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Civil Aircraft Airworthiness Data Recording Programme

Uneven Runways Encountered by Subsonic Jet Transport Aircraft during Scheduled Airline Operations

by

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CIVIL AIRCRAFT AIRWORTHINESS DATA RECORDING PROGRAMME

UNEVEN RUNWAYS ENCOUNTERED BY SUBSONIC JET TRANSPORT AIRCRAFT DURING SCHEDULED AIRLINE OPERATIONS

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SUMMARY

During the Civil Aircraft Airworthiness Data Recording Programme instances were found where runway unevenness at two international airports produced CG normal acceleration oscillations of unusually large amplitudes for brief periods during the take-off or landing run.

Flight records of events are reproduced and discussed, one runway/aircraft combination being dealt with in particular detail owing to the phenomenon occurring frequently and being a source of comment from pilots.

There has been no known evidence of aircraft damage resulting from the events but some contribution to fatigue damage could occur, particularly on aircraft types with heavy wing-mounted appendages. It is suggested that selective resurfacing of the runways could considerably alleviate the loading action.

CAADRP Technical Report 25

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* Replaces RAE Technical Report 72095 - ARC 34499

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Negs. C 9063 to C 9064

1 INTRODUCTION

During a seven-year period terminating in 1969 the Civil Aircraft Airworthiness Data Recording Programme[1] (CAADRP) monitored a small number of civil jet transport aircraft in regular airline service which were fitted with continuous trace recorders measuring up to 14 control surface and performance parameters. The first three years involved two early types of jet aircraft designated Types B and C. The last four years of the period were devoted to two 'second generation' jet aircraft designated Types D and E (with rear-fuselage-mounted engines).

From time to time unusual or extreme events (termed Special Events) worthy of detailed study were noted. Several events were noted comprising abnormally large normal (vertical) accelerations measured at the aircraft CG during the take-off or landing run involving aircraft Types C and E, each at a different airport (CAADRP code numbers 53 and 63). One particular runway was found to produce abnormally high accelerations on a large number of occasions and consequently is dealt with in greater detail. This was runway number 03/21 at airport number 63.

Accelerations due to landing impacts are dealt with in an earlier report[2].

2 AIRCRAFT TYPE C AT AIRPORT NUMBER 53

Reproduced* in Fig.1 is a portion of a flight recording taken during take-off of an aircraft Type C on runway 22R at airport number 53. This was one of three events from the same aircraft, taking off from the same runway, possessing CG acceleration oscillations virtually identical in character and maximum amplitudes ranging from ±0.34 Δg (increment from 1 g datum) to ±0.5 Δg. The most severe is not illustrated as the recording paper speed was slower and the record clarity degraded. The three take-offs were the only ones to be performed from this runway when the Type C CAADRP aircraft was recording data and are to be found reproduced in Ref.3. In each case the patch of abnormal oscillations lasted for about 10 seconds, commencing at a low aircraft speed of about 40 kn (ias) and ceasing at about 80 kn, reaching a maximum amplitude at about 60 kn. The oscillations contained very little structural vibration, the motion being almost entirely in the heave mode at a frequency of 1.5 Hz. The wing bending natural frequency, with full fuel tanks, is not far removed from the heave frequency on this aircraft type and may cause additional stresses in

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* The definition of the original record is unavoidably degraded to a small degree during photographic copying and publication.

the structure. The amplitude of the oscillation built up to a peak over several cycles suggesting that a succession of runway bumps excited the heave mode of the aircraft. Hall[4] has shown that this mode is lightly damped on a typical undercarriage when the damping coefficient of the oleo legs are chosen to optimise heavy landing performance. The frequency of 1.5 Hz at 60 kn (the speed at maximum amplitude) corresponds to a wavelength of 67 feet. Information received from the aircraft's operator stated that the runway dips and is rough where it intersects with runway 31R. The runway layout is shown in Fig.2.

The aircraft oscillations induced on this runway have not created any apparent concern, probably owing to the low aircraft speed at which they occurred and to the rarity of the occurrence, the runway being seldom used.

3 AIRCRAFT TYPE E AT AIRPORT NUMBER 63

Many Special Events were noted which contained abnormally high CG normal accelerations measured on aircraft Type E. These occurred during the take-off and landing run on runway 03 and 21 (the same runway strip but observed in opposite directions) at airport number 63 and the phenomenon was found to be fairly consistent, particularly on take-off from runway 03. The cause and significance of the accelerations and the effect of aircraft rotation (during the take-off) on the acceleration severity is investigated.

3.1 Description and cause of phenomenon

Portions of flight recordings obtained during take-off and landing runs on runway 03/21, showing the abnormally high CG accelerations in each case, are reproduced in Fig.3. In each case the oscillation frequency was at about 1.1 Hz and the amplitude rose and decayed very rapidly, the patch lasting only about 2 seconds. The wing natural frequency of about 3 Hz on this aircraft type is far removed from the CG oscillation frequency recorded and this first structural response mode therefore does not enhance the importance of the event. All amplitude values quoted are the extreme values recorded, i.e. response at all frequencies contribute to the peak reading up to the limit of the accelerometer system at about 17 Hz but recorder trace resolution prevents identification of frequencies above 4 Hz. The response curve of the accelerometer system is shown in Fig.4.

The large amplitude accelerations were due to a dip in the runway surface in the vicinity of the intersection with taxiway number 3. The airport's runway layout is shown in Fig.5. The approximate position of the dip can be confirmed from a recording of a take-off run along direction 03 by integration of the airspeed from the start of roll to the time of the CG acceleration oscillations, assuming the aircraft starts at a point close to the threshold. Subjective witness reports suggest that the longitudinal profile of the dip is shaped as shown in Fig.6.

The reason for the runway irregularity not being revealed earlier in the CAADRP programme on aircraft of Type C (which also operated at this airport) was that the take-off run was shorter and the aircraft was invariably airborne before the runway dip was reached.

3.2 Landing case

When traversing the runway irregularity after landing the aircraft's response was generally much lower than during the take-off owing to the lower aircraft speed and the effect of the irregularity was felt much less often on landing (see section 3.4.1). Also, on the landing run, the irregularity was traversed during a non-critical period of flight when the crew's work load is low. The effect of the runway abnormality is thus much less important in the landing case than in the take-off case.

From a sample of 277 landings on runway 03/21, 76 (33%) displayed the characteristic patch of CG acceleration oscillations peaking to 0.2g increment or more (the greatest was +0.48 Δg and is reproduced in Fig.3d), 34% displayed the characteristic patch but peaked to less than 0.2 Δg and in the remaining 33% of the sample the patch was not detected. Of the 76 landings where the response peaked to 0.2 Δg or more 58 were while travelling in direction 21.

3.3 Take-off case

3.3.1 Effect of pitch attitude on aircraft response

Due to the proximity of the aircraft's rotation point to the runway dip it was inevitable that initiation of rotation would occur sometimes before and sometimes after the dip. It is known that, due to changes in aerodynamic and undercarriage loading, the response of the aircraft is different when in the normal ground-borne tricycle attitude before rotation than when in the nose-wheel-up attitude during rotation. However, a study, detailed below, showed that the aircraft attitude had no significant effect on the average maximum CG acceleration.

The study consisted of selecting 100 take-offs from runway 03/21 which displayed the abnormally large fluctuations in CG acceleration. Selection was such that in 50 of these the characteristic accelerations were experienced prior to the start of rotation and in the remaining 50 during rotation. Tables 1 and 2 present, for each group of 50 take-offs, runway number, aircraft weight, extreme positive CG acceleration increment, extreme negative CG acceleration increment, airspeed at the time of the extreme positive increment, CG oscillation frequency (i.e. the frequency of the CG acceleration fluctuation about the 1g (absolute) mean) and mean pitch angle during the oscillatory period. The average extreme positive and negative peak accelerations of the group prior to rotation were 0.42 Δg and -0.52 Δg and of the group during rotation 0.43 Δg and -0.45 Δg, respectively.

Plotted in Fig.7 for each group of 50 take-offs is the maximum positive CG acceleration increment *versus* the pitch angle. No correlation is present, indicating that the severity at the CG was not a function of pitch angle.

3.3.2 Effect of pitch oscillations on response at cockpit

In some cases a small degree of pitching motion at about 1 Hz was apparent at the time of the high amplitude CG oscillation. This was shown to be a factor in increasing the motion at the cockpit, and hence the crew's discomfort. The 100 take-offs in Tables 1 and 2 were studied in respect of pitching amplitude and frequency and the phase difference in relation to the CG vertical motion. Where pitching variations of 0.5° or more were measured Tables 1 and 2 also show the peak-to-peak fluctuation and frequency. Twenty-one take-offs in the sample could not be assessed in this respect as the recording paper speed was too low to provide sufficient separation between adjacent oscillation peaks. In 54 of the remaining 79 take-offs there were no fluctuations in pitch greater than 0.5°, and oscillations with peak-to-peak fluctuations greater than 0.5° were measured on nine take-offs. As would be expected all of these nine were found in the first group of the sample, no pitch fluctuations greater than 0.5° being found when rotation had commenced. The phase differences between the pitch and CG heave motions were difficult to measure but appeared to be about 90°, i.e. the maximum peak acceleration at the cockpit due to the pitching motion usually occurred about ¼ second before the maximum peak CG acceleration. The largest pitch oscillation of 1.5° peak-to-peak was measured on flight number 53699 (see Table 1). The recording is reproduced on an expanded time scale in Fig.8. In this particular case the vertical acceleration at the cockpit was modified by the pitching oscillation as shown in the Appendix assuming simple harmonic motion and was estimated to be 0.85 Δg maximum for a maximum CG acceleration of 0.52 Δg (an increase of 0.33 g or 63%) assuming a phase difference of 90°.

No correlation of elevator motion with pitching was detectable.

3.3.3 Effect on crew comfort and performance

On the take-off run the runway dip was generally negotiated close to the time of rotation and lift-off and the crew experienced a 'fairly hefty jolting' at this critical moment of flight. This has been a source of comment from pilots for some years and the subject of complaint to the appropriate airport authorities by the airline concerned. Use of the airport, however, was due to be run down and for this reason the airport authorities were reluctant to authorise large expenditures. However, means of effecting inexpensive improvements are discussed in section 4.

3.3.4 Effect on aircraft structure

No structural damage has been known to have occurred as a result of operating on this runway but the loads generated could add to the overall fatigue of the aircraft structure. The effect on the aircraft fatigue from ground loads measured during take-off was assessed and Fig.9 provides a basis for determining future fatigue test ground load spectrums for the take-off case.

In order to assess the effect of aircraft fatigue it was necessary to determine the distribution of peak acceleration exceedances during the overall flying time of the aircraft. Each take-off during one complete year on one aeroplane was studied. From the start of each take-off run until lift-off positive normal CG acceleration peaks exceeding various levels from a minimum threshold of 0.10 Δg were counted. Distinction between the nosewheel being on or off the ground was ignored owing to the difficulty of identifying the start of rotation in some cases. In the majority of take-offs the duration of rotation was up to 3 seconds (about one-tenth of the take-off run), during which time peak vertical accelerations were generally no larger than in the preceding length of the run. The contribution to the fatigue load distribution (see below) during this time was therefore small.

To improve the accuracy of the distribution of accelerations (Fig.9) above 0.45 Δg the sample size was increased by 3611 to 5030 by including data from Tables 1 and 2. The author is confident that no contributions were made to the distribution above this level by any runway other than 03/21. Each of the two samples were from different aircraft (both Type E) but the proportion of take-offs from runway 03/21 were approximately the same for each at 5.9% and 6.5%.

From the above information the aircraft manufacturer's Stress Office was able to ascertain that the fatigue damage occurring to the undercarriages was no greater than that caused by their current test load spectrum for this aircraft type. On assuming the BCAR undercarriage drag and side-load coefficients of 0.4 and 0.2 of the vertical load respectively (unrealistically severe for this case being considered) the worst recorded case, i.e. 0.62 Δg, theoretically produced a maximum load equivalent to 54% of the design ultimate condition at one point on the leg assembly but because of the relative severity and infrequent application (once in 4150 flights) this is not considered to be critical from a fatigue point of view by the manufacturers. As for the remainder of the aircraft it is felt that no additional fatigue damage is being done.

3.4 Frequency of encounter

In order to determine how often the CAADRP-instrumented aeroplanes of Type E experienced the rough ride from runway 03/21 measurements from single aircraft taken over two consecutive periods of 6 months and 3 months, respectively, were studied. During the total period of 9 months (from 13.12.66 to 8.6.67) the two aircraft completed a total of 1175 flights. The total number of take-offs and landings on runway 03/21 by the two aircraft was 154 (13.1%) and abnormally high CG accelerations were measured on 80 of these. In the remainder lift-off occurred prior to the dip in the case of the take-off runs and in the landings the aircraft speed was too low for significant response at the CG to result. These 80 represent 3.4% of total take-offs and landings performed on any runway and 52% of take-offs and landings on runway 03/21. The frequency with which the runway dip is traversed and CG accelerations of greater than 0.2 Δg result is, therefore, assessed at 108 per aircraft year.

It is seen from Tables 1 and 2 that from the sample of 100 take-offs only one took place along direction 21 but an investigation showed that during the period covered by the sample 16% of all take-offs from the runway (with or without high CG accelerations) occurred in this direction. The reason for the large accelerations not being recorded on more than one occasion must be that lift-off occurred almost invariably before reaching the dip (at about intersection number 3) when on take-off. One contributory factor accounting for this is the slight downhill slope in this direction which marginally assists the aircraft's acceleration, another is that take-offs were performed four times more often in direction 03 than 21.

4 IMPROVEMENT OF RUNWAY IRREGULARITIES

The oscillation of aircraft Type C at airport number 53 (see section 2) may well have been excited by malalignment of concrete runway sections and selective tarmacadom surfacing might remove the irregularities almost entirely.

The irregularity in runway 03/21 at airport number 63 is thought to be of the form shown in Fig.6. Total elimination of such irregularities is not necessary to produce acceptable improvements, modification of the profile to alter suitably the wavelength, amplitude and/or shape being sufficient to achieve a considerable reduction in aircraft response. The profile in Fig.6 is shown modified in such a manner and, based on the roughly estimated dimensions shown, it is found that about 0.5×10^6 kg of material would be sufficient to effect this improvement.

5 CONCLUSIONS

A runway at each of two international airports were found to cause unusually large vertical accelerations at the CG of aircraft for brief periods during the take-off run. Only three runs which produced large CG accelerations were found at one airport (number 53), due to the aircraft only operating this number of times from the runway concerned, while at the other (number 63) the phenomenon occurred frequently. Oscillations from the same cause were also found during landings at the latter airport but were less severe. Pitching of the aircraft while traversing the uneven surface at the latter airport was sometimes found to increase the accelerations at the cockpit above those at the CG theoretically by up to 0.33 g. The mean pitch attitude was found to have no influence upon the maximum accelerations at the aircraft CG.

The resulting loads on the aircraft (Type E) operating at airport number 63 are considered to be generally catered for in the aircraft manufacturer's undercarriage fatigue test load spectrum. The maximum load recorded (0.62 Δg) theoretically represents no more than 54% of the design ultimate condition at one point of the undercarriage assembly and is not considered critical from the fatigue aspect.

It is suggested that by selectively resurfacing offending runway surfaces such as these, and thus altering the surface profile, the undesirably large responses in aircraft could be reduced to such an extent as to remove the problem.

Appendix

DETERMINATION OF RESULTANT OF TWO SIMULTANEOUS SIMPLE HARMONIC MOTIONS AT EQUAL FREQUENCY BUT OUT OF PHASE

From Fresnel's[5] vector diagram in Fig.10: amplitude of resultant acceleration at cockpit,

$$\ddot{Z}_R = \sqrt{\ddot{Z}_{CG}^2 + \ddot{Z}_P^2 + 2\ddot{Z}_{CG}\ddot{Z}_P \cos \phi} \tag{1}$$

where $\ddot{Z}_{CG}$ = vertical acceleration amplitude due to heave motion as measured at the CG. Upwards is positive (m/s^2)

$\ddot{Z}_P$ = vertical acceleration amplitude at cockpit due to pitch motion. Upwards is positive (m/s^2)

ϕ = phase angle of pitch motion relative to vertical CG motion.

Cockpit vertical displacement amplitude relative to CG,

$$Z_P = L \sin \alpha \qquad \text{for small values of } \alpha$$

where L = cockpit to CG distance (m)

α = pitch oscillation amplitude (deg).

$$\ddot{Z}_P = Z_P\omega^2 \cos \omega t$$

$$= \pm\, \omega^2 L \sin \alpha \qquad (\cos \omega t = \pm 1)$$

where ω = common frequency of CG heave and pitching motions

t = time.

Substituting in equation (1)

$$\ddot{Z}_R = \sqrt{\ddot{Z}_{CG}^2 + (\omega^2 L \sin \alpha)^2 \pm 2\ddot{Z}_{CG}\omega^2 L \sin \alpha \cos \phi} \; . \tag{2}$$

To calculate phase difference (β) of resultant acceleration at cockpit ($\ddot{Z}_R$) relative to acceleration at CG ($\ddot{Z}_{CG}$) from vector diagram:

$$\ddot{Z}_P^2 = \ddot{Z}_{CG}^2 + \ddot{Z}_R^2 - 2\ddot{Z}_{CG}\ddot{Z}_R \cos \beta$$

$$\underline{\underline{\beta = \cos^{-1} \frac{\ddot{Z}_{CG}^2 + \ddot{Z}_R^2 - \ddot{Z}_P}{2\ddot{Z}_{CG}\ddot{Z}_R}}} \quad . \tag{3}$$

Substituting into equation (2) the following values measured from flight 53699:

$$L = 16 \text{ m}$$

$$\ddot{Z}_{CG} = 0.52 \times 9.81 \text{ m/s}^2$$

$$\alpha = 0^\circ 45' \left(\text{i.e. } \frac{1.5^\circ}{2}\right)$$

$$\phi = 90^\circ$$

$$\omega = 0.9 \text{ rad/s}$$

we find

$$\ddot{Z}_R = 8.39 \text{ m/s}^2$$

or

$$0.85 \text{ g}$$

and from equation (3)

$$\beta = 52^\circ \quad .$$

This result represents an increase in acceleration at the cockpit over that at the CG of 0.33 g (63%).

Table 1

AIRCRAFT TYPE E
TAKE-OFFS EXHIBITING LARGE AMPLITUDE CG OSCILLATIONS PRIOR TO START OF ROTATION

Flight number	Run-way	Aircraft weight (1000 kg)	Extrm. positive CG accel. incr. (Δg)	Air-speed (kn)	Extrm. negv. CG accel. incr. (Δg)	CG oscill. freq. (Hz)	Mean pitch angle (deg)	Peak to peak pitch flucn. (deg)	*Pitch oscill. freq. (Hz)
50628	03	44.8	0.53	142	-0.35	1.7	2.3	0.5	1.7
50712	03	46.7	0.44	151	-0.50	1.7	1.9	0	-
50724	03	48.0	0.37	143	-0.35	1.1	1.7	0	-
50840	03	46.7	0.29	137	-0.54	1.3			
51111	03	48.3	0.53	141	-0.55	1.7	2.8	0	-
51139	03	46.8	0.53	142	-0.68		1.1		
51145	03	48.0	0.38	139	-0.61		3.4		
50914	03	45.9	0.43	146	-0.65	1.3	2.3	0	-
50928	03	46.0	0.44	147	-0.65	1.0	2.6	0	-
50938	03	44.8	0.43	149	-0.64	1.4	1.9	<0.5	-
50982	03	48.0	0.43	144	-0.68	1.0	2.6	0	-
51066	03	46.8	0.44	146	-0.58	1.0	1.7	0	-
51247	03	47.5	0.48	143	-0.64		2.1		
51289	03	48.4	0.62	149	-0.56		2.3		
51325	03	43.3	0.43	142	-0.30		1.8		
51383	03	47.0	0.37	136	-0.55		1.5		
52419	03	48.0	0.48	140	-0.19	1.1	1.8	0.5	1.1
52259	03	48.2	0.30	139	-0.43	1.0	2.3	0.5	0.7
52228	03	47.7	0.41	146	-0.53	1.3	1.9	0	-
52234	03	47.3	0.41	147	-0.50	1.3	2.3	0	-
52203	03	46.2	0.47	140	-0.53	0.9	1.0	0.5	0.9
51977	03	47.9	0.33	139	-0.49	1.0	1.5	0	-
51913	03	45.3	0.41	138	-0.48	1.1	1.9	<0.5	-
51905	03	47.3	0.37	136	-0.53	0.9	1.3	0.5	0.9
51877	03	47.0	0.33	138	-0.50	1.3	2.0	0.5	1.3
51848	03	46.9	0.50	140	-0.60	1.3	2.3	0.5	1.3
51808	03	48.3	0.43	140	-0.41	1.0	2.0	0.5	1.0
51734	03	43.0	0.35	136	-0.56		1.4		
51732	03	44.7	0.33	139	-0.58		1.4		
51730	03	45.7	0.35	140	-0.52		1.8		
51648	03	46.8	0.33	136	-0.47	0.9	1.0	1.0	0.9
51656	03	47.5	0.30	137	-0.43	0.9	1.0	1.0	0.9
51642	03	47.5	0.33	137	-0.45	0.9	0.8	0.5	0.9
51615	03	45.5	0.33	130	-0.47	1.1	1.1	0	-
51603	03	47.5	0.30	131	-0.44	1.1	1.3	1.0	1.1
52675	03	45.1	0.48	133	-0.14	0.9	1.0	1.0	0.9
53699	03	47.3	0.52	137	-0.60	0.9	0.8	1.5	0.9
53600	03	47.8	0.48	141	-0.52	0.9	1.0	1.0	0.9
54173	03	48.1	0.50	137	-0.56	1.1	1.5	1.0	1.1
40002	03	46.7	0.42	140	-0.57	1.1	2.3	<0.5	-
40012	03	47.8	0.41	136	-0.63	1.1	2.0	0	-
40059	03	46.9	0.39	139	-0.55	0.9	1.8	<0.5	-
40067	03	48.3	0.47	128	-0.62	1.3	1.6	0	-
40108	03	45.1	0.41	138	-0.62	1.3	1.2	0	-
40118	03	46.1	0.45	138	-0.66	0.9	3.9	0	-
40120	03	48.2	0.39	141	-0.54	0.9	2.3	0	-
40139	03	46.0	0.47	132	-0.60	0.9	1.8	0	-
51782	03	45.6	0.40	139	-0.50	1.1	1.6	0	-
53452	03	47.8	0.54	134	-0.50	0.8	1.5	1.0	0.7
53446	03	48.9	0.50	135	-0.50	1.0	1.8	1.0	1.0
Average		46.8	0.42	140	-0.52	1.1	1.8	0.3	

* Dashes are inserted where the pitch fluctuation was less than 0.5°.
Blank spaces appear where record measurement was not possible.

Table 2

AIRCRAFT TYPE E
TAKE-OFFS EXHIBITING LARGE AMPLITUDE CG OSCILLATIONS DURING ROTATION

Flight number	Run-way	Aircraft weight (1000 kg)	Extrm. positive CG accel. incr. (Δg)	Air-speed (kn)	Extrm. negv. CG accel. incr. (Δg)	CG oscill. freq. (Hz)	Mean pitch angle (deg)	Peak to peak pitch flucn. (deg)	*Pitch oscill. freq. (Hz)
50634	03	47.5	0.43	147	-0.61	1.3	3.6	0	-
50752	03	45.7	0.44	147	-0.42	1.3	5.1	0	-
50788	03	44.9	0.43	148	-0.32	1.1	4.9	0	-
51133	03	47.2	0.48	142	-0.65		2.8		
51127	03	47.2	0.41	141	-0.59		3.2		
50910	03	44.3	0.50	146	-0.45	1.1	4.3	0	-
50920	03	45.5	0.46	145	-0.64	1.3	1.3	0	-
51076	03	46.6	0.38	142	-0.52	1.1	1.3	0	-
51187	03	48.3	0.39	139	-0.59		2.8		
51209	03	49.2	0.48	145	-0.30		5.1		
51261	03	46.1	0.49	143	-0.45		6.5		
51287	03	48.8	0.38	143	-0.55		2.5		
51309	03	45.0	0.57	143	-0.59		3.9		
51323	03	42.6	0.43	140	-0.35		6.2		
51437	03	44.8	0.53	145	-0.64		3.0		
51634	21	47.9	0.56	147	-0.33	1.2	2.3	0	-
51971	03	44.4	0.41	144	-0.35	1.0	5.1	0	-
51989	03	48.7	0.33	139	-0.48	1.3	2.8	0	-
52057	03	45.2	0.47	140	-0.41	0.8	3.4	0	-
52118	03	43.7	0.22	145	-0.23	1.3	4.9	0	-
52179	03	44.6	0.40	146	-0.33	0.9	4.5	0	-
52238	03	47.3	0.33	147	-0.27	0.9	4.5	0	-
52226	03	44.8	0.34	143	-0.27	0.9	3.6	0	-
52273	03	45.7	0.40	142	-0.56	0.8	2.8	0.5	0.8
52271	03	44.7	0.37	143	-0.55	1.3	2.6	0	-
52261	03	46.8	0.40	142	-0.53	1.1	3.4	0	-
52193	03	46.2	0.23	138	-0.26	0.9	5.3	0	-
52417	03	48.7	0.47	138	-0.43	0.9	2.1	0	-
52397	03	43.7	0.42	143	-0.32	1.3	3.6	0	-
52480	03	42.6	0.40	145	-0.34	1.0	3.6	0	-
52506	03	46.1	0.48	144	-0.36	0.9	3.0	0.5	0.9
53709	03	47.3	0.42	140	-0.35	0.9	4.1	0	-
53795	03	45.5	0.56	139	-0.56	0.8	1.3	0.5	0.8
53831	03	49.7	0.44	142	-0.31	0.9	2.4	0	-
53835	03	47.4	0.52	139	-0.49	1.0	2.1	0	-
53876	03	46.4	0.29	135	-0.31	0.9	3.7	0	-
53596	03	49.5	0.49	132	-0.49	0.9	3.4	0	-
54134	03	42.0	0.28	136	-0.30	1.1	3.6	0	-
54239	03	46.7	0.40	130	-0.38	0.8	4.5	0	-
40225	03	48.3	0.52	139	-0.48	0.9	2.9	0	-
40277	03	45.6	0.32	135	-0.63	1.1	2.2	0	-
40457	03	45.3	0.46	149	-0.27	0.8	3.1	0	-
40429	03	46.6	0.39	141	-0.58		1.0		
40488	03	46.0	0.53	136	-0.44		6.4		
40510	03	46.2	0.49	143	-0.58	0.8	2.2	0	-
40686	03	46.7	0.46	144	-0.54	0.9	2.5	0	-
40708	03	45.1	0.49	143	-0.54	0.9	4.5	0	-
40712	03	46.8	0.53	146	-0.54	0.9	4.7	0	-
52762	03	45.6	0.44	140	-0.51	1.0	1.9	0	-
54054	03	48.0	0.40	143	-0.56	1.0	1.9	0	-
Average		46.1	0.43	142	-0.45	1.0	3.4	0	-

* Dashes are inserted where the pitch fluctuation was less than 0.5°.
Blank spaces appear where record measurement was not possible.

SYMBOLS

L	cockpit to CG distance (m)
t	time (s)
$\ddot{Z}_{CG}$	vertical acceleration amplitude due to heave motion as measured at the CG. Upwards is positive (m/s^2)
$\ddot{Z}_P$	vertical acceleration amplitude at cockpit due to pitch motion. Upwards is positive (m/s^2)
$\ddot{Z}_R$	amplitude of resultant vertical acceleration at cockpit. Upwards is positive (m/s^2)
α	pitch oscillation amplitude (deg)
β	phase angle of $\ddot{Z}_R$ relative to $\ddot{Z}_{CG}$ (deg)
ϕ	phase angle of $\ddot{Z}_P$ relative to $\ddot{Z}_{CG}$ (deg)
ω	common frequency of CG heave and pitching motions (rad/s)

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No.	Author	Title, etc.
1	The CAADRP Technical Panel	The civil aircraft airworthiness data recording programme. RAE Technical Report 64004 (ARC 26490) (1964)
2	The CAADRP Special Events Working Party (Coordinated by G.B. Hutton)	Civil aircraft airworthiness data recording programme. Hard landings encountered by subsonic civil jet aircraft. ARC CP 1182 (1970)
3	The CAADRP Special Events Working Party (Coordinated by A.W. Cardrick and K.D. Mephan)	Civil aircraft airworthiness data recording programme. Special Events relating to handling and control (January 1963 to February 1966) ARC CP 1080 (1969)
4	H. Hall	Some theoretical studies concerning oleo damping characteristics. ARC CP 951 (1966)
5	Jules Haag (Translated by Reinhardt M. Rosenberg)	Oscillatory motions. London, Constable and Co.Ltd.

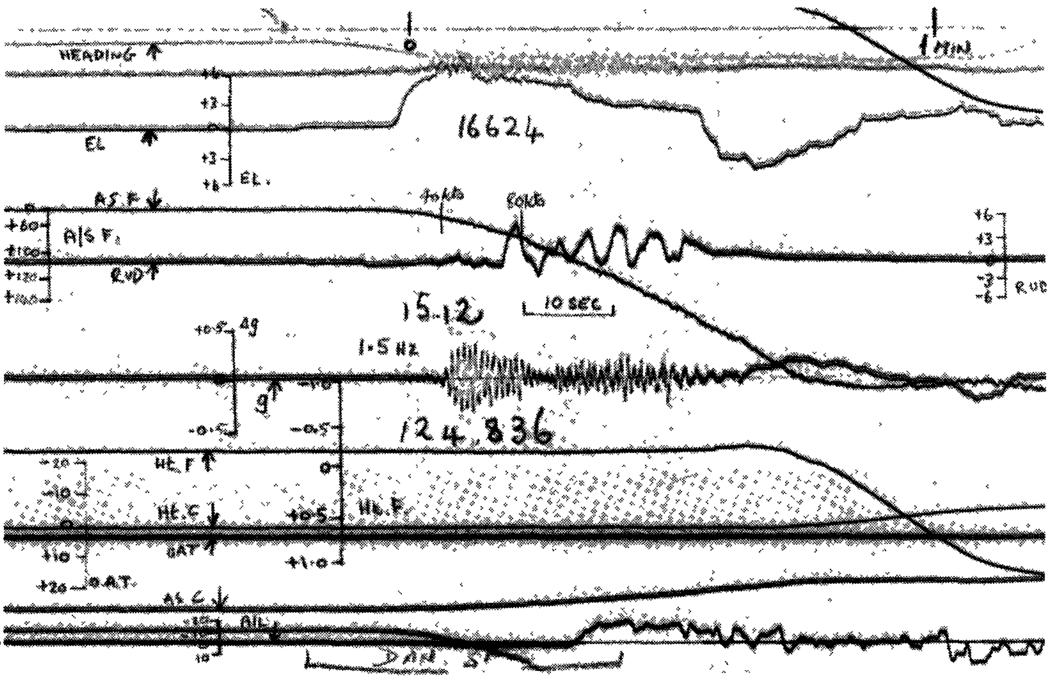


Fig.1 Take-off of aircraft Type C on Runway 22R at airport No.53

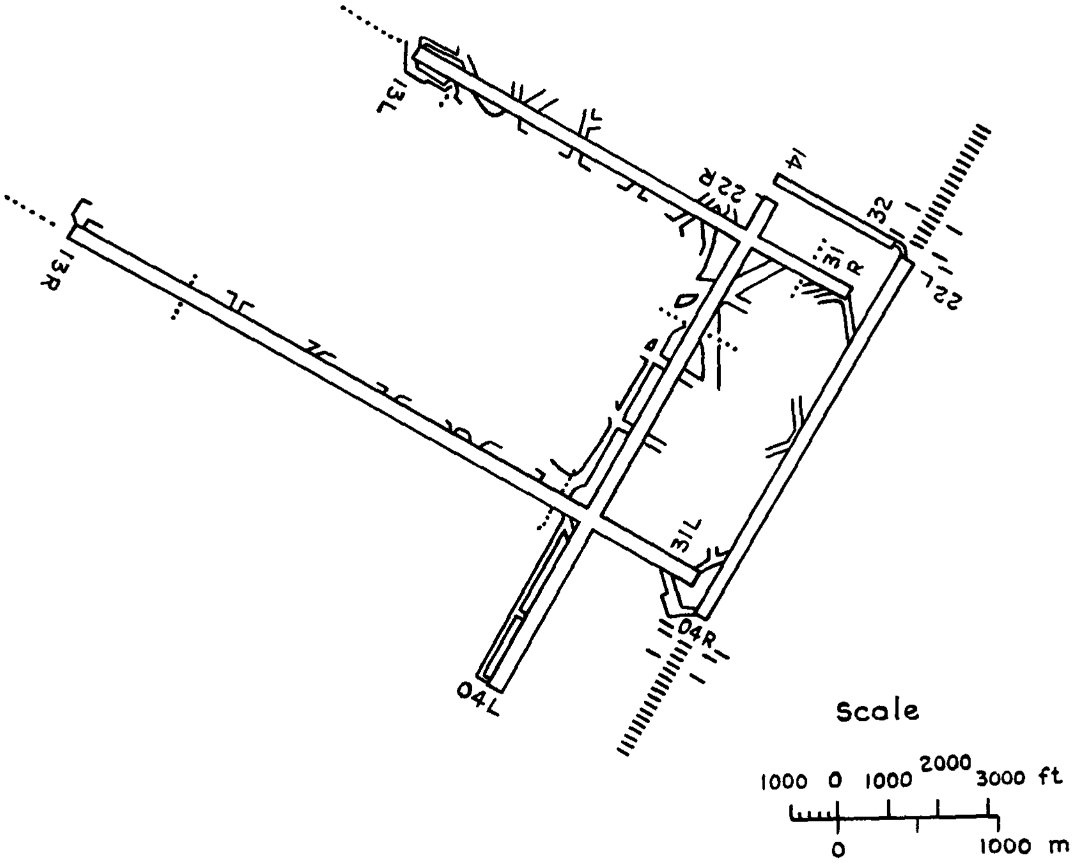
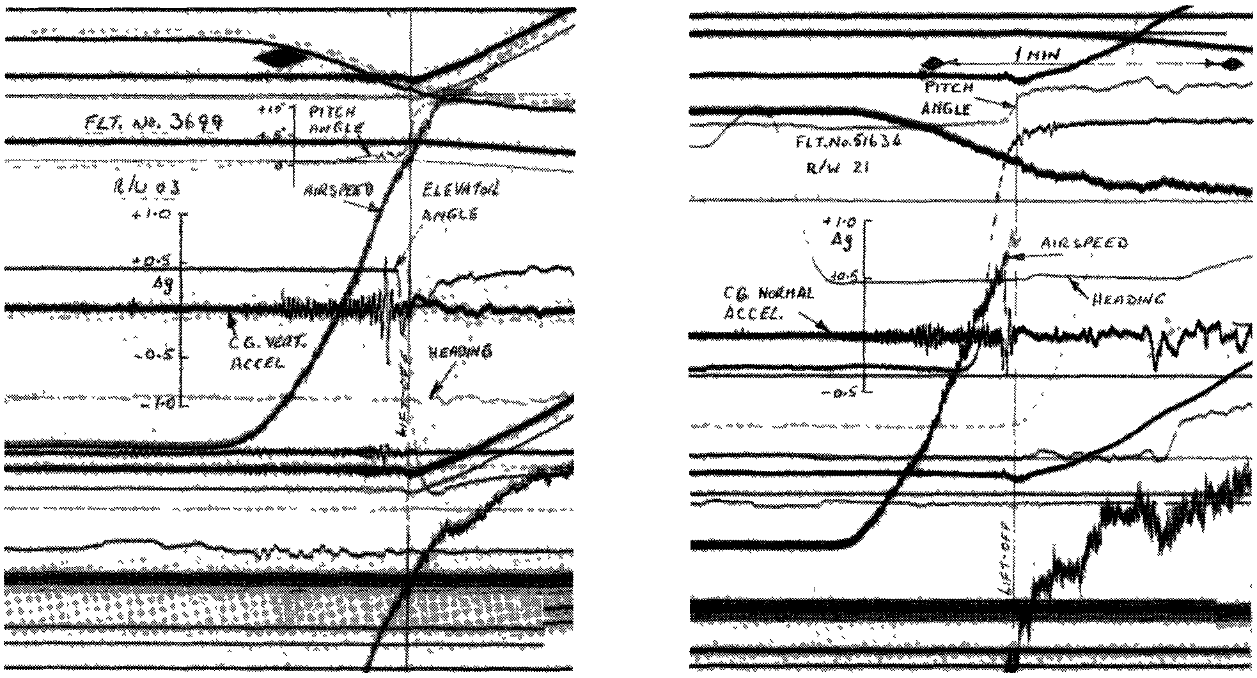
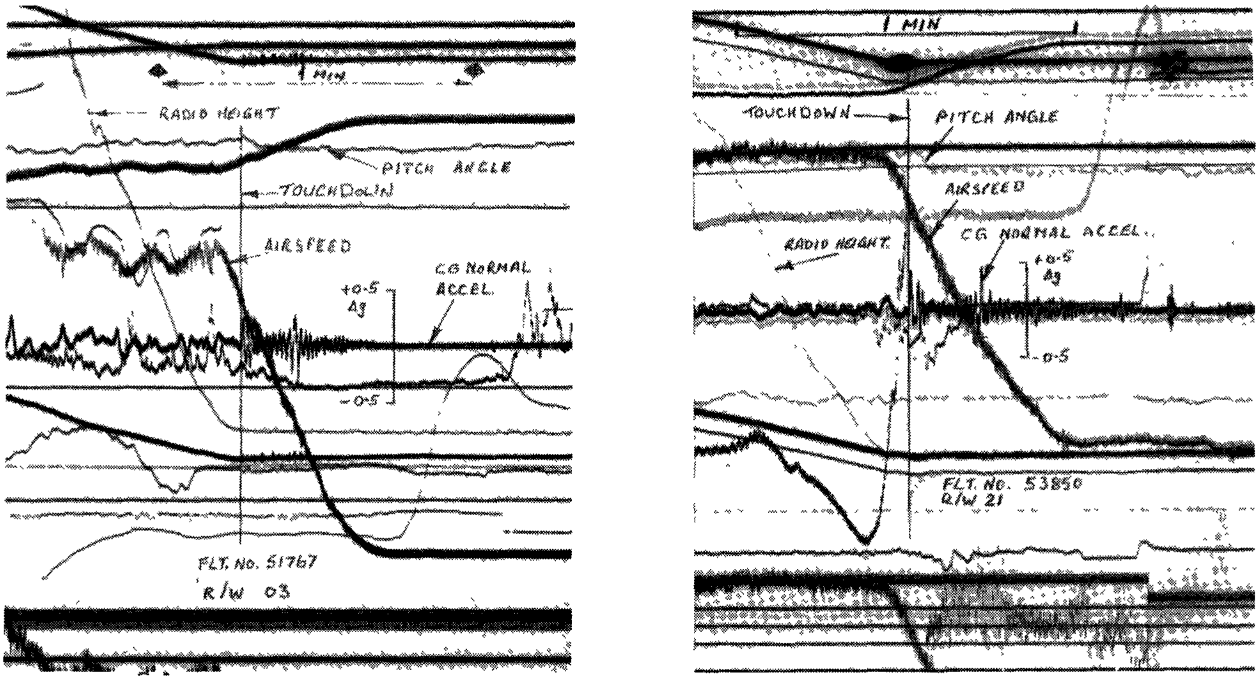


Fig. 2 Runway layout at airport No 53



(a) Take-off in direction 03

(b) Take-off in direction 21



(c) Landing in direction 03

(d) Landing in direction 21

Fig.3 Flight recordings of take-offs and landings on Runway 03/21

Aircraft type E

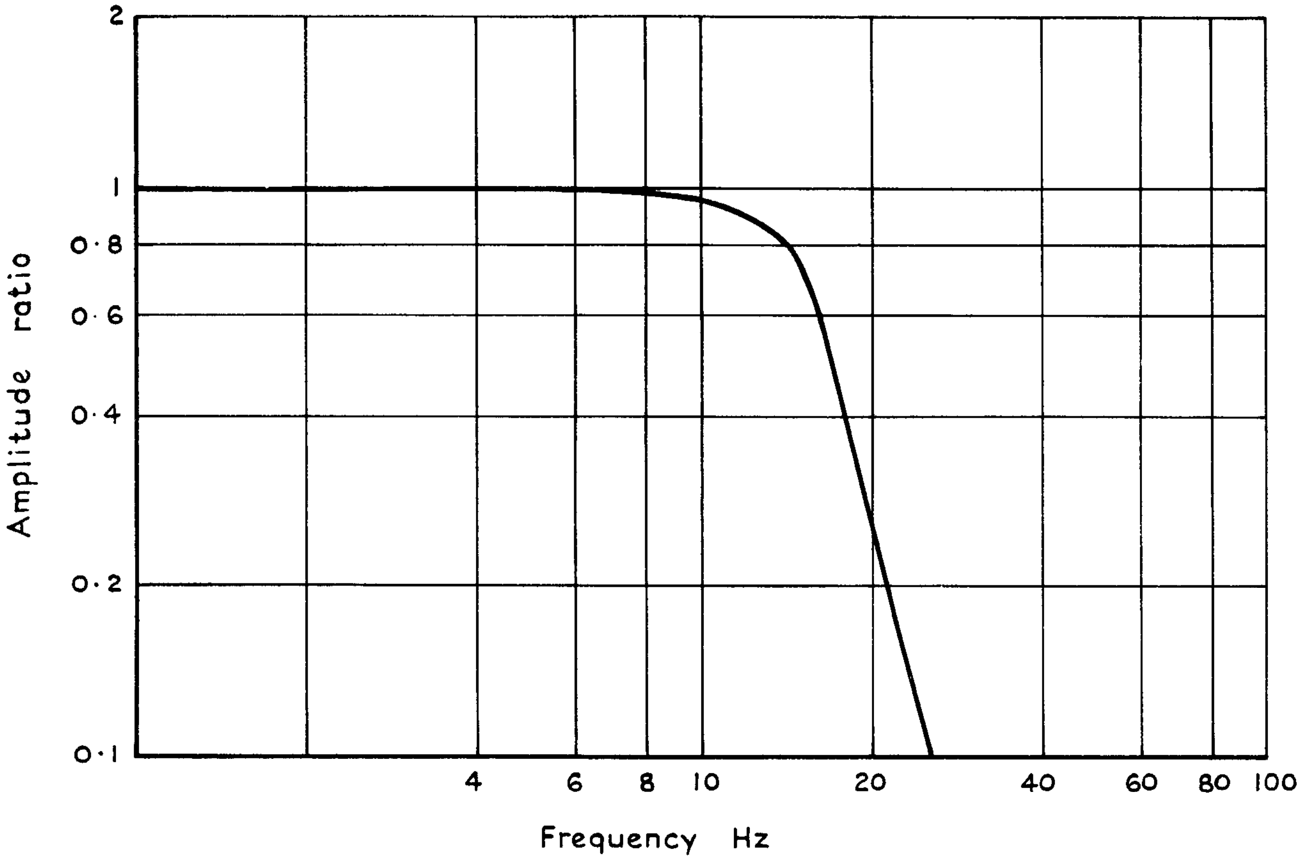


Fig.4 Frequency response of the normal CG acceleration instrumentation on aircraft type E

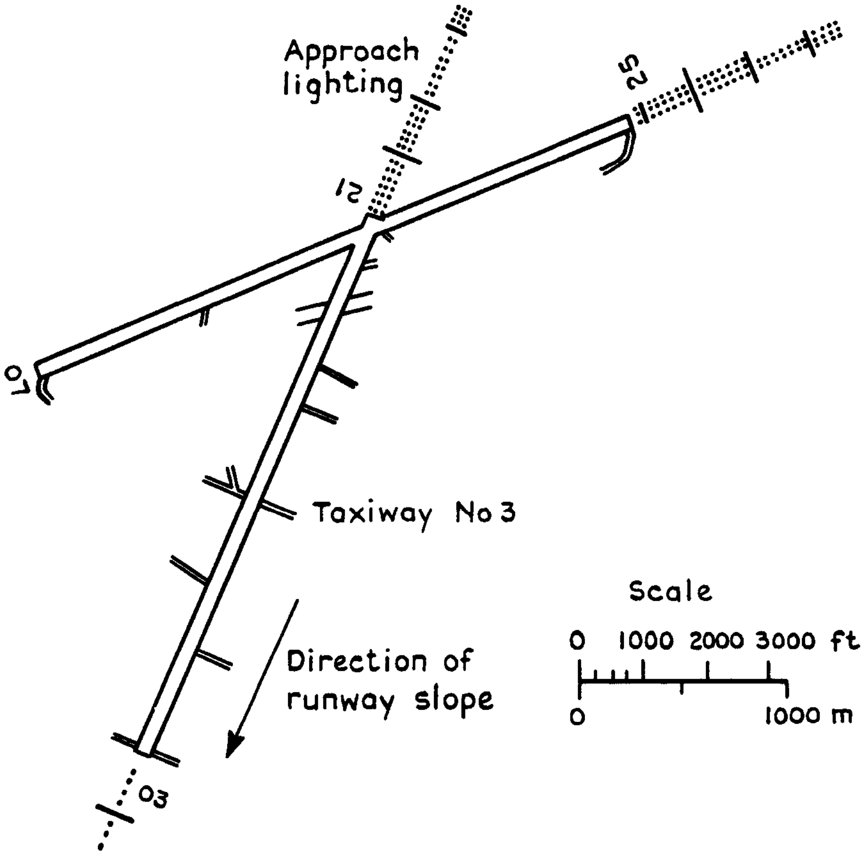


Fig.5 Runway layout at airport No 63

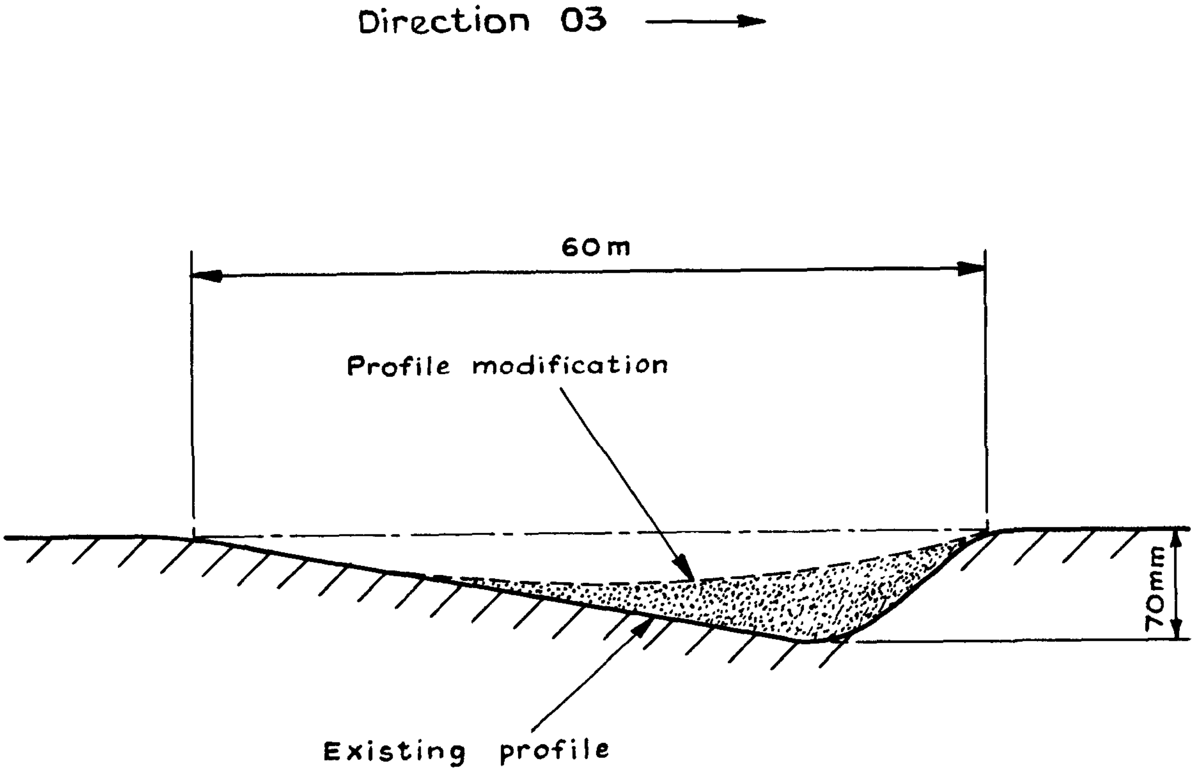


Fig. 6 Possible profile of irregularity in runway 03/21 at airport 63 and suggested improvement

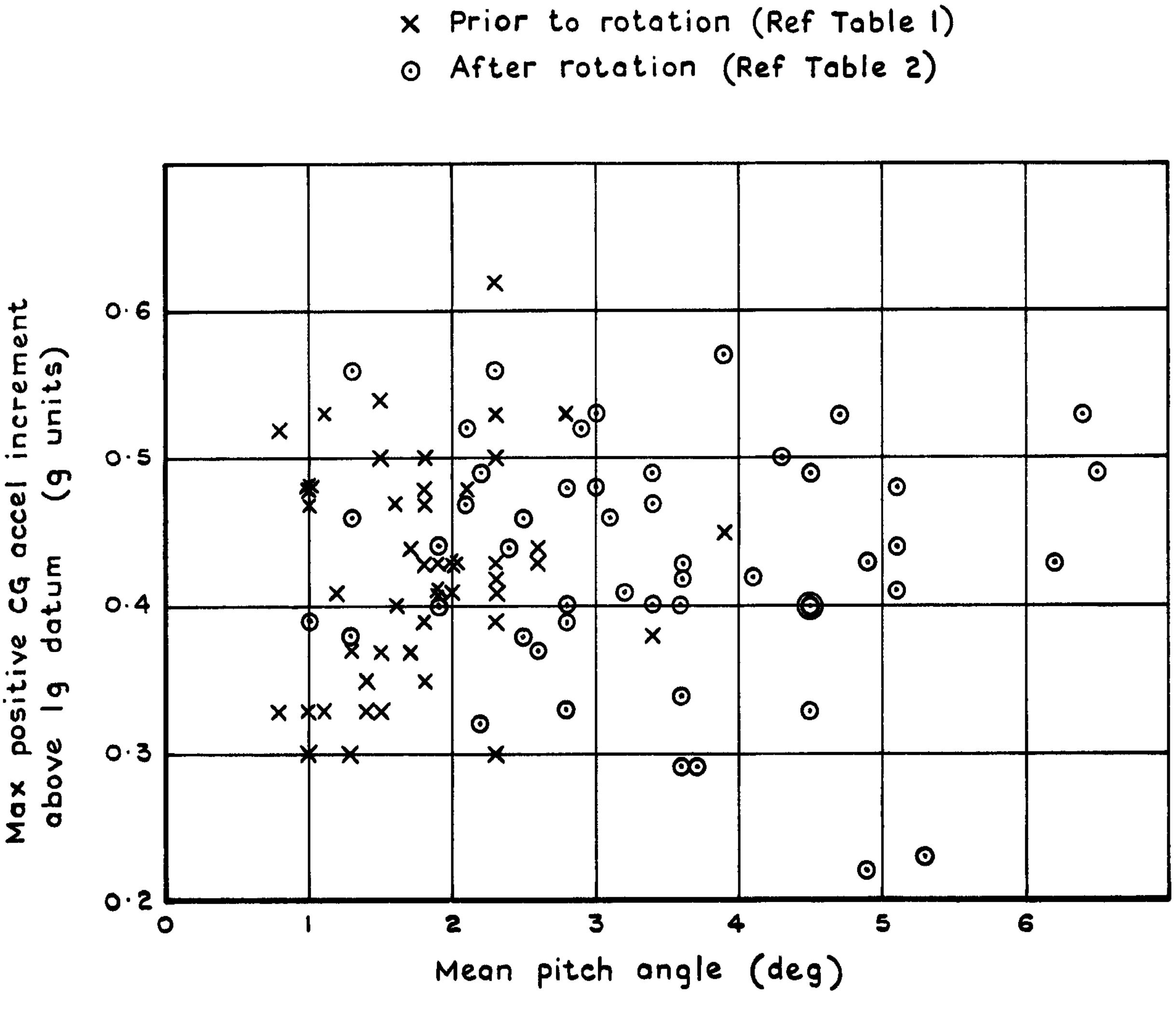


Fig. 7 Aircraft type E at airport No 63

Relationship between mean pitch angle and maximum positive CG acceleration increment on encountering the runway uneveness

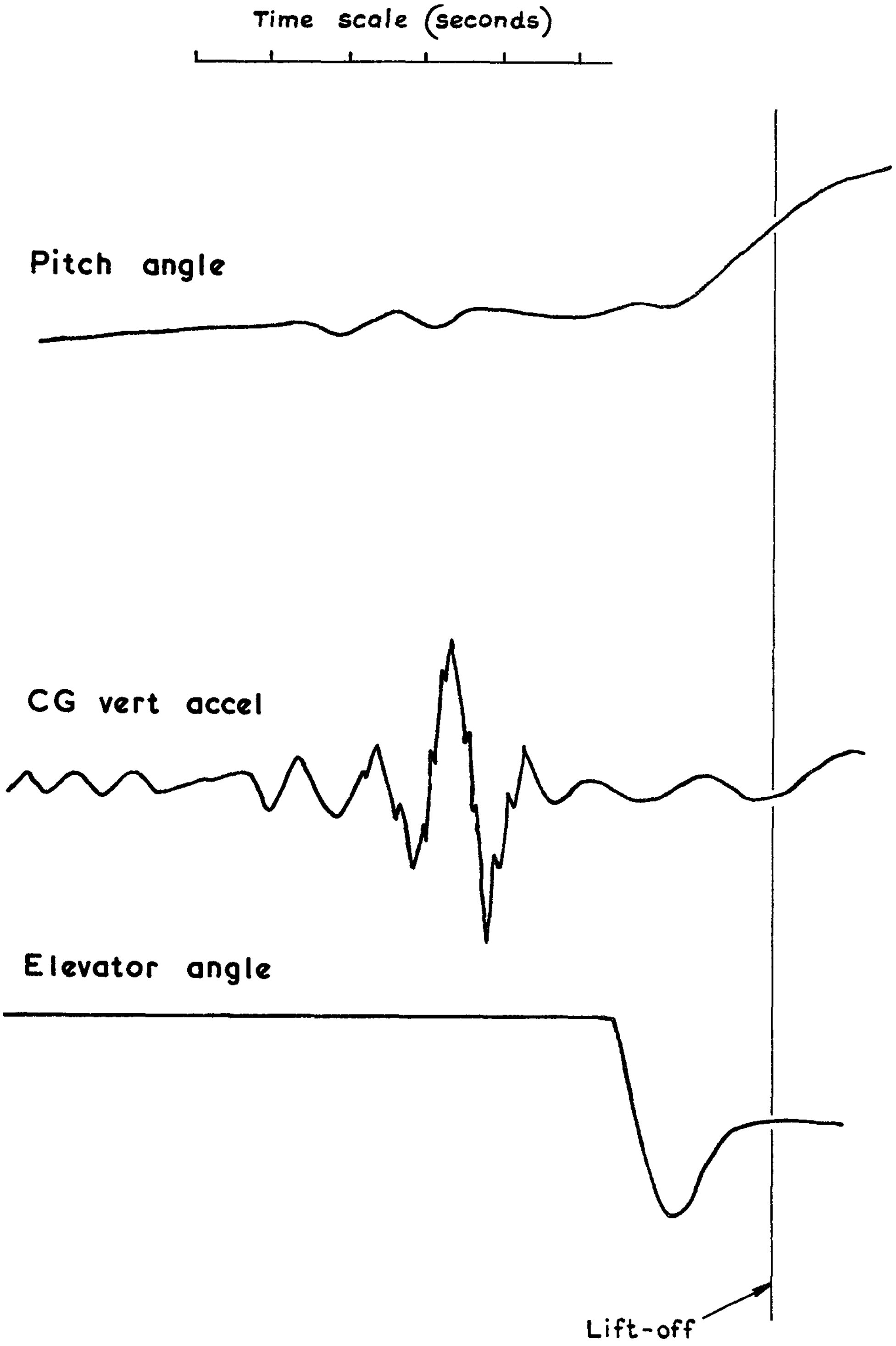


Fig. 8 Take off run of aircraft type E from runway 03/21 at airport 63 on flight No 536 99 (see also Fig. 3)

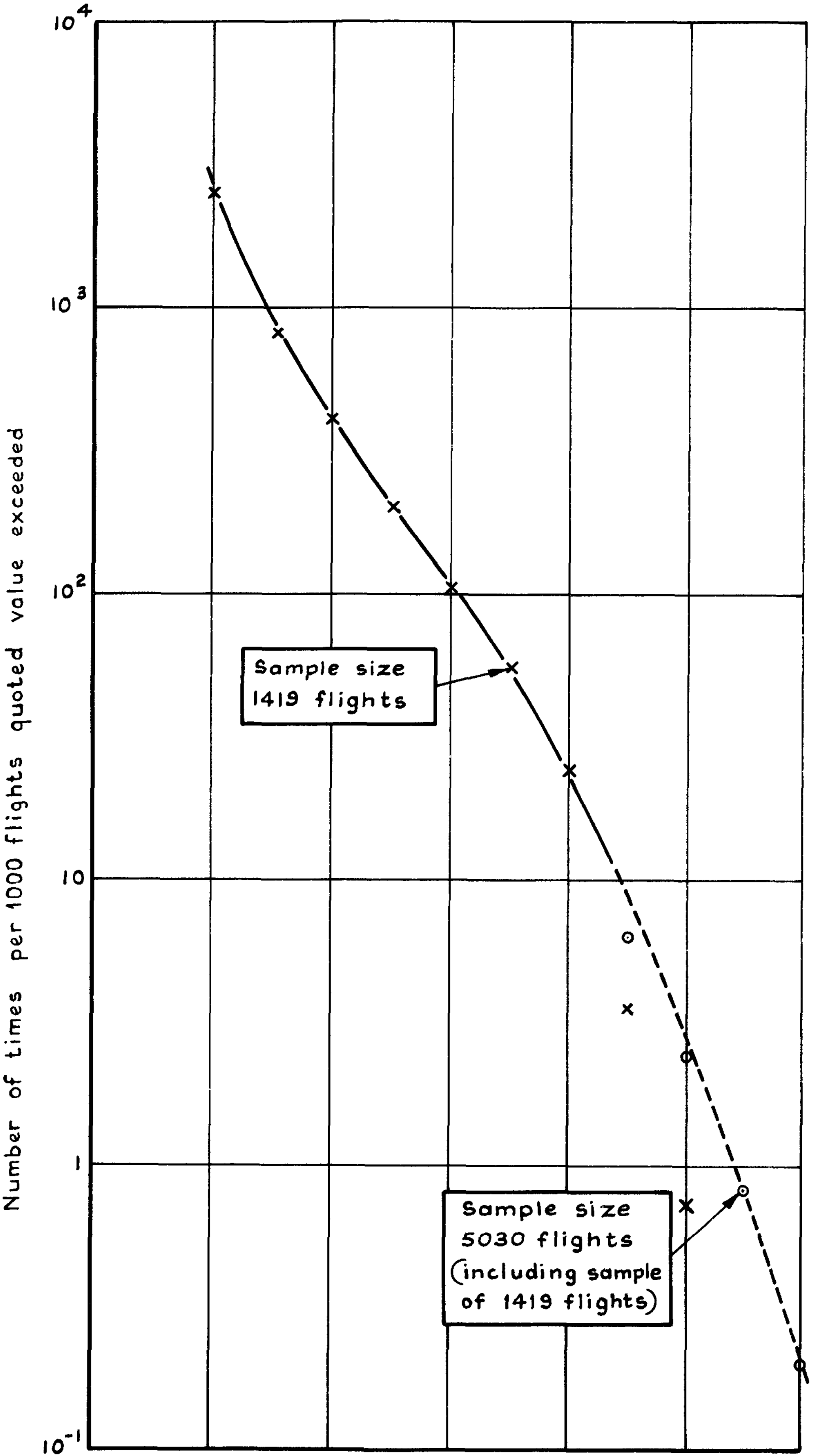
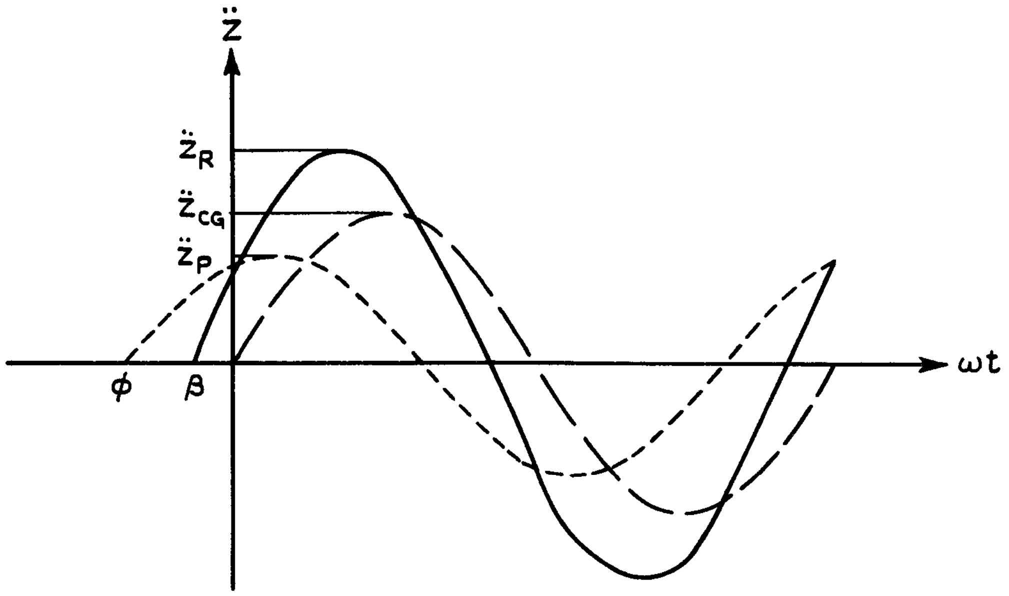
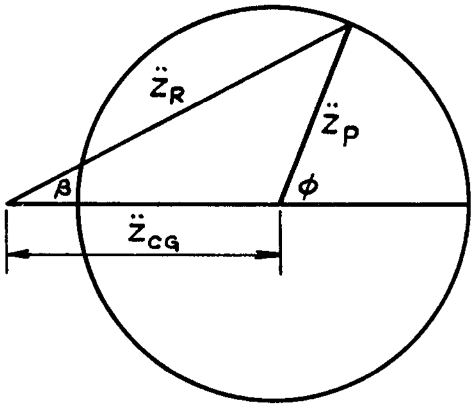


Fig.9 Positive peak CG acceleration during take-off Aircraft type E



a Oscillatory acceleration components and resultant



b Fresnel vector diagram

Fig.10 a & b Determination of resultant of two instantaneous oscillations of equal frequency

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Flight records of events are reproduced and discussed, one runway/aircraft combination being dealt with in particular detail owing to the phenomenon occurring frequently and being a source of comment from pilots.

There has been no known evidence of aircraft damage resulting from the events but some contribution to fatigue damage could occur, particularly on aircraft types with heavy wing-mounted appendages. It is suggested that selective resurfacing of the runways could considerably alleviate the loading action.

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