780	38	146	70	-0.40	0.30					1	2	6	19	27	27	51	35	27	15	8	3							
60	20	na	115510	32	145	100	0.39	0.23					1	5	15	17	27	40	38	19	10	6	3	3	2						
61	20	15L	113730	34	148	110	-0.39	0.25			2	2	3	5	15	22	22	22	30	22	12	6	4	3		1					
62	21	na	121760	41	148	120	0.40	0.29		1		1	2	2	7	26	45	40	34	22	14	7	4	2							
63	21	na	99170	35	135	80(+),135(-)	±0.25	0.20						2		23	32	32	32	23	13										
64	22	na	94940	30	128	140	-0.34	0.20				2	3	9	3	3	9	22	30	18	2	3	3								
65	22	na	92350	29	128	70	0.22	0.16				2	3	3	6	3	3	19	11	6	5	1									
66	22	na	90820	24	122	100	-0.37	0.16						5	6	2	4	12	18	11	5	2	1	1	1						
67	22	na	83850	28	130	80	0.42	0.16				1	1	1	2	2	4	12	10	4	2	3	1								
68	23	03	105910	37	135	110	0.38	0.19				1	5	8	6	6	5	14	21	14	11	3	1	1	1						
69	23	na	102199	36	136	±0.130(+)	±0.45	0.25					5	5	2	2	3	11	37	18	15	2	2								
70	23	na	100860	35	135	115(-),130(+)	0.39	0.18					3	3	2	3	10	33	29	14	17	2	3	3	1						
71	23	na	99620	29	130	110	0.42	0.16				1	3	3	1	1	12	12	20	10	4	1	1	1							
72	24	na	117400	39	142	120	0.61	0.33					1	4	7	16	11	12	19	6	11	2	3	1	1						
73	24	20	115980	44	143	120	0.68	0.33					6	8	8	17	24	15	17	9	5	2		1	1						
74	24	02	94300	32	125	125	0.38	0.25			2	2	3	5	7	7	21	33	10	13	20	8	4	1							
75	25	na	98124	27	125	122	0.20	0.13									11		32	3	1										
76	26	na	119535	41	150	65	0.35	0.27						1	6	13	7	32	38	28	25	12	3	1							
77	26	na	105850	31	140	85	0.29	0.24							2	8	1		21	4		5	3								
78	27	na	123370	37	150	100	0.23	0.14						1	7	1	1	20	13	4	13	4									
79	27	na	109770	34	140	120	0.35	0.24							2	12	24			12	7	3									
80	27	25R	92850	34	130	95	0.29	0.23						1	7	7	19			26	13	4	1								

Table 1 (contd)

Acceleration peaks exceeding listed levels, g

Take-off No.	Airport	Runway	Weight kg	Time to rotation sec	Rotation speed kt	Speed at max. accel. kt	Δn_1	Δn_{10}	-0.55	-0.50	-0.45	-0.40	-0.35	-0.30	-0.25	-0.20	-0.15	-0.10	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
81	28	na	123350	41	152	135	-0.27	0.22							2	3	10	23	36	31	13		1									
82	28	na	121280	41	150	60	0.31	0.17								1	5	16	48	15	2	1										
83	28	13	111794	34	140	65	0.26	0.19								1	3	26	34	24	7											
84	28	na	107500	33	140	45	0.22	0.16									2	15	37	12	2	2										
85	28	13	106260	30	140	70,145	0.20	0.15									1	16	29	8	3											
86	28	na	96740	30	140	70	0.20	0.15									2			9	1											
87	29	25	114142	39	142	80	0.34	0.27						2	3	11	24	27	20	33	23	12	3									
88	29	07	110571	37	142	145	0.30	0.17								1	3			12	5	2	1									
89	29	07	109665	40	142	115	0.32	0.23								3	8			22	16	5	3									
90	30	na	140070	46	156	102	0.33	0.26						1	5	15	23			38	17	6	1									
91	30	na	104320	38	136	72	0.21	0.15								1	3	20	21	8	2											
92	30	na	102566	34	135	30	0.24	0.15								2	2	19	29	6	2											
93	31	na	118990	41	145	100	-0.30	0.24						1	3	11	21	22	40	24	11	1	1									
94	31	30	111150	35	140	75(-),120(+)	±0.25	0.21							2	5	10			21	8	1	1									
Total									5	9	16	27	47	115	249	607					997	477	237	109	49	27	15	10	6	3	1	1	1

14

Table 2

COCKPIT AND cg ACCELERATIONS DURING TAKE-OFF

Take-off	Airport	Weight kg	Δn_{10} cockpit acceleration	Δn_{10} cg acceleration	$\dfrac{\Delta n_{10} \text{ cockpit}}{\Delta n_{10} \text{ cg}}$
1	1	136170	0.15	0.105	1.43
2	1	133920	0.17	0.140	1.25
6	3	116370	0.23	0.235	0.98
17	7	141080	0.26	0.175	1.48
18	7	141060	0.29	0.205	1.44
19	7	137780	0.28	0.185	1.52
20	7	135078	0.33	0.155	2.20
21	7	120270	0.20	0.145	1.38
22	7	98650	0.20	0.145	1.38
23	7	97960	0.14	0.165	0.88
24	7	96940	0.18	0.150	1.20
25	7	96330	0.17	0.155	1.10
30	10	124338	0.16	0.130	1.27
33	11	139310	0.35	0.245	1.43
40	15	132390	0.34	0.200	1.70
41	15	122320	0.34	0.190	1.79
42	15	120950	0.34	0.145	2.35
43	15	109140	0.26	0.175	1.49
44	15	109050	0.30	0.200	1.50
45	15	107890	0.22	0.165	1.33
46	16	118610	0.32	0.250	1.28
47	16	116690	0.31	0.210	1.48
48	16	109910	0.29	0.230	1.26
50	17	110560	0.14	0.120	1.17
51	17	109029	0.14	0.120	1.17
52	17	104570	0.19	0.180	1.05
53	17	104348	0.19	0.160	1.19
54	18	118740	0.35	0.24	1.46
56	18	101750	0.21	0.21	1.00
61	20	113730	0.25	0.205	1.22
71	23	99620	0.16	0.150	1.07
84	28	107500	0.16	0.145	1.10
92	30	102566	0.15	0.115	1.30

Table 3

VARIATION IN RESPONSE WITH TIME

Take-off	Airport	Runway	Weight kg	Date	Δn_{10} cockpit acceleration, g		Δn_{10} cg acceleration Airport 17
					Airport 17	Airport 29	
50	17	29	110560	12 Dec 65	0.14		0.120
88	29	07	110571	13 Dec 65		0.17	
51	17	29	109029	13 Dec 65	0.14		0.120
52	17	29	104570	30 Dec 65	0.19		0.180
87	29	25	114142	31 Dec 65		0.27	
53	17	29	104348	31 Dec 65	0.19		0.160
49	17	–	116820	2 Jan 66	0.20		
89	29	07	109665	2 Jan 66		0.23	

REFERENCES

No.	Author	Title, etc.
1	G.T. Morris	Response of a turbojet and a piston-engine transport airplane to runway roughness. NASA Technical Note D-3161 (1965)
2	H. Hall	Vibration levels experienced in take-off on a large flexible aircraft. R.A.E. Technical Report 68193 (1968)
3	The CAADRP Technical Panel	The Civil Aircraft Airworthiness Data Recording Programme. R.A.E. Technical Report 64004 A.R.C. 26490 (1964)
4	G. C. Hutton	Vertical cockpit accelerations measured on an operational jet transport aircraft during take-off and landing. R.A.E. Technical Report 69214 (1969)
5	I. McLaren	The design and testing of a low range acceleration transducer with predictable response characteristics. A.R.C. C.P. No.575 (1961)
6	T.G. Foxworth	The airline pilot views supersonic transport operations. AIAA Preprint 68-1001 (1968)
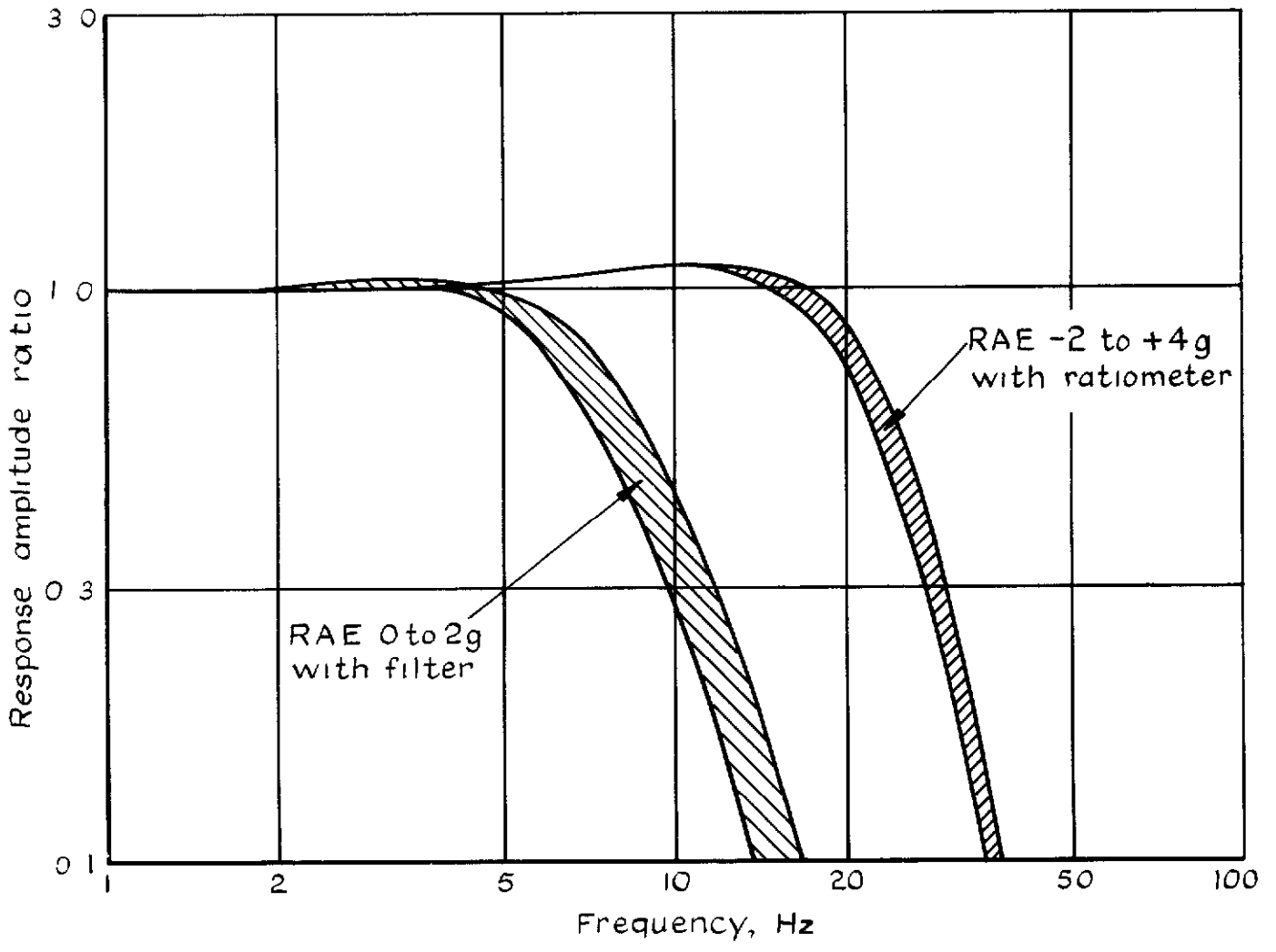
Fig. I Estimated frequency response characteristics of the cockpit and cg accelerometers fitted to the recorder
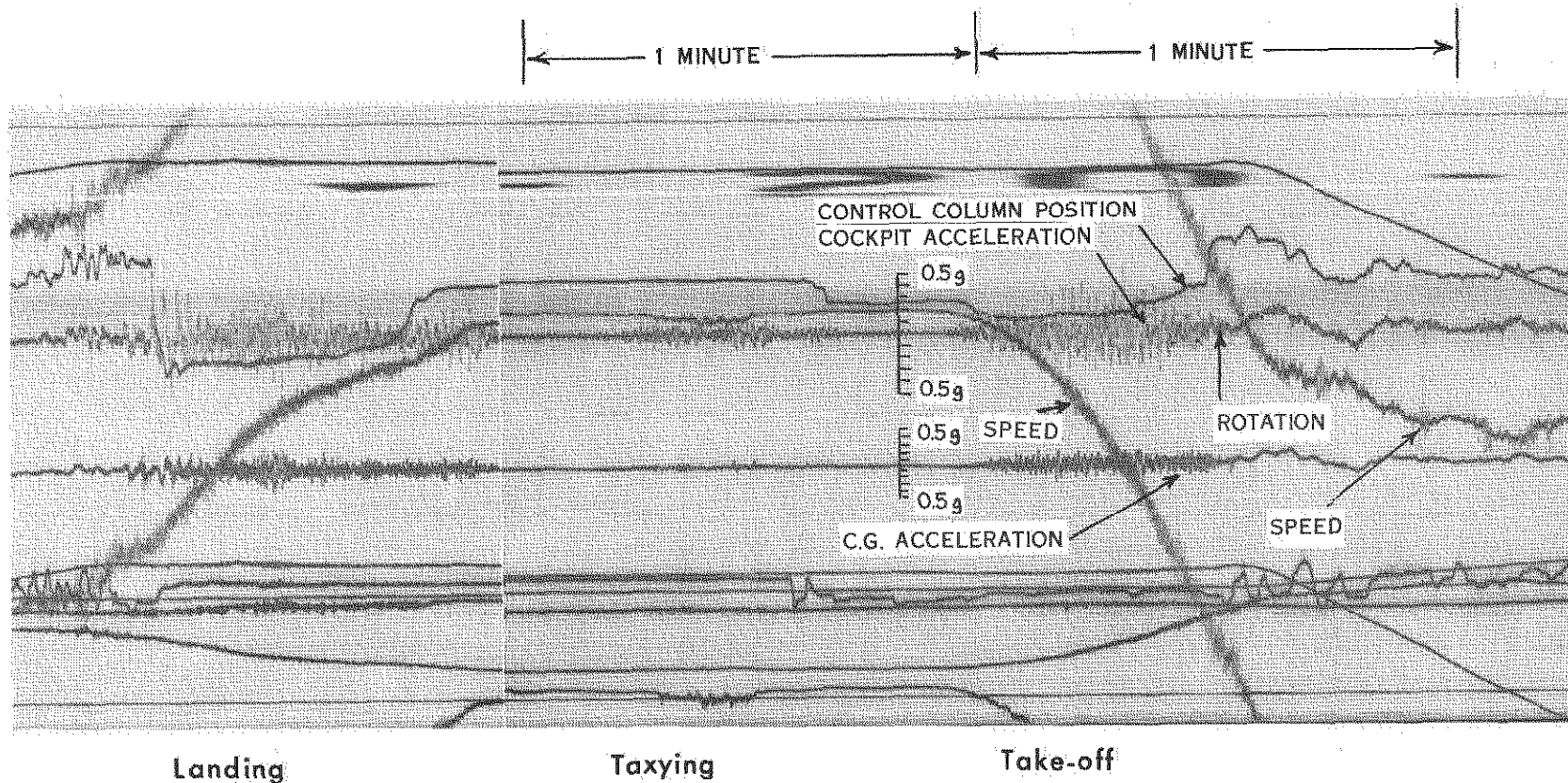
Fig.2. A typical take-off record (take-off No.41, airport No.15)
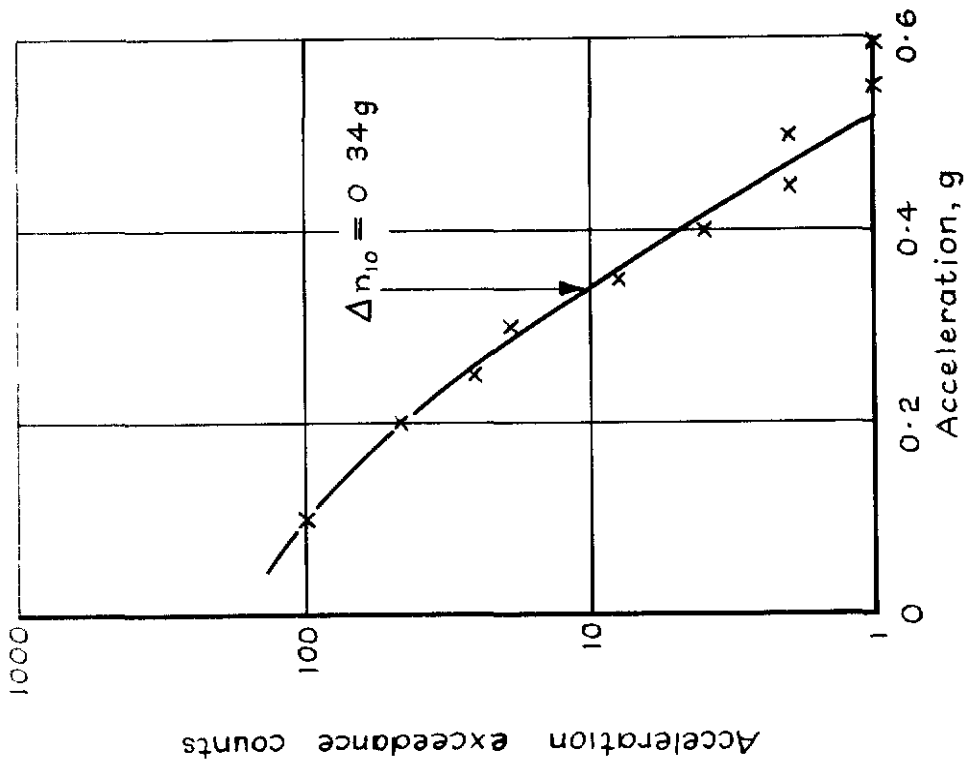
a Take off 41 (Fig.2)
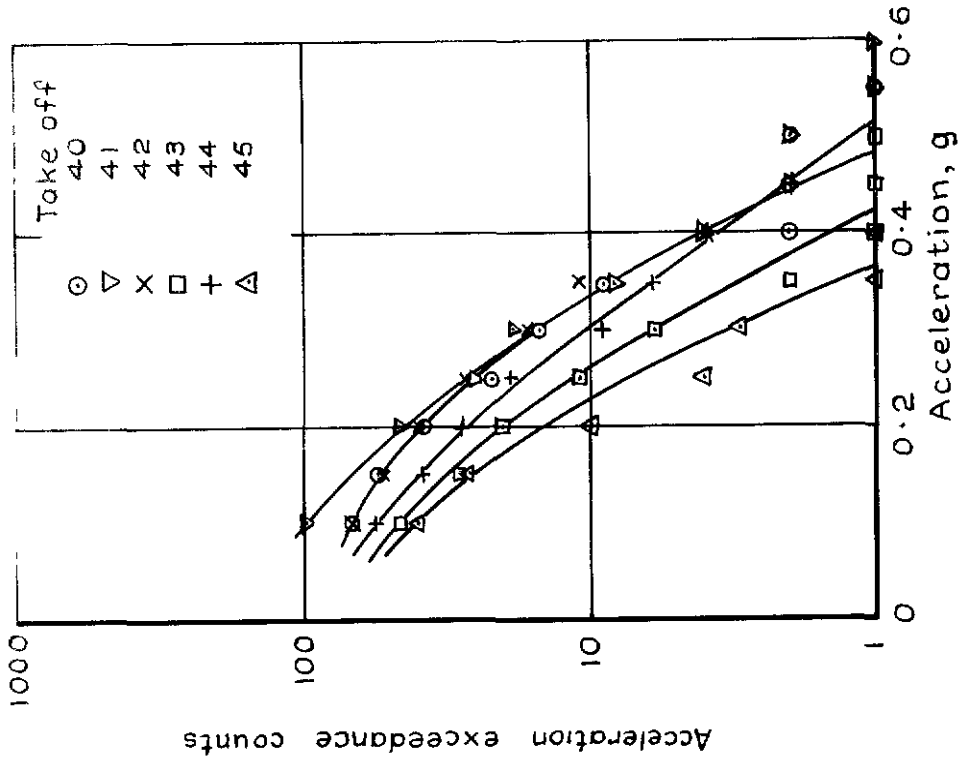
b All take offs at airport 15

Fig.3 a & b Incremental cockpit acceleration exceedance curves
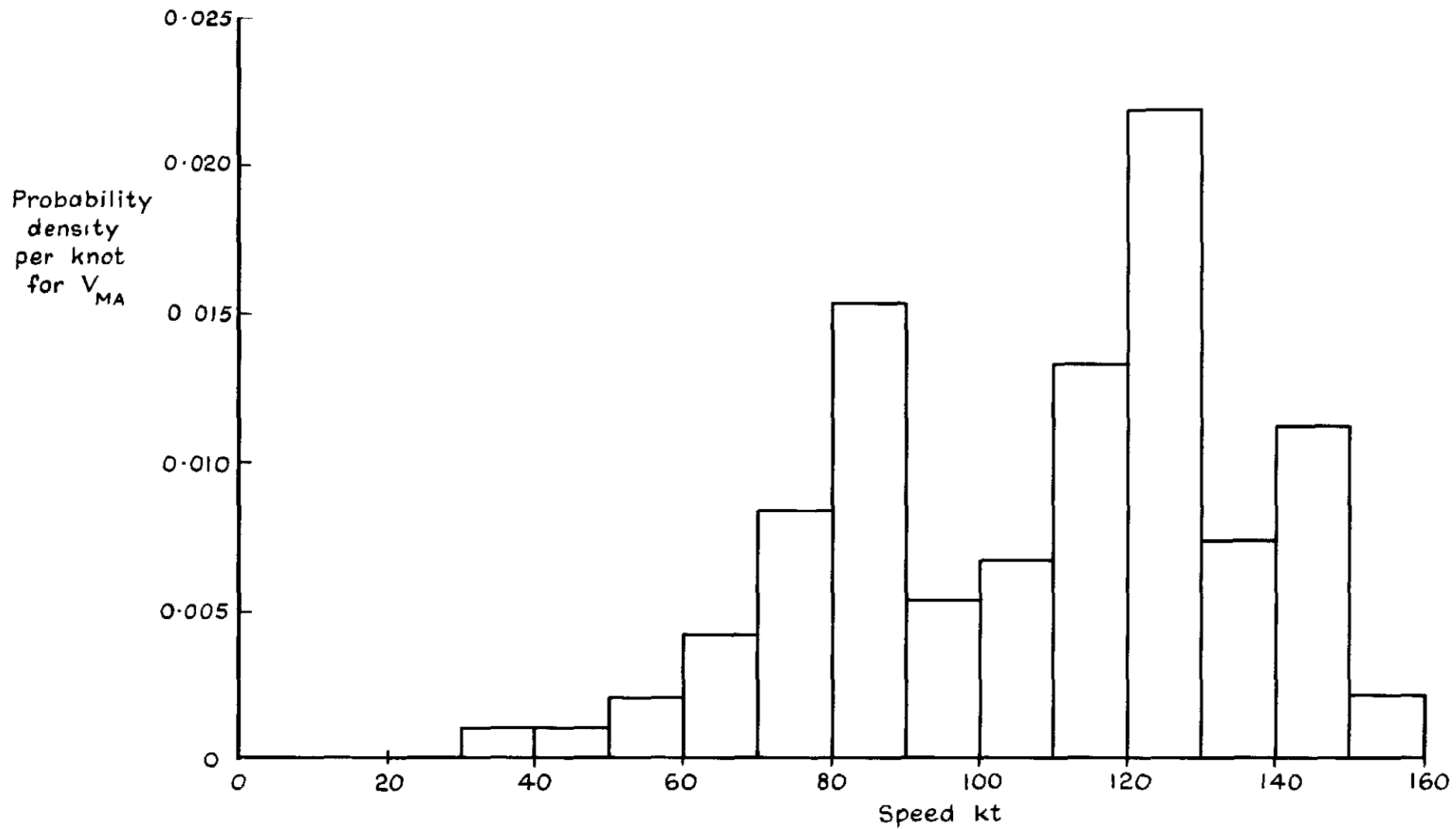
Fig. 4   The probability density for the speed at which the maximum
cockpit acceleration occurs
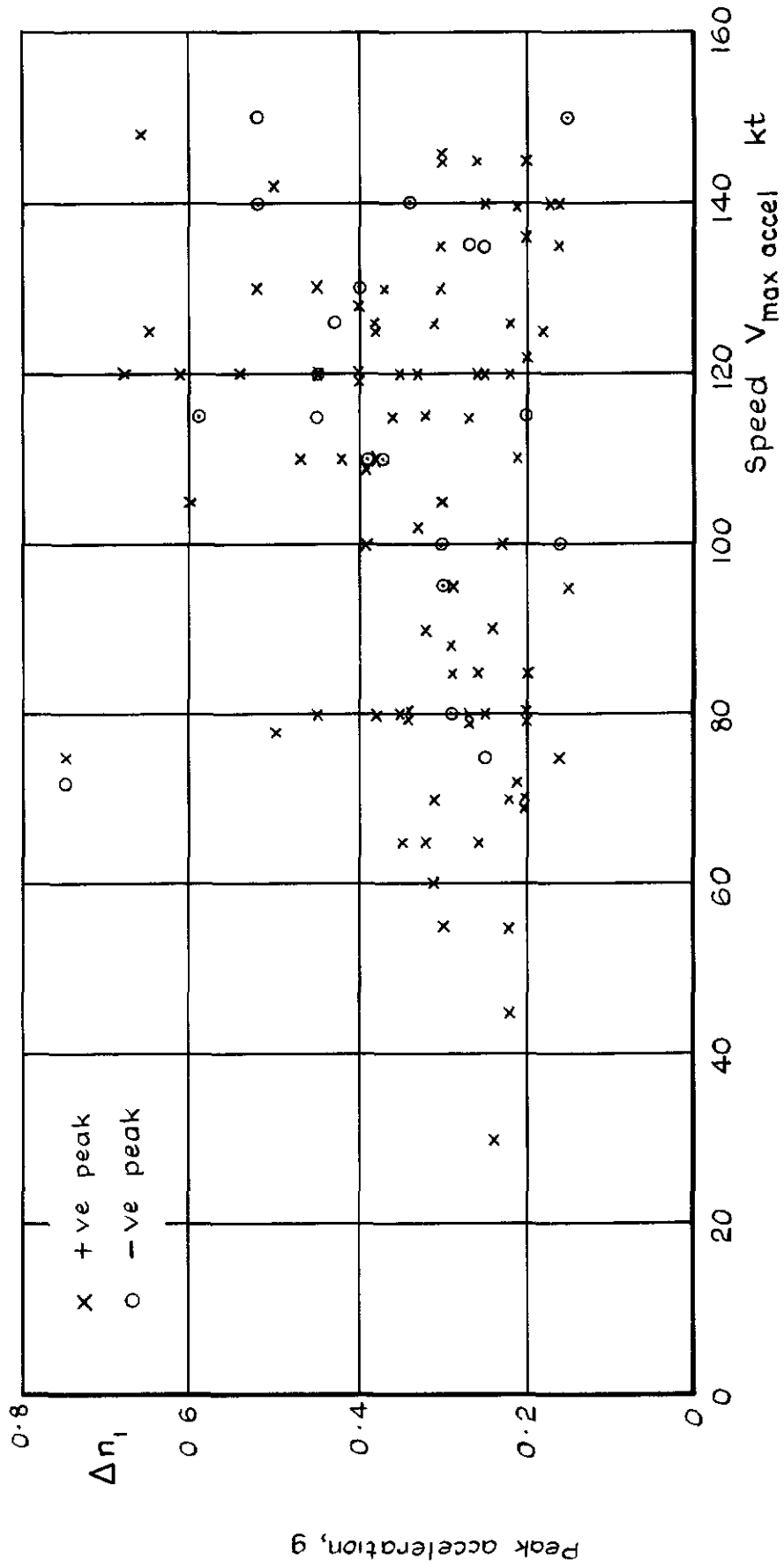
Fig.5 Variation of the maximum cockpit acceleration in one take off
with the speed at which it occurs
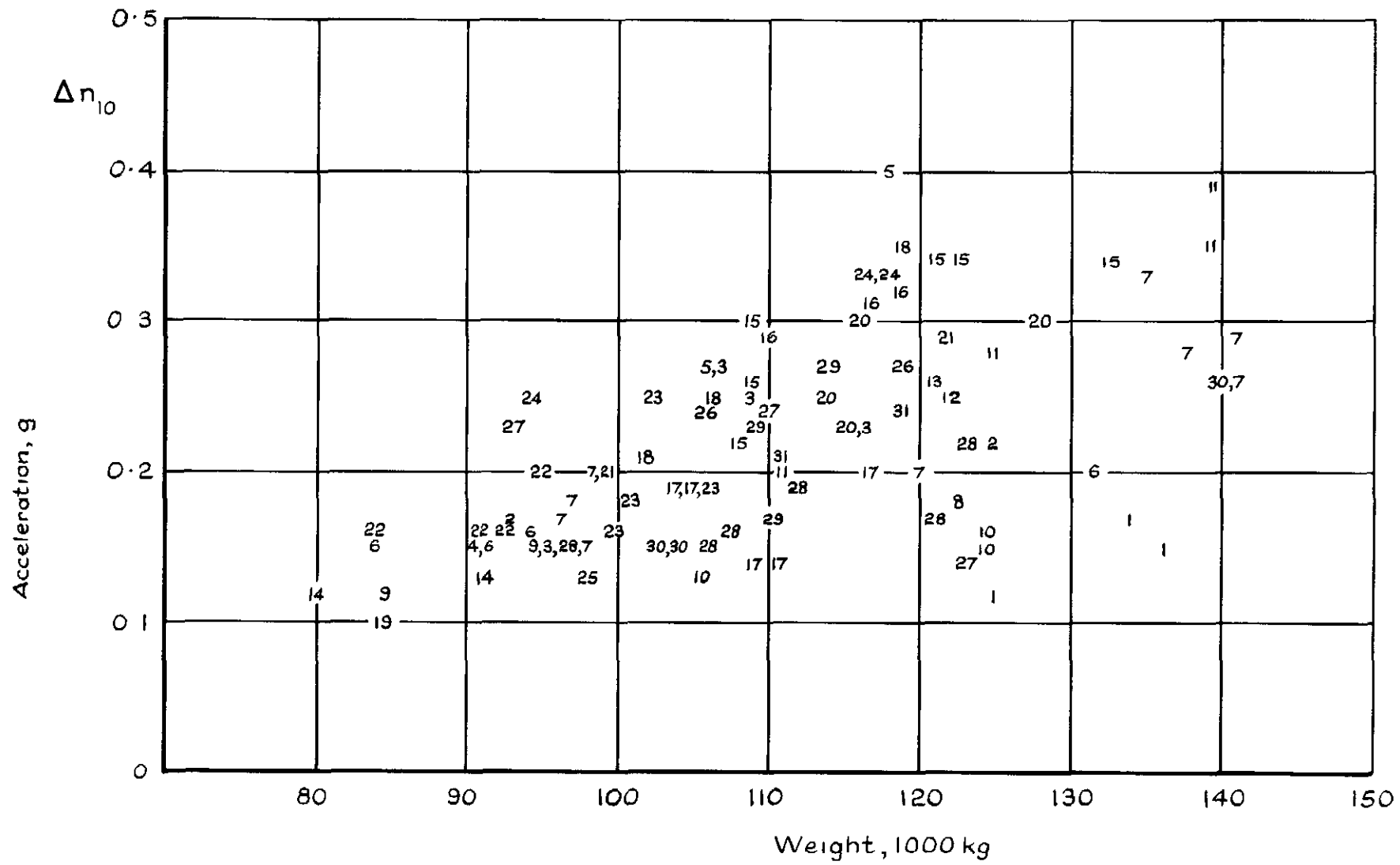
Fig. 6 Variation of Δn_{10} for cockpit acceleration with take off weight
(Numerical symbols identify the airports)

Fig.7 Variation of the maximum cockpit acceleration with take off weight
(Numerical symbols identify the airports)
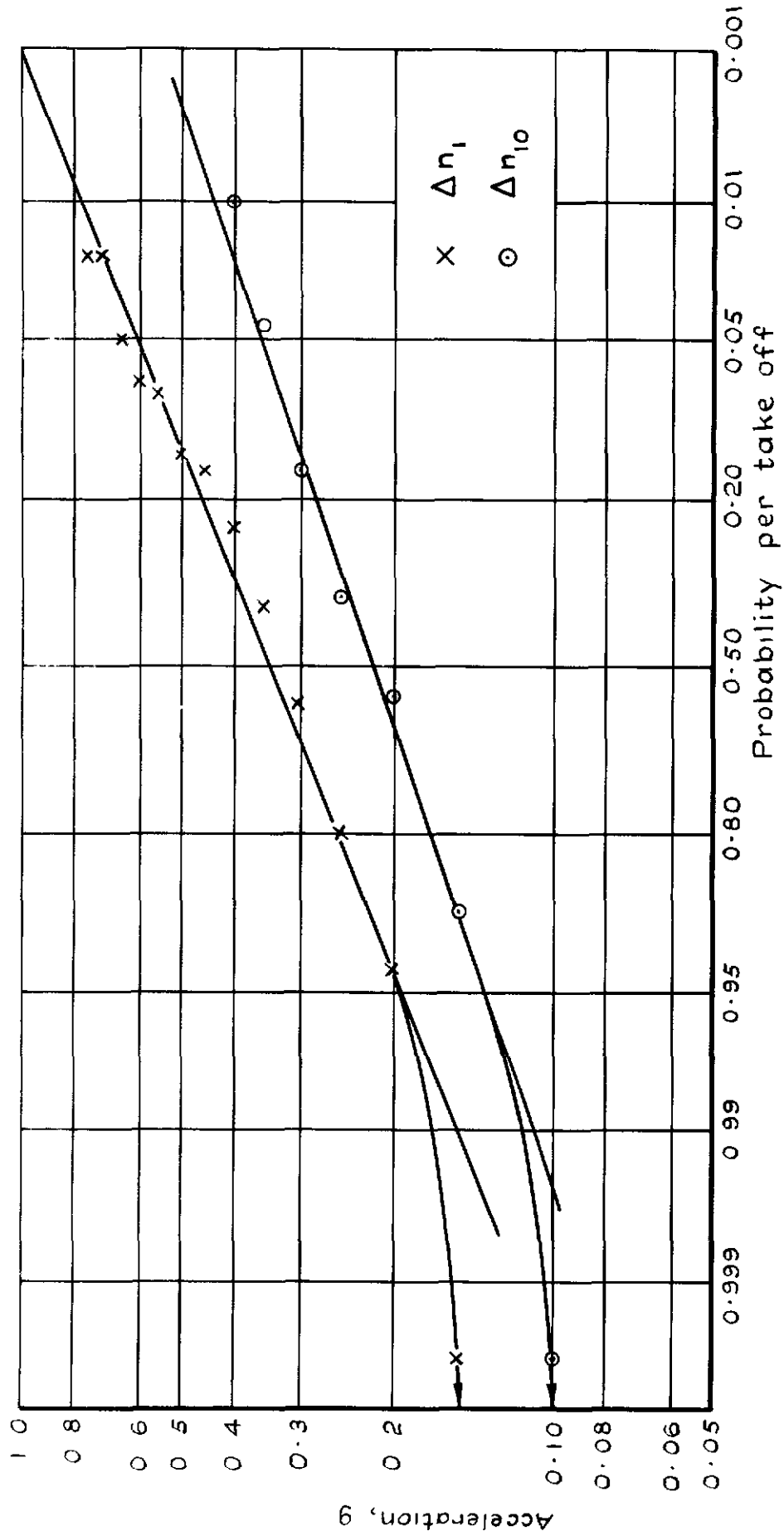
Fig. 8 Probability distributions for Δn_1 and Δn_{10} for cockpit acceleration
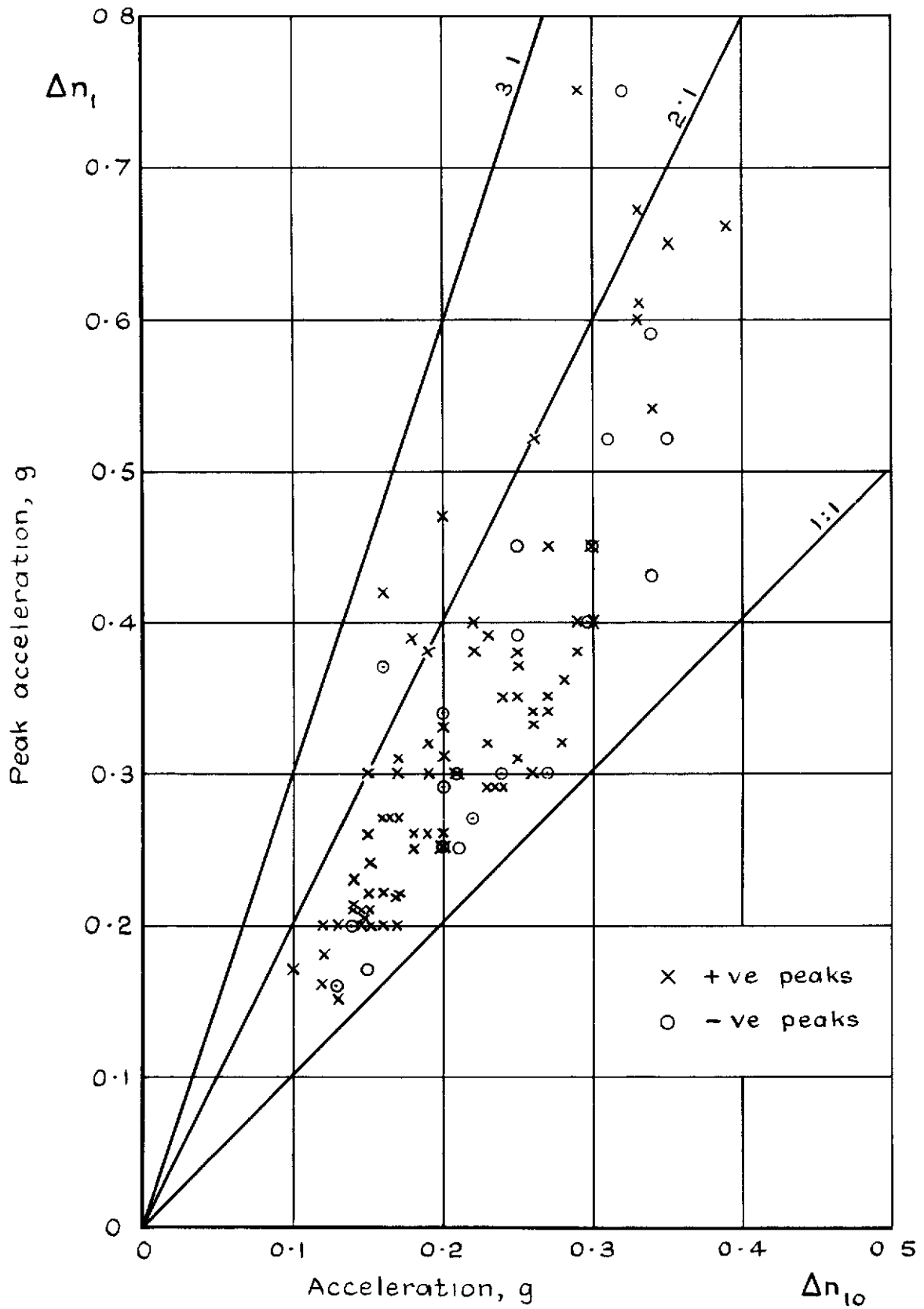
Fig. 9 Variation of Δn_1 with Δn_{10} for cockpit acceleration
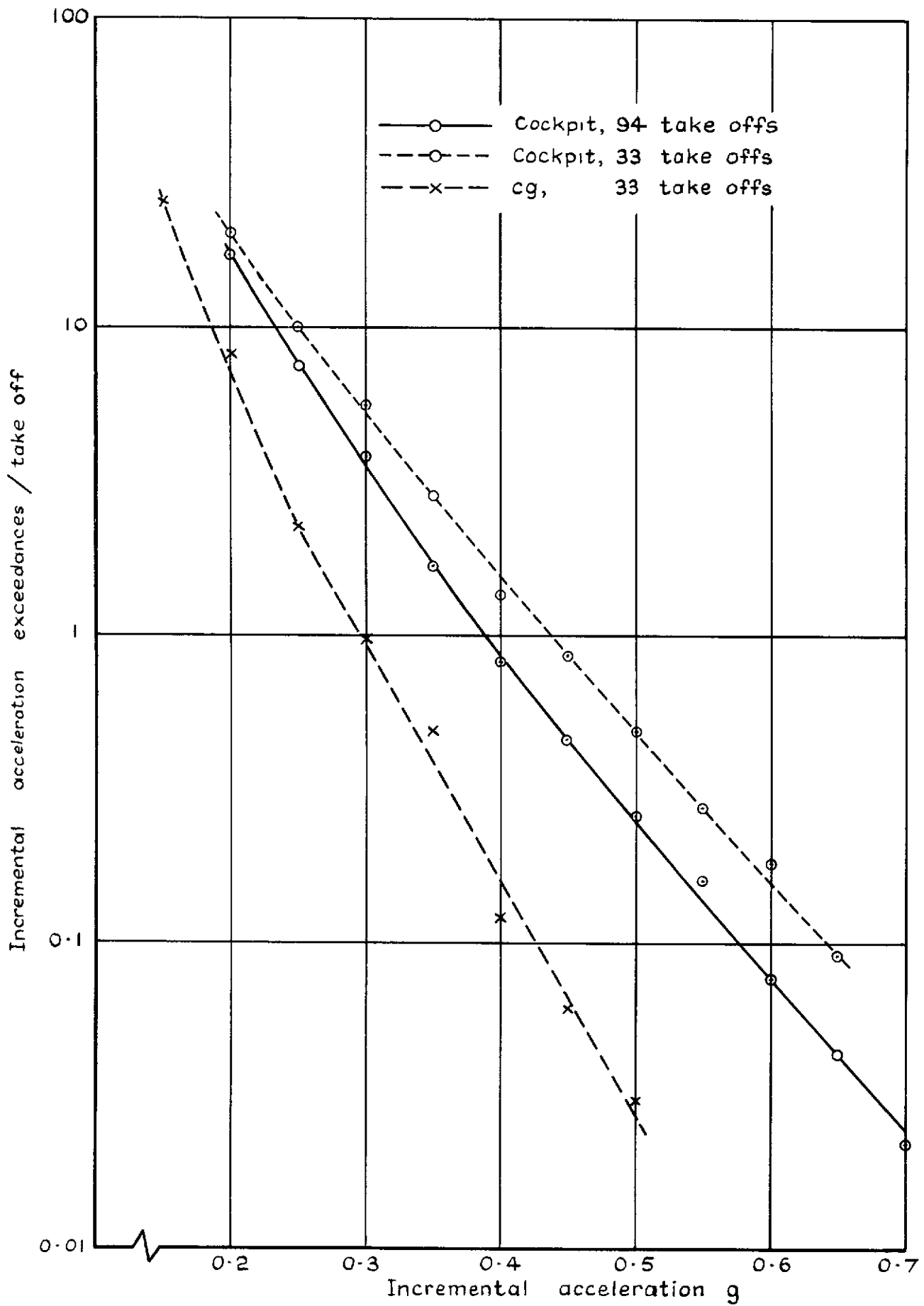
Fig. 10 Cockpit and cg acceleration amplitude
exceedance frequencies

Fig. 11 Variation of Δn_{lo} for cg acceleration with take off weight
(Numerical symbols identify the airports)
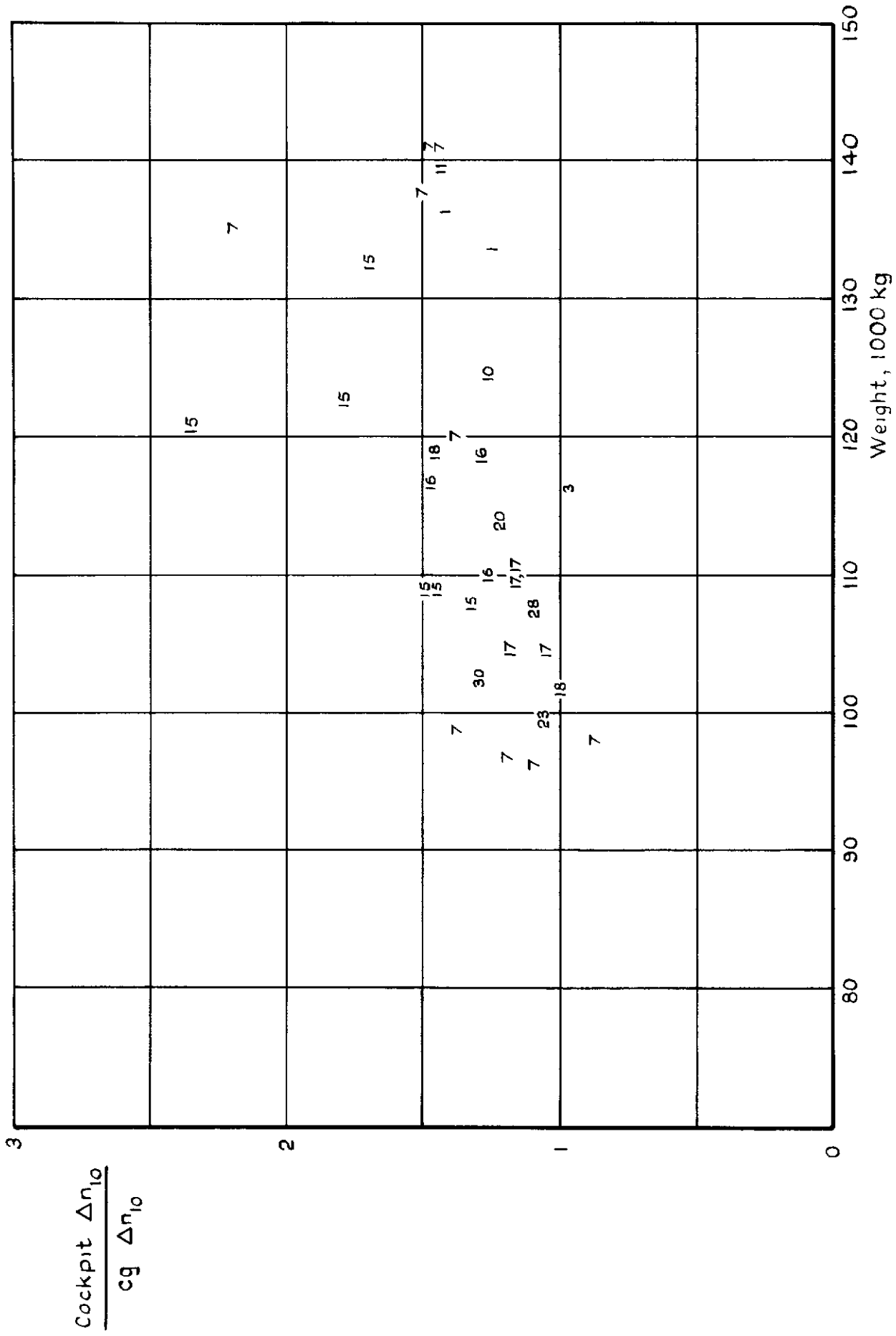
Fig. 12 Variation of Δn_{10} cockpit acceleration / Δn_{10} cg acceleration with take off weight (Numerical symbols identify the airports)
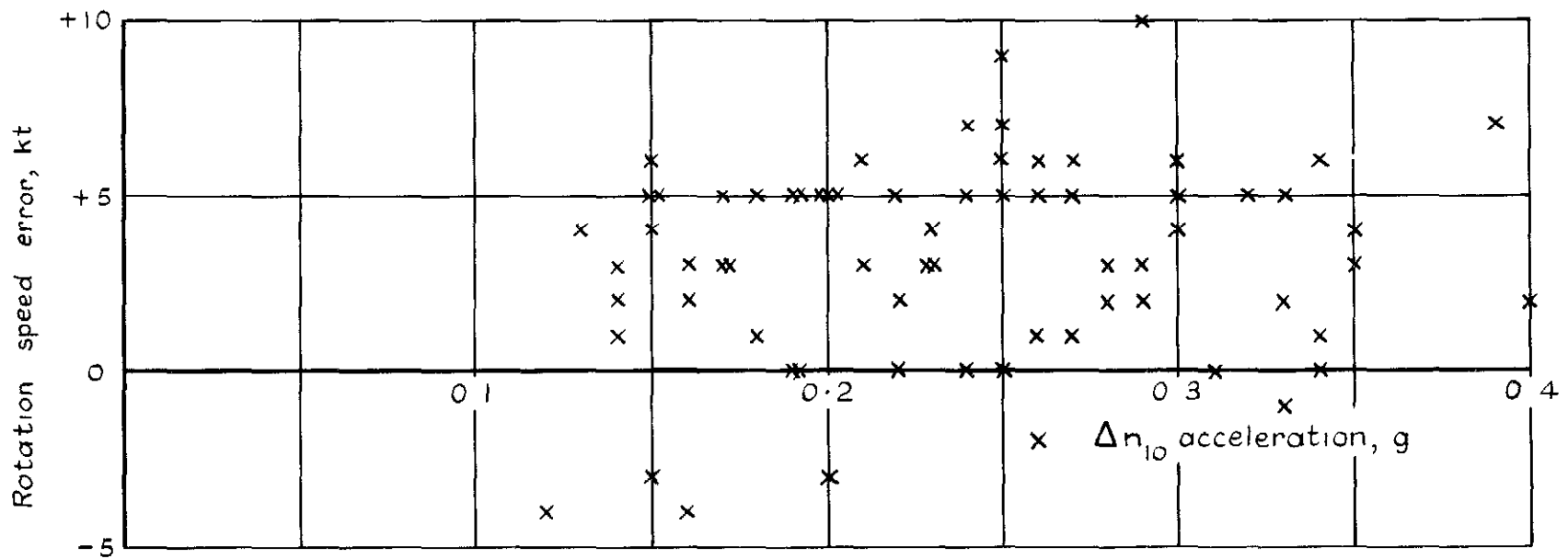
Fig. 13 Variation of rotation speed error with Δn_{10} for
cockpit acceleration during the take off
(All take offs at more than 100 000 kg)
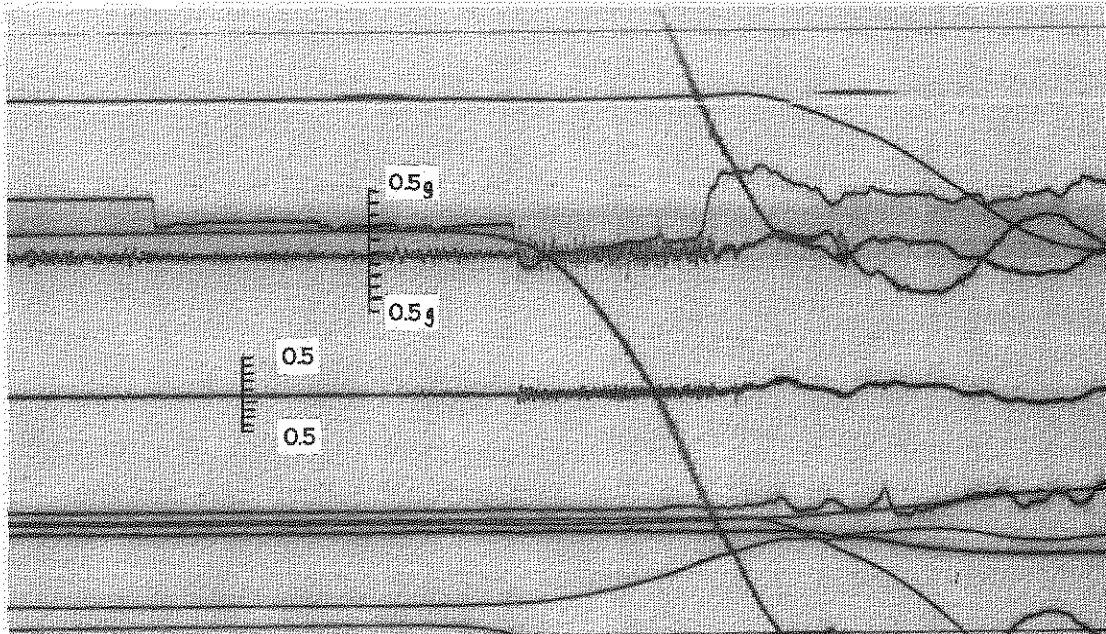
a. Vibration starts when control column pushed forward
(take-off No. 92, airport No. 30)
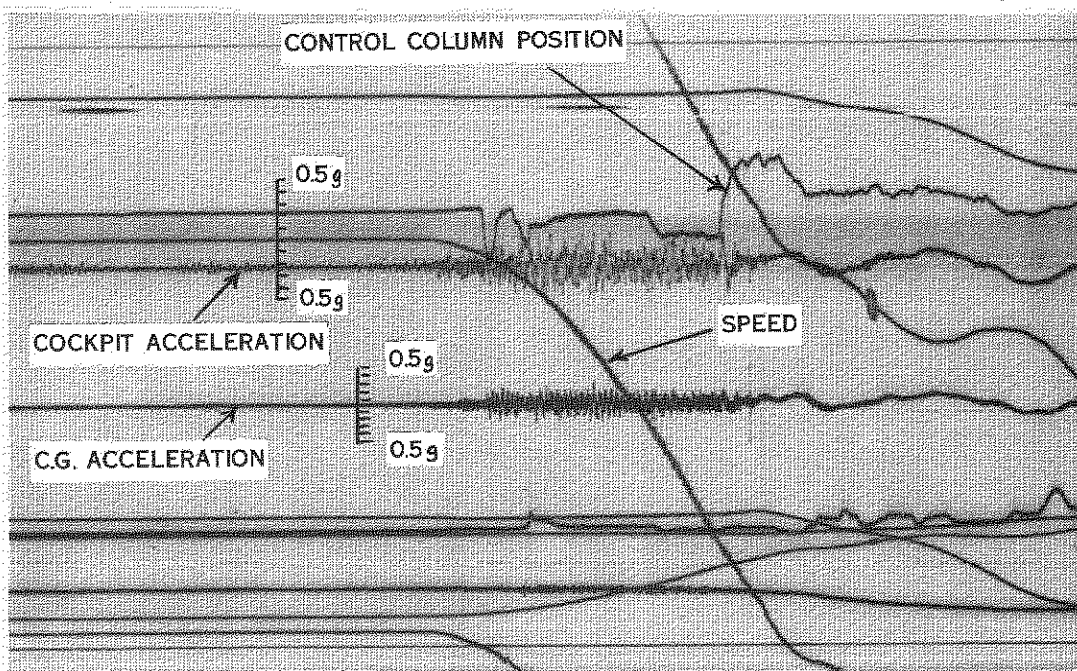
b. C.G. acceleration spike during rotation
(take-off No.6, airport No.3)

Fig.14a&b. Take-off vibration features
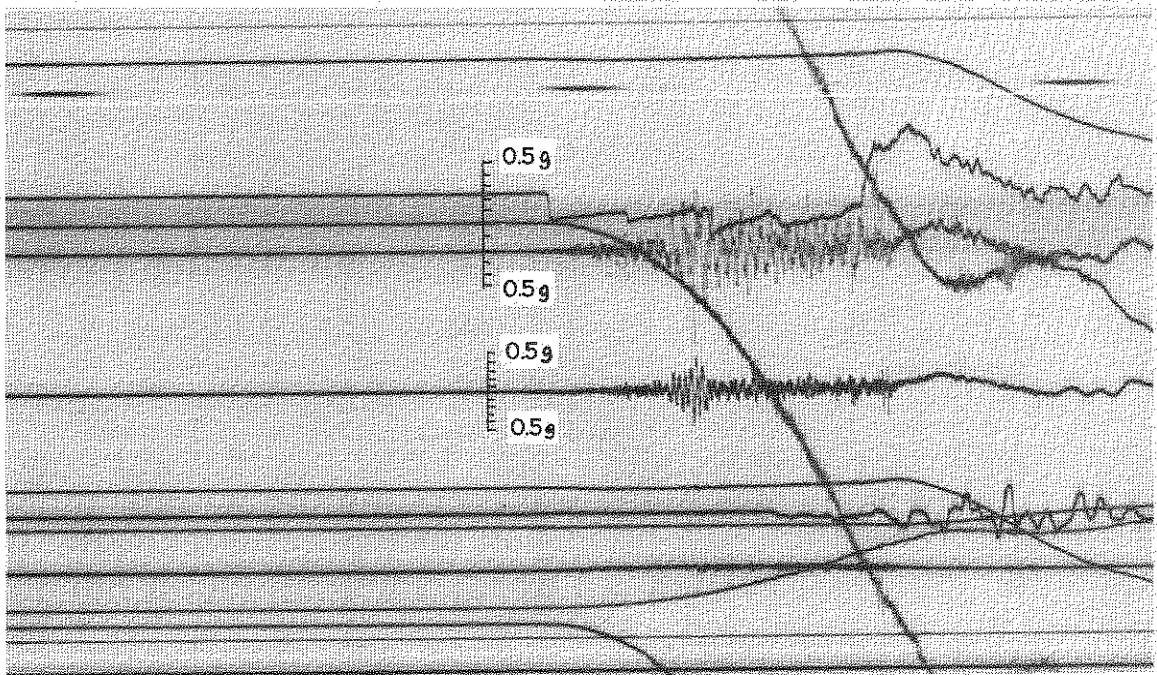
c. Pitching at $0.8H_z$ to $0.9H_z$ (take-off No.46, airport No.16)

Fig.14c. Take-off vibration features

A.R.C. C.P. No. 1120
October 1969

531.113 :
629.13.081 :
534.13 :
629.137.1

Mitchell, C.G.B.

VERTICAL ACCELERATION IN THE COCKPIT OF A SUBSONIC
TRANSPORT AIRCRAFT DURING TAKE-OFF MEASURED DURING
AIRLINE OPERATION

Vertical acceleration in the cockpit of a Boeing 707-436 during take-off has
been measured for 94 take-offs from 31 airports during airline operations.
The vertical acceleration near the centre of gravity was measured during 33
take-offs. The maximum cockpit incremental acceleration was 0.75 g, and this
acceleration exceeded 0.53 g for 10% of the take-offs. At a given airport
the cockpit acceleration at a weight of 140 000 kg was about twice that at
90000 kg but the cg acceleration did not vary with weight. The amplitude of
the cockpit acceleration varied between airports by a factor of about two at
115 000 kg. The cockpit/cg acceleration ratio was between 0.9 and 2.3, but
for more than 80% of take-offs was between 1.0 and 1.5. The vibration levels
experienced had no detectable effect on errors of rotation speed at take-off.