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OPERATIONAL AND THEORETICAL STUDIES ON THE EFFECT OF PILOT ACTION ON HEAVY LANDINGS

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SUMMARY

On the basis of operational evidence and a limited theoretical study it is suggested that pilot action can modify the consequences of heavy landings involving bounce to a very great extent, both beneficially and detrimentally. It is shewn theoretically that large elevator movements, leading to fluctuations in lift, can increase bounce height and structural loadings.

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*Replaces R.A.E., Technical Report 69278 - A.R.C. 32146.

CONTENTS

1 INTRODUCTION

The object of the Civil Aircraft Airworthiness Data Recording Programme (CAADRP) is a systematic study of the operational flight of civil transports. A small number of jet aircraft in regular airline service are fitted with analogue paper trace recorders to collect data on airspeed, barometric height, normal acceleration, outside air temperature and control surface movement. The whole programme is described fully elsewhere[1].

Study of operational records that have become available as a result of CAADRP suggests that pilot action may contribute to undesirable aircraft behaviour leading to higher structural loading in the more severe landings. The type of landing that is considered herein is characterised by bounce of the aircraft after the initial impact and the fact that second and subsequent impacts may involve equal, or more severe, structural loading.

The effect that the aerodynamic lift variations, which produce the aircraft bounce characteristics mentioned above, have in influencing the structural loading is examined theoretically for landings at two high values of vertical velocity of descent. The theoretical model consisted of a rigid aircraft, tyres, unsprung mass, oleo spring and damper.

2 OPERATIONAL EVIDENCE

A record of a heavy landing from one of the CAADRP aircraft having the characteristics studied is shown in Fig.1, where individual traces have been marked for ease of recognition and the time base indicated. The same identifications apply to Figs.3 and 5.

Fig.1 shows a flight recording of a two-bounce landing with the peak acceleration recorded at the aircraft centre of gravity on the second impact larger and the aerodynamic lift smaller than those on the first impact; thus some structural loads are more severe on the second impact. Fig.2 presents on an enlarged scale time histories of pitch attitude, control column movement, elevator angle and normal acceleration due to lift. All but the principal oscillations have been smoothed out for clarity. It is possible to deduce from the acceleration trace that there is an oscillatory variation in the aerodynamic lift during the landing. The initial acceleration peak occurs during the first impact and is approximately 1.03 g, thereafter falls to 0.85 g, 2.6 sec after touchdown, rises to approximately 0.95 g during the second impact, 4.6 sec after initial touchdown, and finally decays to 0.85 g after 6.0 sec.

After this time the lift variations cannot be inferred from the acceleration record. The lift variations noted above result from changes in the aircraft attitude and elevator angle brought about by pilot action and the steady decline of airspeed.

The pilot, responding to some cue that cannot be established from the record, applies up elevator very rapidly (14°/sec) over the 1 sec prior to impact. At the instant of impact he reverses elevator (from 18°). These actions cause pitch up and excess lift at initial touchdown aggravating the tendency of the aircraft to bounce on landing. The pilot then re-applies a large degree of pitch-up elevator (at a rate of 9°/sec) in order to arrest the sink rate for the second touchdown. Nevertheless the effect of pitch-up elevator is an increase in the sink rate for about one second on large aircraft with high pitching inertia[2]. This sequence of actions with elevator is repeated (up to a maximum rate of 33°/sec) prior to, and throughout, the second and subsequent impacts. The pitch attitude of the aircraft varies in the following manner during the complete landing process:- 5.1° during the flare rising to 7.7° (2.0°/sec) as a result of the initial elevator action, falling to 5.7° (-1.4°/sec) during the lift off, peaking to 8.5° after the second impact (1.1°/sec), and finally decaying gradually to the ground running value.

For comparison purposes, and to provide some indication of alternative pilot action in the case of a heavy landing, the operational event in Fig.3 is presented. Fig.4 presents, on a larger scale, time histories of pitch attitude, control column movement, elevator angle and normal acceleration due to lift. As in Fig.2 all but the principal oscillations are smoothed out for clarity. The initial acceleration peak (Fig.3) is of the same order as that depicted in Fig.1 but for this event there is no bounce. A significant difference between the two events is the absence of extreme elevator action in the second. The procedure in this case was to initiate the elevator down action just after touchdown and continue this motion throughout the landing. Aircraft pitching motion resulting from the action is smooth and pitch angle decays in a linear manner down to the nose wheel down attitude. Fig.5 presents the results of a very smooth landing and the pilot action is characterised by a downward trend similar to that in Fig.3. Time histories of the pitch attitude, control column movement, elevator angle and normal acceleration due to lift are present in Fig.6 on an enlarged scale and all but the principal oscillations are smoothed out again for clarity. The similarity of the aircraft behaviour after impact in these two cases and wide difference from the case shown in Figs.1 and 2 is revealed by the figures in Table 1 below and the discussion in the preceding paragraph.

Table 1

	Figs.1 & 2	Figs.3 & 4	Figs.5 & 6
Time to zero pitch	16.7 sec	4.4 sec	4.5 sec
Pitch angle at impact	+ 5.4°	+ 6.7°	+5.4°
Pitch rate after touchdown	+ 2.0°/sec	- 0.94°/sec	-0.94°/sec
Elevator angle at impact	-18°	-10.5°	-8.75°
Mean elevator rate following impact	-	+ 0.94°/sec	+1.53°/sec

In airline circles it has been suggested that pilots can alleviate bounce or ballooning by applying power gently after the bounce commences in order to have the facility to go round again or make a second controlled landing having achieved adequate elevator control. There is no operational evidence to suggest that this action is being taken in the type of heavy landings which have been studied.

The disparity between pilot action revealed in Fig.1 and Figs.3 and 5, and the effects on aircraft behaviour is so great that it was felt to be necessary to investigate theoretically the effect of such differences on the undercarriage loading in heavy landing cases corresponding to vertical velocities at impact of 7 and 11 ft/sec.

3 CALCULATIONS

Having defined the problem on the basis of the operational evidence, section 2, the next problem was to try to simulate the characteristics theoretically. The lift variation throughout the landing revealed by study of Fig.1 is one of a possible infinity of patterns depending on pilot action, runway characteristics, aircraft type etc. It was decided that, to reveal the effects of lift variation, families of theoretical curves would be constructed that covered most operational events. The curves have a decaying sinusoidal characteristic which takes account of the effect of pitch variations and elevator motion. The phasing with respect to the instant of initial touchdown is varied from case to case to simulate the timing of the pilot's use of the elevator.

Two formulae (see below) describing the sinusoidal aerodynamic lift variation are considered. Formula 1 assumes that the pilot's action affects only the phasing of the sinusoidal waveform. The envelope of the decay is a function of time (measured from the instant of touchdown) and is designated Type A lift decay. It was recognised that this form of decay is only one from the infinity that might be achieved in the practical case. Flight records examined indicated that the period of the oscillations were approximately constant at the value chosen, i.e. 4 seconds. In order to illustrate that the effects noticed in the practical case were not a function of a particular decay form a second form was considered. The decay in this case is assumed to depend on time modified by the phase shift, τ, and is designated Type B.

Each lift curve is composed of two parts superimposed:

(i) A component decaying, from a value of 1 g at the instant of touchdown, in accordance with the steady reduction in aircraft speed.

(ii) An exponentially decaying sinusoidal component.

The sinusoidal component has a period of 4 seconds and the constant, k, in the exponent is -0.20125 such that the amplitude of the oscillatory component is reduced by half every 3.4 seconds in all cases.

The oscillatory phase shift/decay relationships investigated were:

(i) Type A (Figs.7 to 12)

$$L = \Delta L e^{kt} \sin \frac{\pi}{2} (t + \tau) \qquad (1)$$

and (ii) Type B (Figs.13 to 18)

$$L = \Delta L e^{k(t + \tau)} \sin \frac{\pi}{2} (t + \tau) \qquad (2)$$

where L = oscillatory lift about mean value at time t
t = time with respect to the instant of initial touchdown
τ = phase shift
ΔL = incremental amplitude from which the oscillatory lift is calculated, hereafter termed the 'basic amplitude'.

The lift variations are plotted in Figs.7 to 18, extending over 10 seconds starting at the instant of touchdown. A total of six curves on any one figure illustrate the variation in phasing of the oscillatory component of the lift with respect to the instant of initial touchdown.

For each of the two landing conditions above three values for the basic amplitude are considered, namely 0.1, 0.2 and 0.3 g and two values of descent velocity namely 11 and 7 ft/sec which represent severe and hard landings respectively. Each of the Figs.7 to 18 considers one basic amplitude. In each case the effect of the phasing of the oscillatory component with respect to the instant of initial touchdown is studied. Six values of phase shift (τ) are considered ranging from -2 to $+1\frac{1}{3}$ sec in steps of $\frac{2}{3}$ sec.

In Figures 7 to 12 (Type A decay) the basic amplitude occurs at touchdown for all values of τ. In Figs.13 to 18 (Type B decay), at negative values of τ, the amplitude decays from a level at touchdown in accordance with formula 2 above and reaches the basic amplitude at a time of $-\tau$; at positive values of τ the amplitude at touchdown is less than the basic amplitude, and has a value as though it had been decaying in accordance with the formula prior to touchdown. Equivalence between the two families, Type A and Type B, is obtained when $\tau = 0$ and thus the bottom left hand curve in Fig.(7 + n) is identical with the corresponding curve in Fig.(13 + n) where $n = 0, 1,$ ---- 5.

For comparison a lift variation obtained from a 'good' pilot landing practice is also considered for each case, i.e. no oscillatory component induced and the aircraft pitch steadily reduced from the moment of initial touchdown. The good practice has been defined in terms of the parameters outlined in section 2. The same pitch rate (-0.94°/sec) as in the events of Figs.3 and 5 and the same elevator rate (1.53°/sec) as in Fig.5 are considered. The lift variation is indicated in Figs.7 to 18.

It was decided in the first instance to use the two degrees of freedom aircraft/undercarriage model incorporating an orifice damper considered in an earlier paper[3] modified in that an undercarriage oleo having a longer stroke of 1.2 ft was considered. This modification meant that the maximum reaction factor obtained in the proof rate of descent touchdown case (11 ft/sec), i.e. 2.02 g increment, was typical of that of a current high-speed subsonic jet. The weight of the lower oleo and wheel assemblies (i.e. the unsprung weight) was 131 lbf compared with the sprung weight of 2411 lbf and the damping constant 60 slug/ft. It was assumed that the nosewheel did not contact the ground during the landing phase. Initial calculations were made with this descent rate at initial touchdown but were subsequently extended to include the hard landing, 7 ft/sec. No extension of the work beyond the two degree of freedom system has been attempted to date.

3.1 Theoretical results

The results of the calculations are indicated in caption form on each of the individual graphs that make up Figs.7 to 18. The parameters that are included in each caption are, in each column

PH = peak height reached by upper mass, i.e. aircraft, on first bounce relative to initial touchdown value (ft)

t_{PH} = time at which peak height achieved (sec)

VV_2 = vertical velocity of the upper mass at instant of second touchdown (ft/sec)

VA_2 = downward acceleration of the upper mass at the instant of second touchdown (ft/sec^2)

t_2 = time at which second touchdown occurs (sec)

F_{S1} = peak undercarriage strut reaction during first impact expressed as a fraction of the total weight

F_{S2} = peak undercarriage strut reaction during second impact expressed as a fraction of the total weight.

The first column contains results appropriate to an undercarriage having an oleo damping constant on extension equal to that on compression for the oscillatory lift case, the second column refers to an undercarriage with a damping constant on extension fifty times that on compression (hereafter called the 50:1 damper) again for the oscillatory lift case, and the third to the 50:1 damper with lift varying according to the 'good' landing practice law. The results are presented for a 'good' landing practice for different levels of aerodynamic lift at touchdown when pitch rate has been set at -0.94°/sec prior to touchdown and throughout the landing.

3.1.1 Severe landings (descent velocity 11 ft/sec)

A study of Figs.7, 8 and 9 for the severe landing in Type A lift conditions shows that the worst conditions at second touchdown (defined in terms of vertical velocity of descent at this instant) obtain when pilot action has led to increasing lift at the instant of touchdown, i.e. elevator up about one second before touchdown, and maximum lift occuring approximately 1 to 2 seconds after touchdown. Table 2 shows the vertical velocity at second touchdown, for the 50:1 rebound damping constant ratio, for the worst condition (VV_2 max) in each of the figures expressed as a percentage of the initial touchdown velocity (VV_1). Also indicated is the peak height reached during the bounce resulting in VV_2 max and, for comparison with VV_2 max, the velocity at second impact achieved with optimum timing of the oscillatory lift (VV_2 min) and that achieved when the 'good landing practice' is adopted. These are again expressed as a percentage of the initial touchdown velocity. All non-dimensional velocities quoted are rounded to the nearest 5%.

The structural severity of these second landings (F_{S2}) as indicated by comparison with F_{S1} (i.e. Fig.7: 80%, Fig.8: 130% and Fig.9: 200%) is greater than indicated by vertical velocity alone because of reduced aerodynamic lift that is experienced at the instant of second impact.

Figs.13 to 15 give results of severe landings effected in Type B lift conditions. They may be summarised in the same terms as above and are presented, again for the 50:1 damper, in Table 2.

Table 2

50:1 damper. Vertical velocity at initial touchdown 11 ft/sec

Fig.	$\frac{VV_2 \text{ max}}{VV_1}$ %	P.H. (ft) corresponding to VV_2 max	$\frac{VV_2 \text{ min}}{VV_1}$ %	$\frac{VV_2 \text{ min}}{VV_1}$ % (good landing practice)
7	80	10.7	20	20
8	120	17.1	25	20
9	165	23.8	15	20
13	85	10.1	25	20
14	120	17.1	10	20
15	165	23.8	20	20

Such differences as do exist in the structural loadings on second impact, which are relatively small, between corresponding cases possessing the alternative type lift oscillation decay can be put down to the relative differences in oscillatory amplitude about the mean.

The results show that bounce and undercarriage loading may be reduced most effectively by the pilot if he can adopt the 'good' landing practice in which control action induces a steady pitch rate of about 1°/sec throughout the landing. The oscillatory elevator movements never lead to significantly reduced loads on the second impact relative to the 'good' practice (see Figs.19 to 22). For aircraft with a large pitching moment of inertia and relatively long response time this would involve initiation of gentle down elevator action immediately before touchdown. A typical time for a large civil aircraft might be 1-2 sec. This elevator movement would be continued throughout the landing. The consequences of alternative pilot action involving rapid reversals of elevator are indicated on Figs.7 to 9 and 13 to 15. The critical nature of the lift phasing relative to initial touchdown time is strikingly brought out. It is unlikely that this type of pilot action will alleviate the heavy landing problem unless the phasing with respect to the instant of initial touchdown is favourable. Operational data suggests that cues allowing this phasing to be accurately controlled are not available to a pilot.

3.1.2 Hard landings (descent velocity 7 ft/sec)

The corresponding tabular notation to that adopted in 3.1.1 for 50:1 dampers is adopted in Table 3 below.

Table 3

50:1 damper. Vertical velocity at initial touchdown 7 ft/sec

Fig.	$\frac{VV_2 \text{ max}}{VV_1}$ %	P.H. (ft) corresponding to VV_2 max	$\frac{VV_2 \text{ min}}{VV_1}$ %	$\frac{VV_2 \text{ min}}{VV_1}$ % (good landing practice)
10	90	5.0	10	5
11	120	10.8	5	5
12	165	17.0	5	5
16	90	4.1	5	5
17	130	10.2	5	5
18	165	16.9	0	5

In the worst cases vertical velocities at second impact are seen to be increased by the same proportion as those in severe landings although, of course, the load levels are less than in the severe landings. Even so these levels can exceed those experienced during the first touchdown and approach the typical design reaction factor. The Type B lift variations lead to similar results and relative values are much the same as those found in the severe landing case.

In some cases on the 50:1 damper the rebound peak height was found to be negative (the loading on the second impact being small). This is due to the tyre leaving the ground with the oleo being only partially extended. Rebound would not have occurred had the oleo extension rate been sufficient for the tyre to remain in contact with the ground.

3.1.3 Impact reactions

Figs.19 to 22 show the peak impact reaction for the 50:1 damper on both initial and second touchdowns (F_{S1} and F_{S2} respectively) plotted against the oscillatory lift phase shift (τ) for the severe and heavy landing cases and types A and B lift oscillation decay. Each figure comprises three diagrams appropriate to basic amplitudes (ΔL) of 0.1, 0.2 and 0.3 g respectively. The graphs show that the maximum value of F_{S2} for a particular oscillatory lift amplitude occurs at values of τ from $-\frac{1}{4}$ to $-\frac{1}{2}$ sec and that its level rises significantly with increase in this amplitude. Also shown in the diagrams are curves representing the reaction at second impact which would be achieved if the lift characteristics appropriate to the 'good landing practice' (as drawn in each diagram of Figs.7 to 18) were to be achieved from the instant of initial touchdown. It can be seen that F_{S2} for the 'good' landing practice remains at a more consistently low value in all cases.

3.1.4 Discussion

We have seen above that oscillatory variations in lift which are attributed to pilot action and ground effect can lead, when the lift is badly phased with respect to the instant of touchdown, to severe loadings on second impact whereas they have a negligible effect on the first impact. It may be conjectured that application of spoilers at a particular time relative to the instant of touchdown could lead to a similar phenomenon. For example, if spoilers are applied during rebound in a landing that is made with lift increasing at the instant of touchdown, a situation exists that is similar to that depicted for the cases when $\tau = 0$ in the figures and might be expected to lead to similar extreme loadings.

Attention has been restricted in this paper to the heavier landings. There is no operational evidence to suggest that this type of extreme pilot action occurs significantly during light landings although it is known[2] that pilots do tend to 'pump' the stick whilst feeling for the ground. There is operational evidence, however, to suggest that the runway surface does play an important role in determining the multiple bump nature of lighter landings. This topic should be explored in a further paper as indeed should the effect of runway roughness on the heavier landings.

4 CONCLUSIONS

On the basis of study of operational records and some simplified calculations it is suggested that pilots should be discouraged from making violent elevator movements in the course of a landing. It has been seen above that, during a heavy landing, these can increase the bounce height and the structural loadings on the second impact, compared with when the 'good' landing practice is used, and they never significantly reduce them. Operational data confirms that these types of elevator movement occur during hard landings and that the timing tends to increase structural loads on the second and subsequent impacts. The risks of exceeding proof load, therefore, can be as high after a bounce as at the initial touchdown using current operating techniques.

SYMBOLS

F_{S1} = Peak undercarriage strut reaction during first impact expressed as a fraction of the total weight.

F_{S2} = Peak undercarriage strut reaction during second impact expressed as a fraction of the total weight.

k = Exponential constant.

L = Oscillatory amplitude of lift above mean value at time t.

ΔL = Incremental amplitude from which the oscillatory lift is calculated, termed the 'basic amplitude'.

PH = Peak height reached by upper mass, i.e. aircraft, on first bounce relative to initial touchdown value (ft).

t = Time with respect to the instant of initial touchdown.

t_{PH} = Time at which peak height achieved during first bounce (sec).

t_2 = Time at which second touchdown occurs (sec).

VA_2 = Downward acceleration of the upper mass at the instant of second touchdown (ft/sec^2).

VV_2 = Vertical velocity of the upper mass at instant of second touchdown (ft/sec).

τ = Phase shift of oscillating lift (sec).

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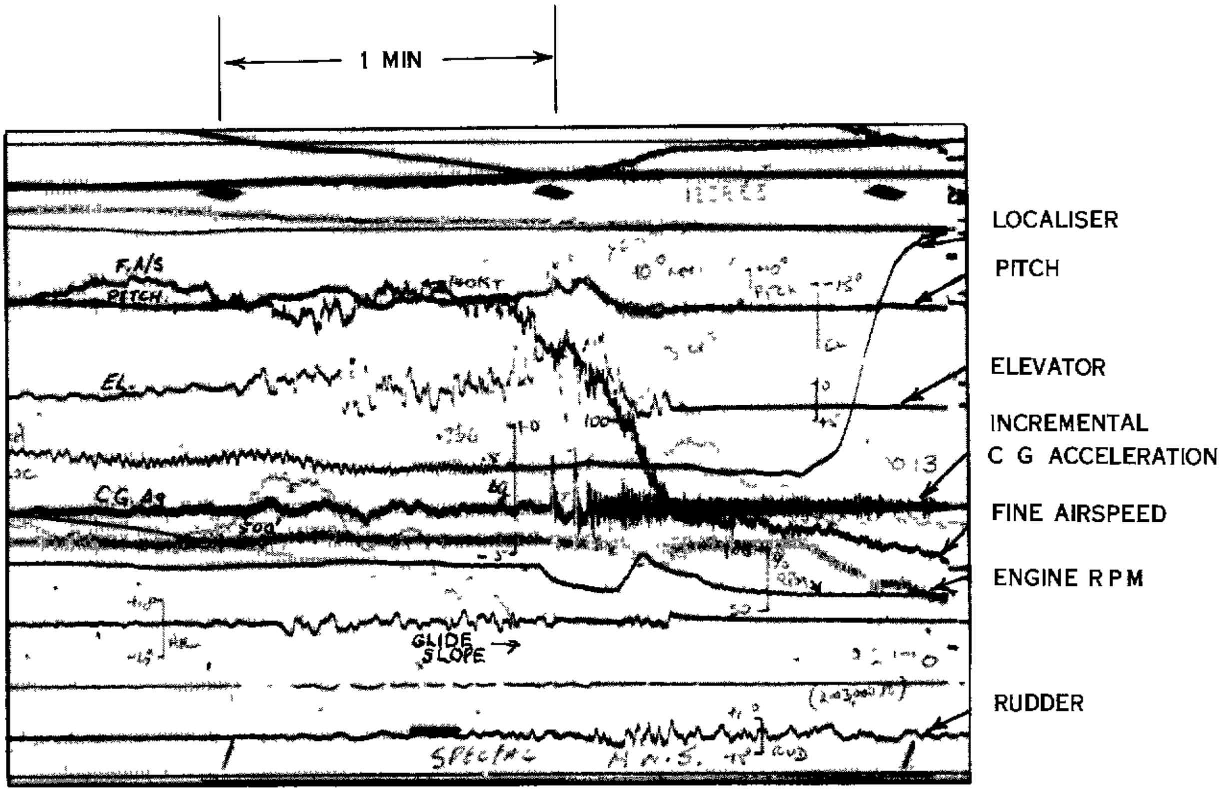

Fig.1. Heavy landing with double bounce

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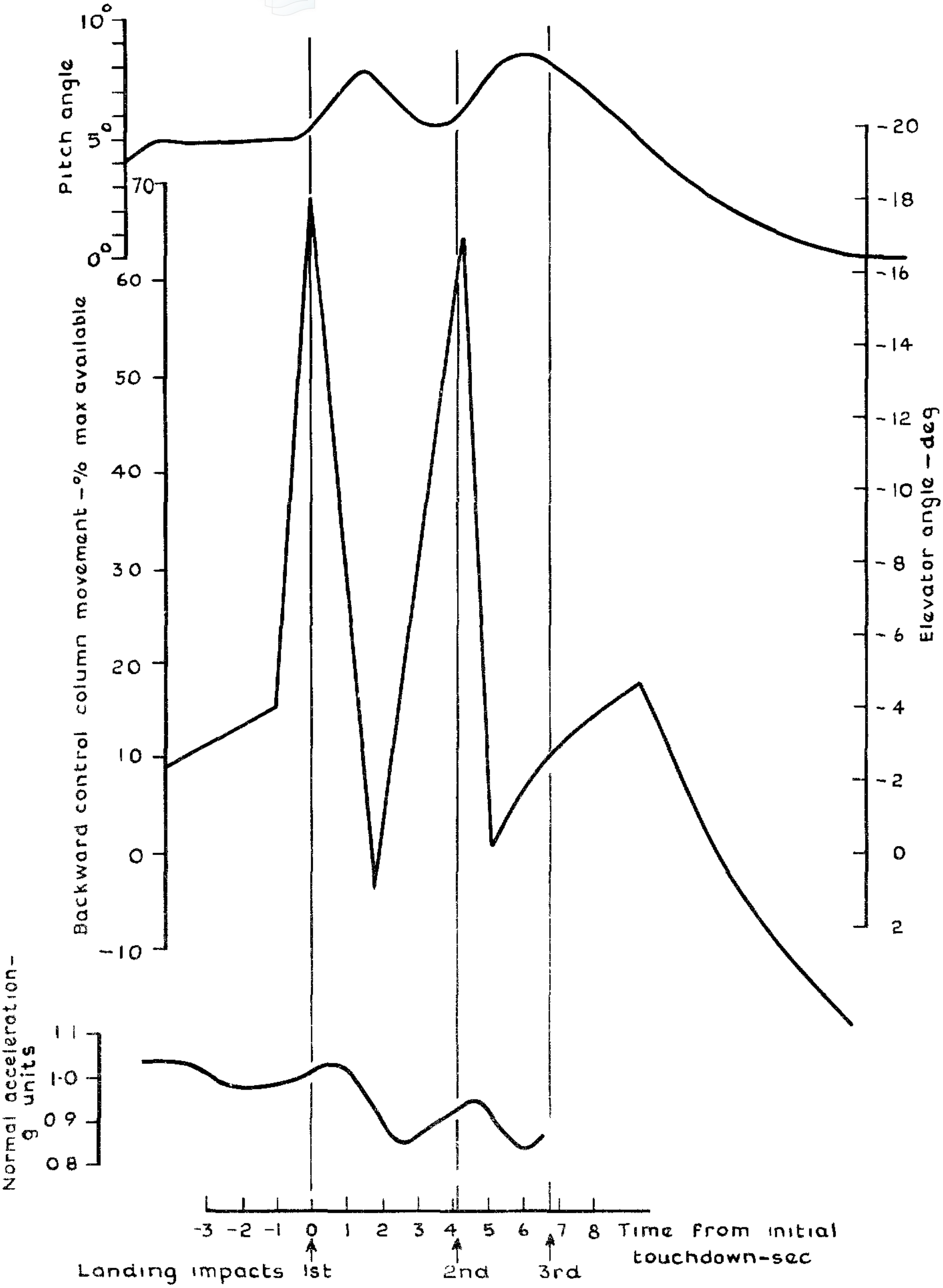

Fig 2 Smoothed pitch attitude, control column movement, elevator angle and normal acceleration due to lift during heavy landing with double bounce (Ref Fig 1)

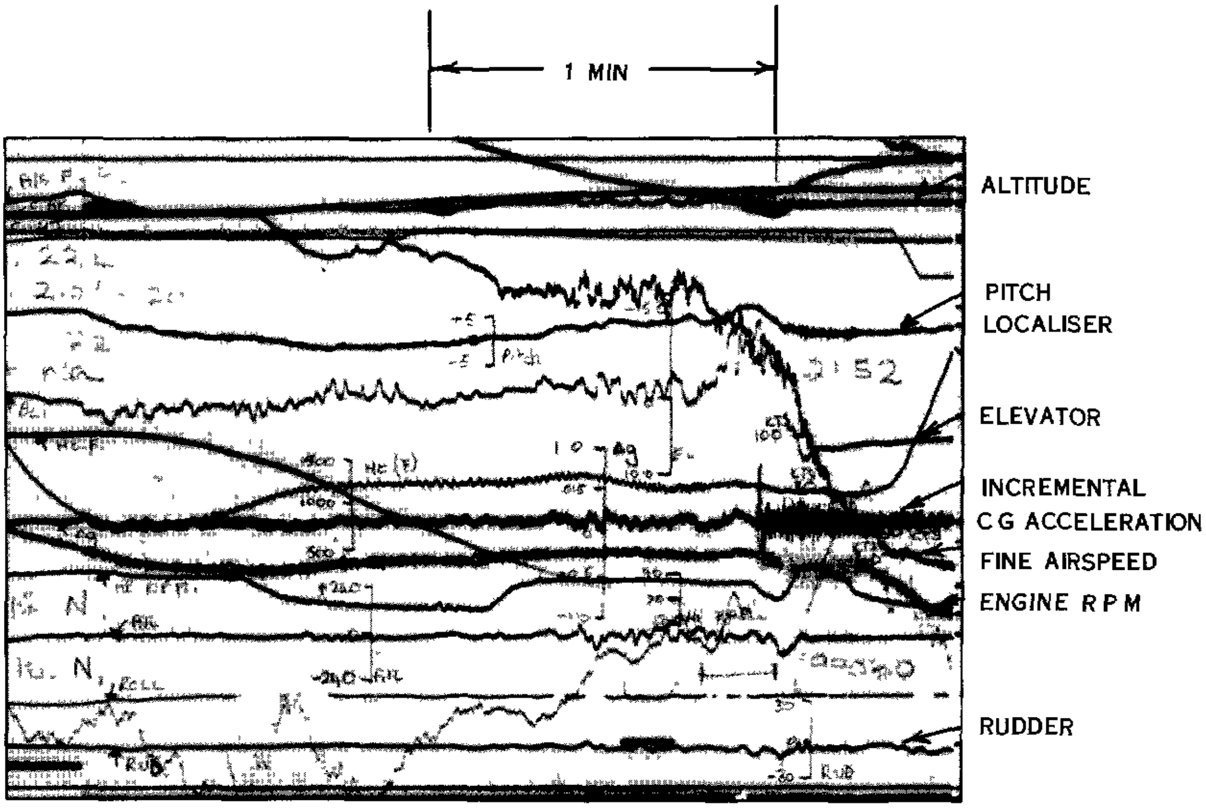

Fig.3. Heavy landing with no bounce

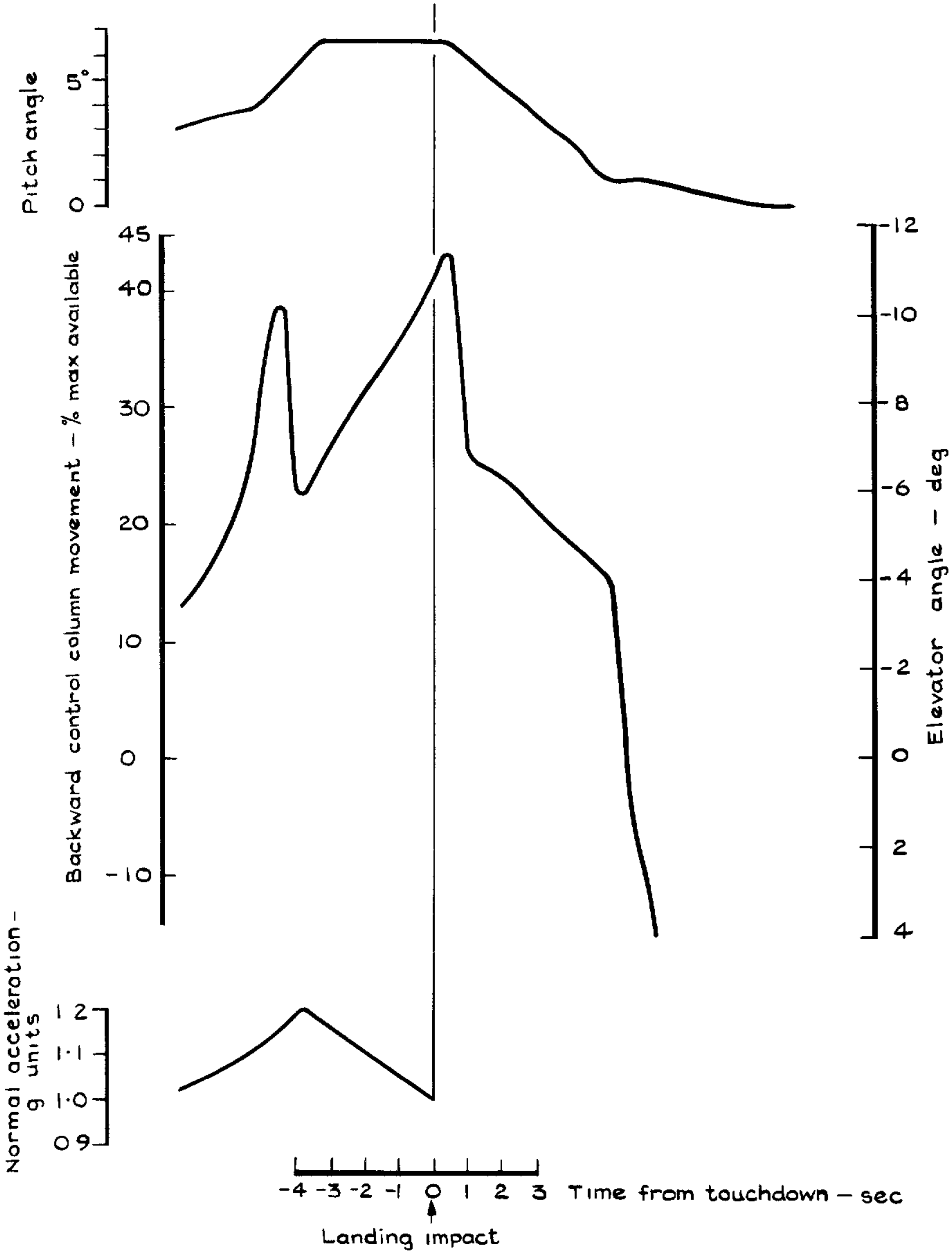

Fig. 4 Smoothed pitch attitude, control column movement, elevator angle and normal acceleration due to lift during heavy landing with no bounce (Ref Fig 3)

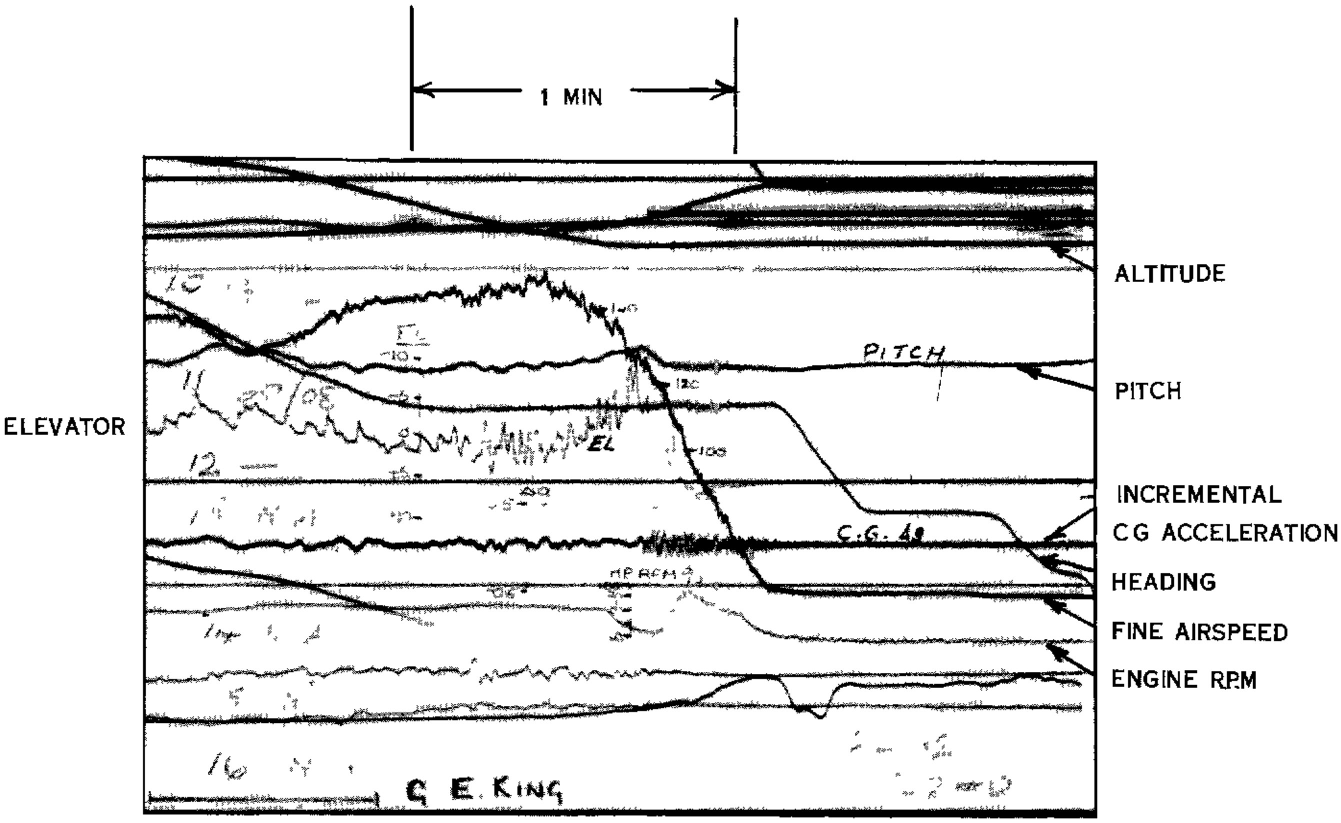

Fig.5. Light landing

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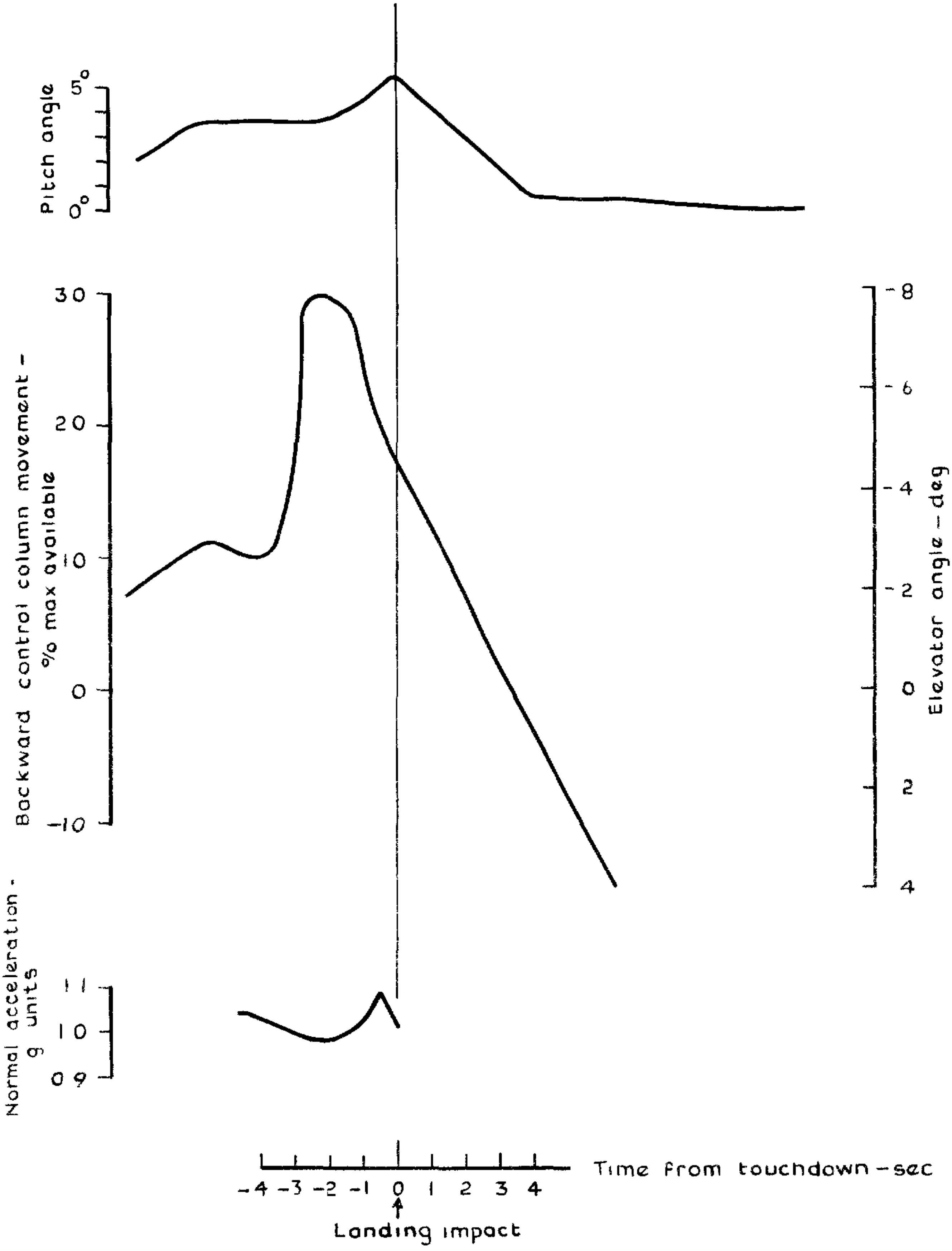
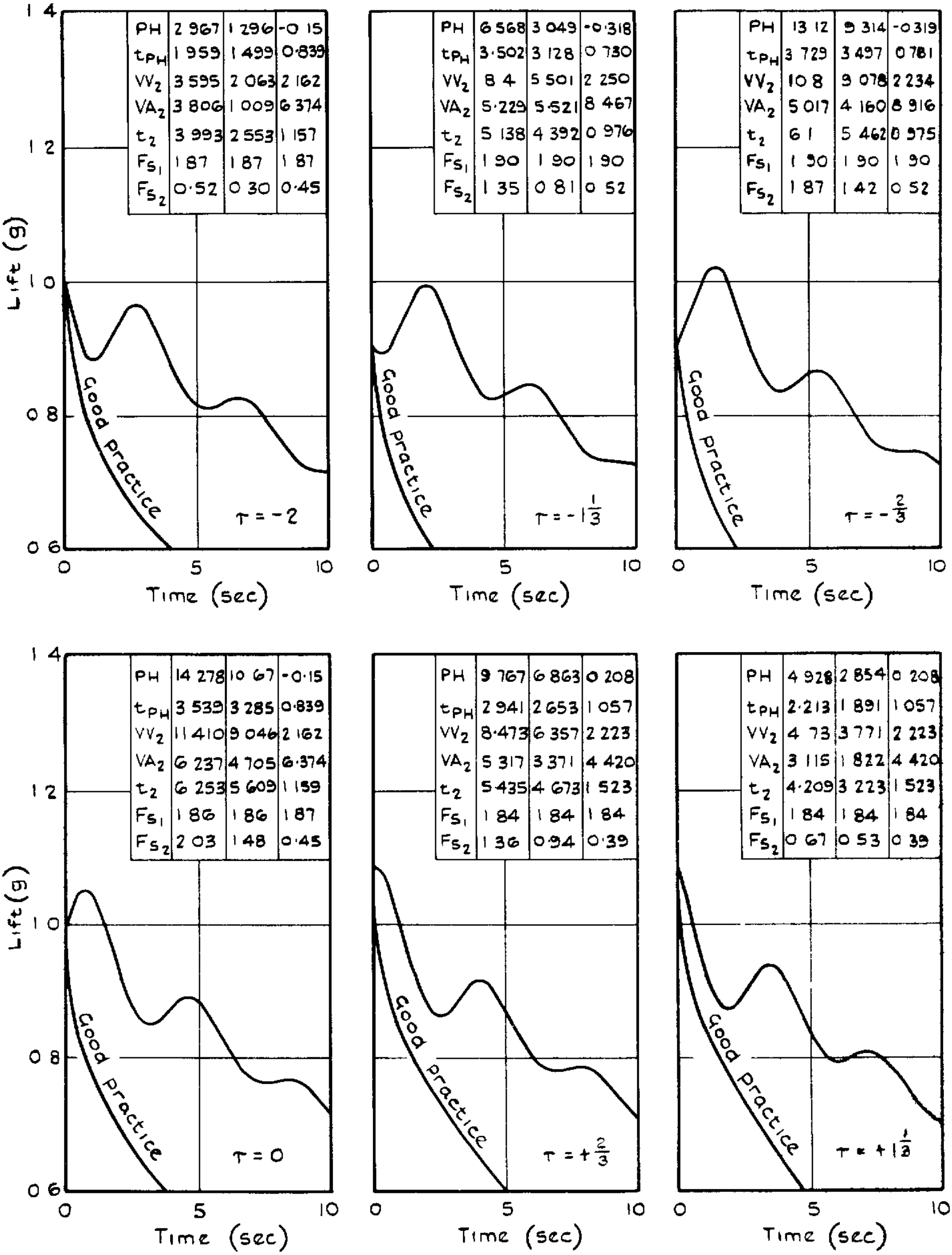


Fig 6 Smoothed pitch attitude, control column movement, elevator angle and normal acceleration due to lift during light landing (Ref Fig 5)



PH	2 967	1 296	-0 15
t_{PH}	1 959	1 499	0·839
VV_2	3 595	2 063	2 162
VA_2	3 806	1 009	6 374
t_2	3 993	2 553	1 157
Fs_1	1 87	1 87	1 87
Fs_2	0·52	0 30	0·45

PH	6 568	3 049	-0·318
t_{PH}	3·502	3 128	0 730
VV_2	8 4	5 501	2 250
VA_2	5·229	5·521	8 467
t_2	5 138	4 392	0 976
Fs_1	1 90	1 90	1 90
Fs_2	1 35	0 81	0 52

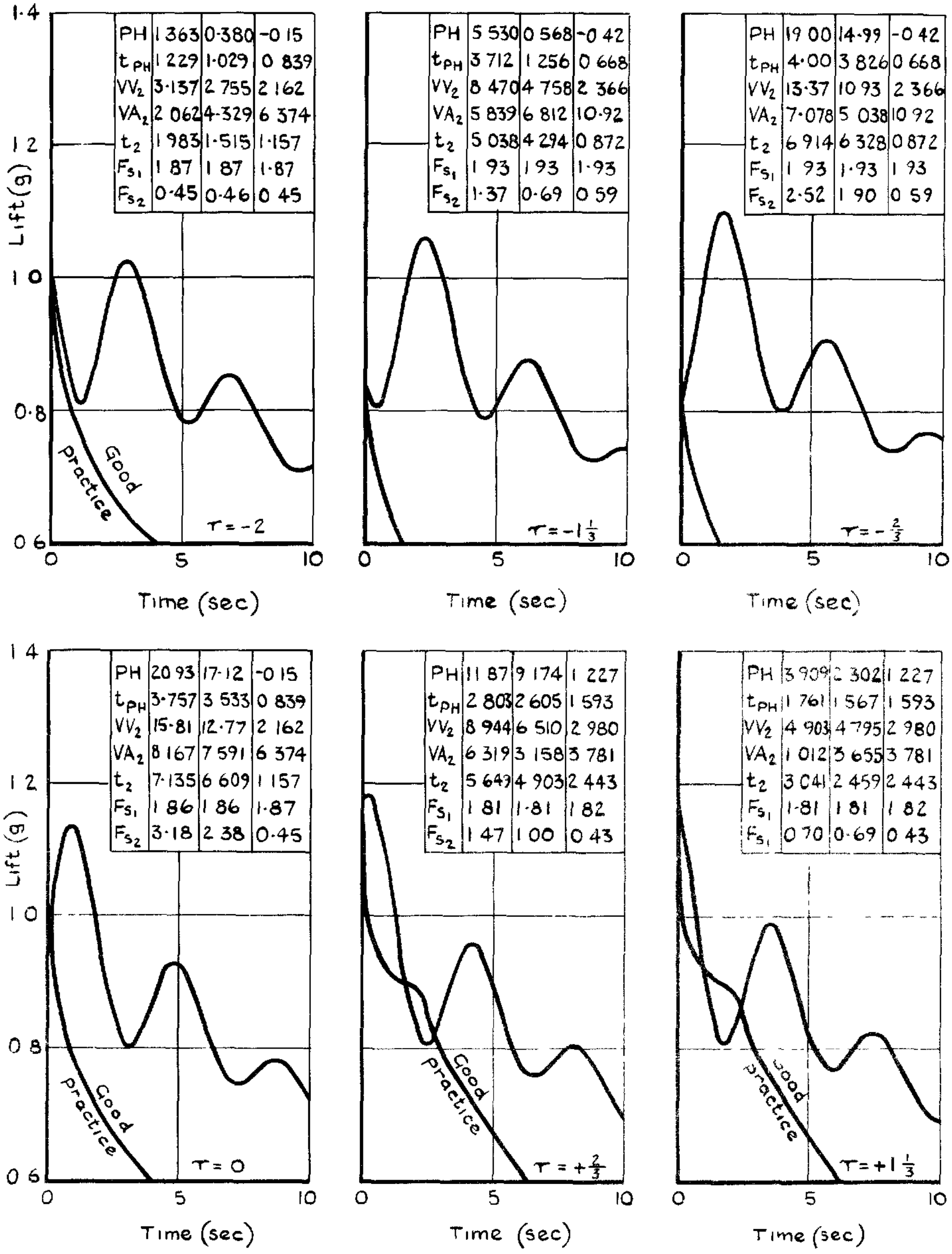
PH	13 12	9 314	-0 319
t_{PH}	3 729	3 497	0 781
VV_2	10 8	9 078	2 234
VA_2	5 017	4 160	8 916
t_2	6 1	5 462	0 975
Fs_1	1 90	1 90	1 90
Fs_2	1 87	1 42	0 52

PH	14 278	10 67	-0·15
t_{PH}	3 539	3 285	0·839
VV_2	11 410	9 046	2 162
VA_2	6 237	4 705	6·374
t_2	6 253	5 609	1 159
Fs_1	1 86	1 86	1 87
Fs_2	2 03	1 48	0·45

PH	9 767	6 863	0 208
t_{PH}	2 941	2 653	1 057
VV_2	8·473	6 357	2 223
VA_2	5 317	3 371	4 420
t_2	5·435	4 673	1 523
Fs_1	1 84	1 84	1 84
Fs_2	1 36	0·94	0·39

PH	4 928	2 854	0 208
t_{PH}	2·213	1 891	1 057
VV_2	4 73	3 771	2 223
VA_2	3 115	1 822	4 420
t_2	4·209	3 223	1 523
Fs_1	1 84	1 84	1 84
Fs_2	0 67	0 53	0 39

Fig. 7 Type A lift decay
Basic amplitude 0·1g
Vertical velocity at initial touchdown 11ft/sec



PH	1 363	0·380	-0 15
t_{PH}	1 229	1·029	0 839
VV_2	3·137	2 755	2 162
VA_2	2 062	4·329	6 374
t_2	1 983	1·515	1·157
F_{s_1}	1 87	1 87	1·87
F_{s_2}	0·45	0·46	0 45

PH	5 530	0 568	-0 42
t_{PH}	3 712	1 256	0 668
VV_2	8 470	4 758	2 366
VA_2	5 839	6 812	10·92
t_2	5 038	4 294	0 872
F_{s_1}	1 93	1 93	1·93
F_{s_2}	1·37	0·69	0 59

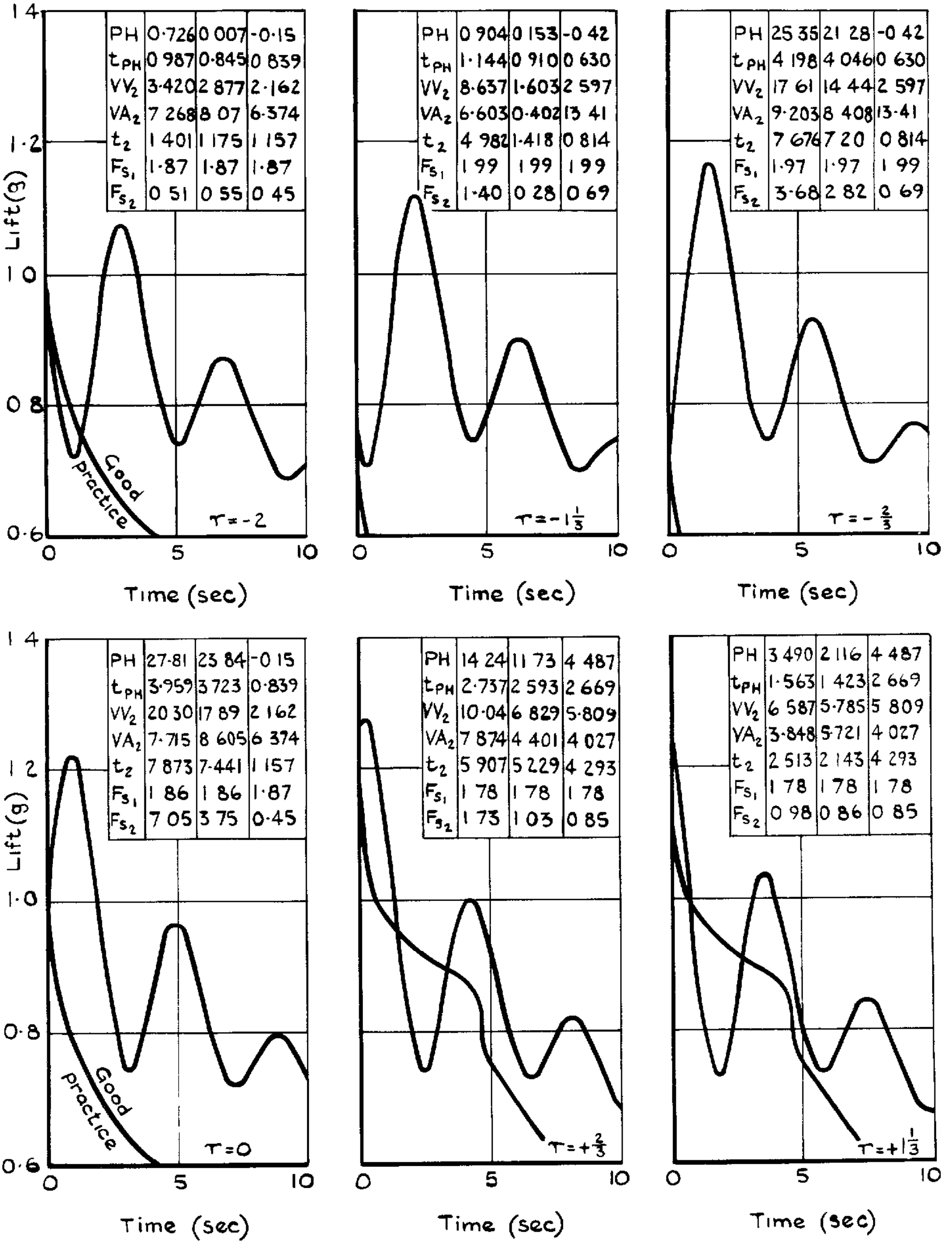
PH	19 00	14·99	-0 42
t_{PH}	4·00	3 826	0 668
VV_2	13·37	10 93	2 366
VA_2	7·078	5 038	10 92
t_2	6 914	6 328	0 872
F_{s_1}	1 93	1·93	1 93
F_{s_2}	2·52	1 90	0 59

PH	20 93	17·12	-0 15
t_{PH}	3·757	3 533	0 839
VV_2	15·81	12·77	2 162
VA_2	8 167	7 591	6 374
t_2	7·135	6 609	1 157
F_{s_1}	1 86	1 86	1·87
F_{s_2}	3·18	2 38	0·45

PH	11 87	9 174	1 227
t_{PH}	2 803	2 605	1 593
VV_2	8 944	6 510	2 980
VA_2	6 319	3 158	3 781
t_2	5 649	4 903	2 443
F_{s_1}	1 81	1·81	1 82
F_{s_2}	1 47	1 00	0 43

PH	3 909	2 302	1 227
t_{PH}	1 761	1 567	1 593
VV_2	4 903	4 795	2 980
VA_2	1 012	3 655	3 781
t_2	3 041	2 459	2 443
F_{s_1}	1·81	1 81	1 82
F_{s_1}	0 70	0·69	0 43

Fig. 8 Type A lift decay
Basic amplitude 0·2g
Vertical velocity at initial touchdown 11ft/sec



PH	0·726	0 007	-0·15
t_{PH}	0 987	0·845	0 839
VV_2	3·420	2 877	2·162
VA_2	7 268	8 07	6·374
t_2	1 401	1 175	1 157
F_{S_1}	1·87	1·87	1·87
F_{S_2}	0 51	0 55	0 45

PH	0 904	0 153	-0 42
t_{PH}	1·144	0 910	0 630
VV_2	8·637	1·603	2 597
VA_2	6·603	0·402	13 41
t_2	4 982	1·418	0 814
F_{S_1}	1 99	1 99	1 99
F_{S_2}	1·40	0 28	0 69

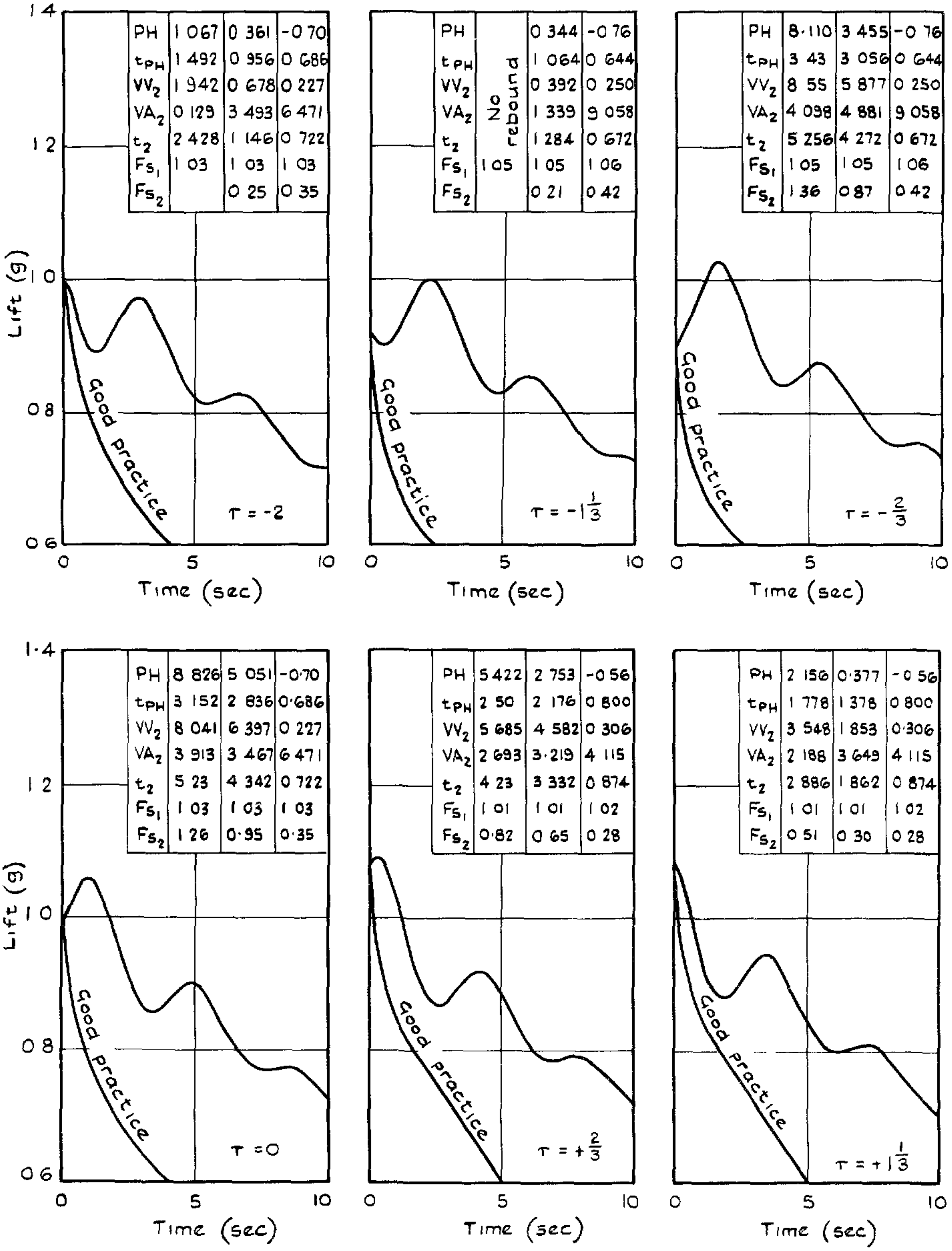
PH	25 35	21 28	-0 42
t_{PH}	4 198	4 046	0 630
VV_2	17 61	14 44	2 597
VA_2	9·203	8 408	13·41
t_2	7 676	7 20	0 814
F_{S_1}	1·97	1·97	1 99
F_{S_2}	3·68	2 82	0 69

PH	27·81	23 84	-0 15
t_{PH}	3·959	3 723	0·839
VV_2	20 30	17 89	2 162
VA_2	7·715	8 605	6 374
t_2	7 873	7·441	1 157
F_{S_1}	1 86	1 86	1·87
F_{S_2}	7 05	3 75	0·45

PH	14 24	11 73	4 487
t_{PH}	2·737	2 593	2 669
VV_2	10·04	6 829	5·809
VA_2	7 874	4 401	4 027
t_2	5 907	5 229	4 293
F_{S_1}	1 78	1 78	1 78
F_{S_2}	1 73	1 03	0 85

PH	3 490	2 116	4 487
t_{PH}	1·563	1 423	2 669
VV_2	6 587	5·785	5 809
VA_2	3·848	5·721	4 027
t_2	2 513	2 143	4 293
F_{S_1}	1 78	1 78	1 78
F_{S_2}	0 98	0 86	0 85

Fig. 9 Type A lift decay
Basic amplitude 0·3g
Vertical velocity at initial touchdown 11ft/sec



PH	1 067	0 361	-0 70
t_{PH}	1 492	0 956	0 686
VV_2	1 942	0 678	0 227
VA_2	0 129	3 493	6 471
t_2	2 428	1 146	0 722
Fs_1	1 03	1 03	1 03
Fs_2		0 25	0 35

PH		0 344	-0 76
t_{PH}	No rebound	1 064	0 644
VV_2		0 392	0 250
VA_2		1 339	9 058
t_2		1 284	0 672
Fs_1	1 05	1 05	1 06
Fs_2		0 21	0 42

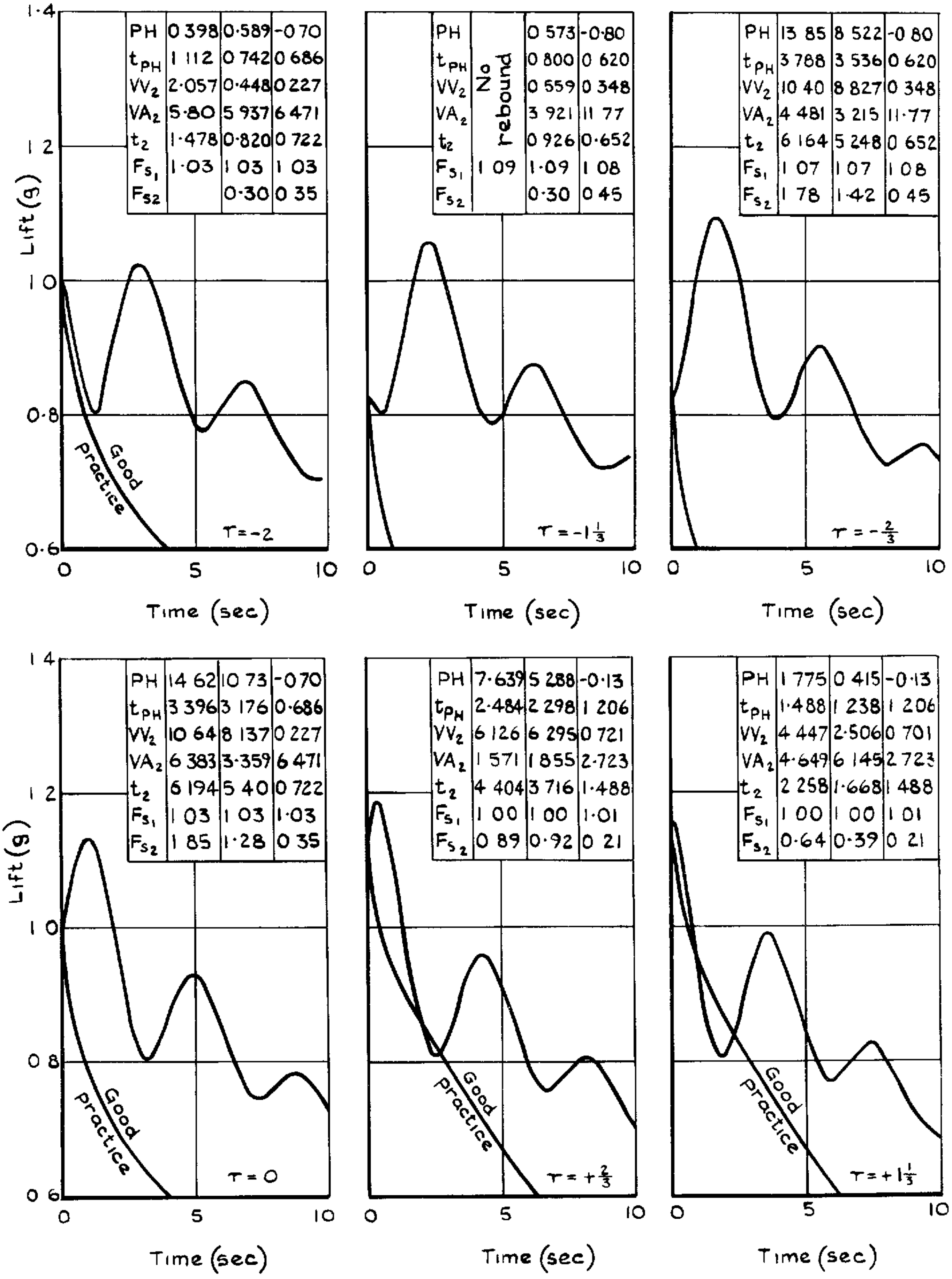
PH	8·110	3 455	-0 76
t_{PH}	3 43	3 056	0 644
VV_2	8 55	5 877	0 250
VA_2	4 098	4 881	9 058
t_2	5 256	4 272	0 672
Fs_1	1 05	1 05	1 06
Fs_2	1 36	0 87	0 42

PH	8 826	5 051	-0·70
t_{PH}	3 152	2 836	0·686
VV_2	8 041	6 397	0 227
VA_2	3 913	3 467	6 471
t_2	5 23	4 342	0 722
Fs_1	1 03	1 03	1 03
Fs_2	1 26	0·95	0·35

PH	5 422	2 753	-0 56
t_{PH}	2 50	2 176	0 800
VV_2	5 685	4 582	0 306
VA_2	2 693	3·219	4 115
t_2	4 23	3 332	0 874
Fs_1	1 01	1 01	1 02
Fs_2	0·82	0 65	0 28

PH	2 156	0·377	-0 56
t_{PH}	1 778	1 378	0 800
VV_2	3 548	1 853	0·306
VA_2	2 188	3 649	4 115
t_2	2 886	1 862	0 874
Fs_1	1 01	1 01	1 02
Fs_2	0 51	0 30	0 28

Fig 10 Type A lift decay
Basic amplitude 0 1g
Vertical velocity at initial touchdown 7ft/sec



$\tau = -2$

PH	0·398	0·589	-0·70
t_{PH}	1·112	0·742	0·686
VV_2	2·057	0·448	0·227
VA_2	5·80	5·937	6·471
t_2	1·478	0·820	0·722
F_{S_1}	1·03	1·03	1·03
F_{S_2}		0·30	0·35

$\tau = -1\frac{1}{3}$

PH	No rebound	0·573	-0·80
t_{PH}		0·800	0·620
VV_2		0·559	0·348
VA_2		3·921	11·77
t_2		0·926	0·652
F_{S_1}	1·09	1·09	1·08
F_{S_2}		0·30	0·45

$\tau = -\frac{2}{3}$

PH	13·85	8·522	-0·80
t_{PH}	3·788	3·536	0·620
VV_2	10·40	8·827	0·348
VA_2	4·481	3·215	11·77
t_2	6·164	5·248	0·652
F_{S_1}	1·07	1·07	1·08
F_{S_2}	1·78	1·42	0·45

$\tau = 0$

PH	14·62	10·73	-0·70
t_{PH}	3·396	3·176	0·686
VV_2	10·64	8·137	0·227
VA_2	6·383	3·359	6·471
t_2	6·194	5·40	0·722
F_{S_1}	1·03	1·03	1·03
F_{S_2}	1·85	1·28	0·35

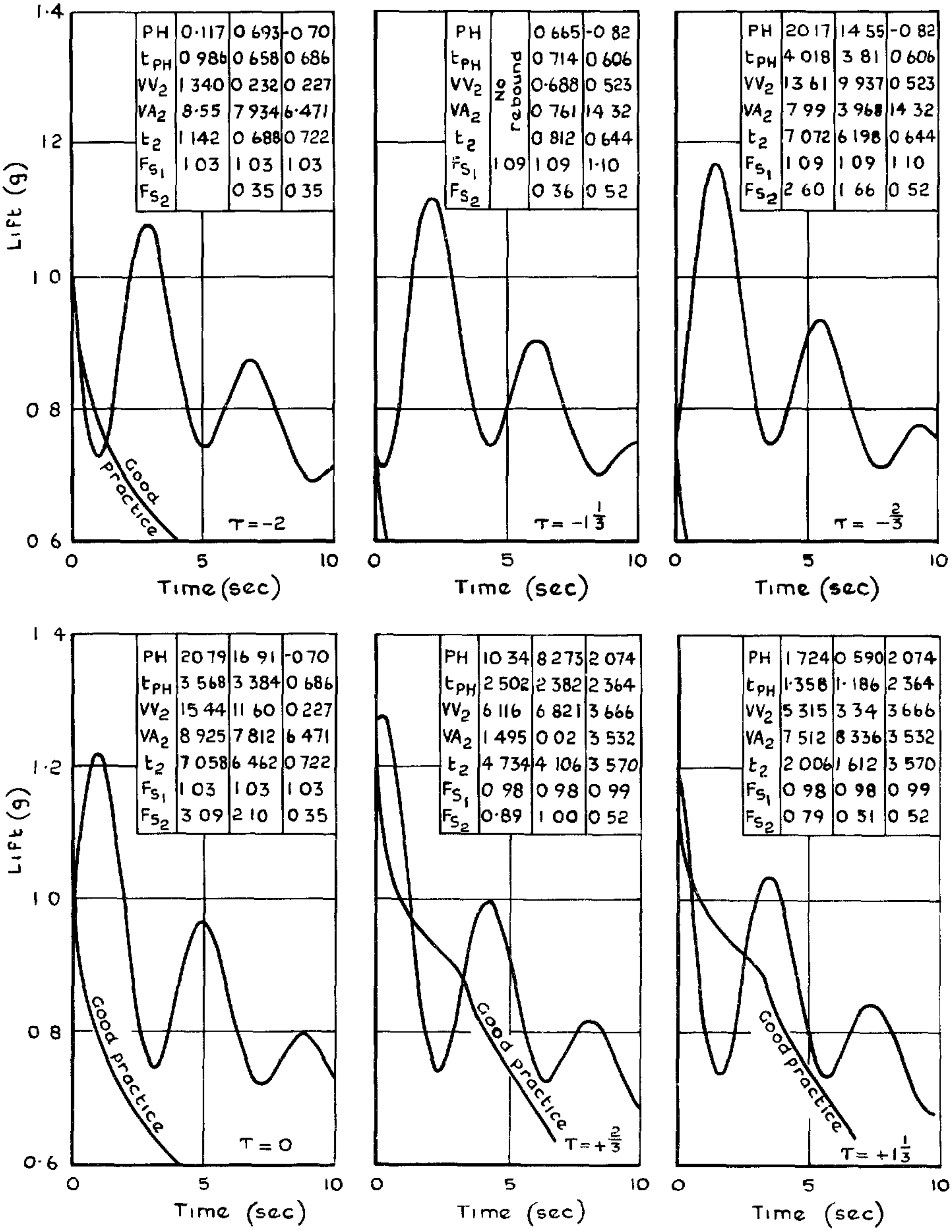
$\tau = +\frac{2}{3}$

PH	7·639	5·288	-0·13
t_{PH}	2·484	2·298	1·206
VV_2	6·126	6·295	0·721
VA_2	1·571	1·855	2·723
t_2	4·404	3·716	1·488
F_{S_1}	1·00	1·00	1·01
F_{S_2}	0·89	0·92	0·21

$\tau = +1\frac{1}{3}$

PH	1·775	0·415	-0·13
t_{PH}	1·488	1·238	1·206
VV_2	4·447	2·506	0·701
VA_2	4·649	6·145	2·723
t_2	2·258	1·668	1·488
F_{S_1}	1·00	1·00	1·01
F_{S_2}	0·64	0·39	0·21

Fig.11 Type A lift decay
Basic amplitude 0·2g
Vertical velocity at initial touchdown 7ft/sec



PH	0·117	0 693	-0 70
t_{PH}	0 986	0 658	0 686
VV_2	1 340	0 232	0 227
VA_2	8·55	7 934	6·471
t_2	1 142	0 688	0 722
F_{S_1}	1 03	1 03	1 03
F_{S_2}		0 35	0 35

PH	No rebound	0 665	-0 82
t_{PH}		0 714	0 606
VV_2		0·688	0 523
VA_2		0 761	14 32
t_2		0 812	0 644
F_{S_1}	1 09	1 09	1·10
F_{S_2}		0 36	0 52

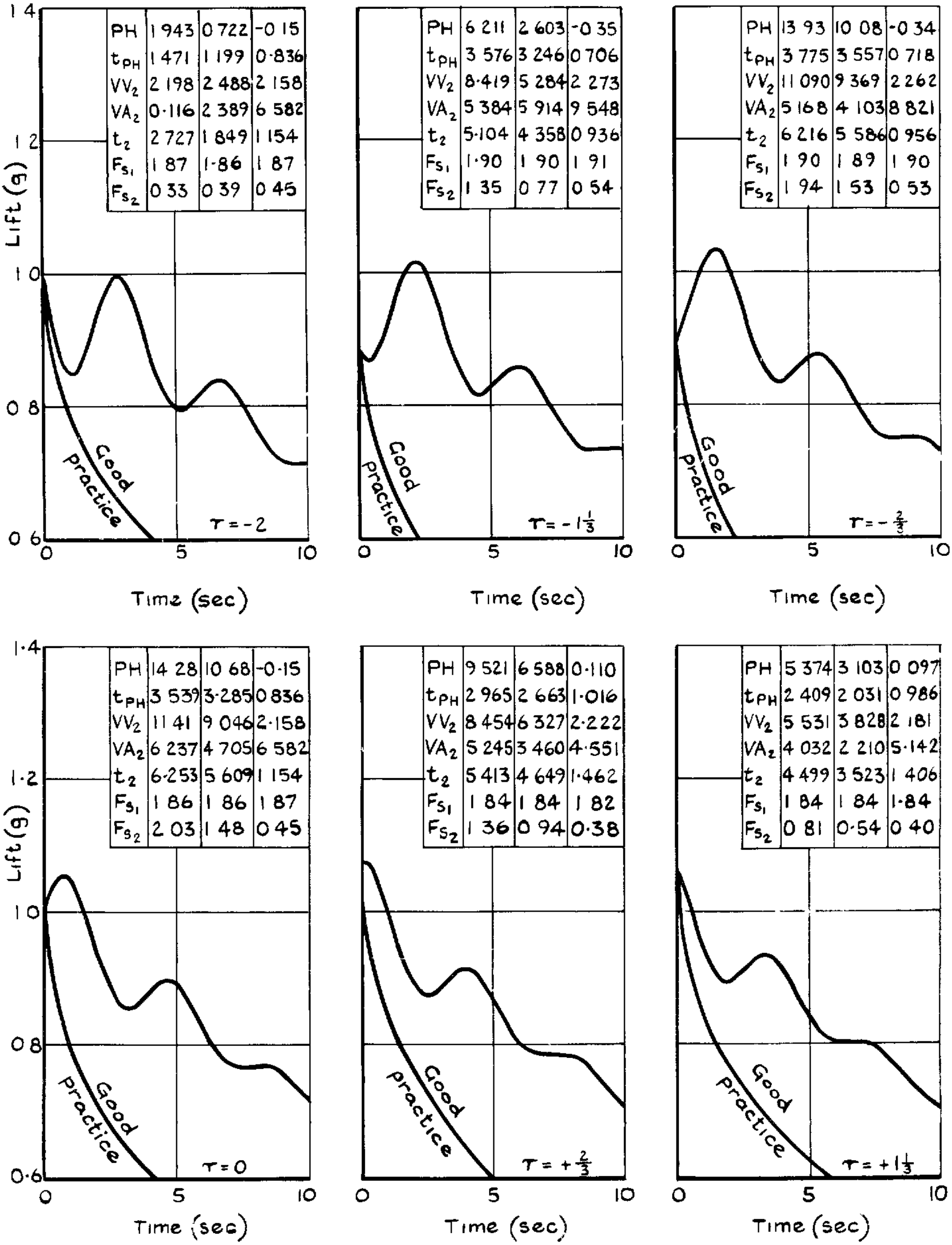
PH	20 17	14 55	-0 82
t_{PH}	4 018	3 81	0 606
VV_2	13 61	9 937	0 523
VA_2	7 99	3 968	14 32
t_2	7 072	6 198	0 644
F_{S_1}	1 09	1 09	1 10
F_{S_2}	2 60	1 66	0 52

PH	20 79	16 91	-0 70
t_{PH}	3 568	3 384	0 686
VV_2	15 44	11 60	0 227
VA_2	8 925	7 812	6 471
t_2	7 058	6 462	0 722
F_{S_1}	1 03	1 03	1 03
F_{S_2}	3 09	2 10	0 35

PH	10 34	8 273	2 074
t_{PH}	2 502	2 382	2 364
VV_2	6 116	6 821	3 666
VA_2	1 495	0 02	3 532
t_2	4 734	4 106	3 570
F_{S_1}	0 98	0 98	0 99
F_{S_2}	0·89	1 00	0 52

PH	1 724	0 590	2 074
t_{PH}	1·358	1·186	2 364
VV_2	5 315	3 34	3 666
VA_2	7 512	8 336	3 532
t_2	2 006	1 612	3 570
F_{S_1}	0 98	0 98	0 99
F_{S_2}	0 79	0 51	0 52

Fig. 12 Type A lift decay
Basic amplitude 0·3g
Vertical velocity at initial touchdown 7ft/sec



τ = -2

PH	1 943	0 722	-0 15
t_{PH}	1 471	1 199	0·836
VV_2	2 198	2 488	2 158
VA_2	0·116	2 389	6 582
t_2	2 727	1 849	1 154
F_{s_1}	1 87	1·86	1 87
F_{s_2}	0 33	0 39	0 45

τ = - 1⅓

PH	6 211	2 603	-0 35
t_{PH}	3 576	3 246	0 706
VV_2	8·419	5 284	2 273
VA_2	5 384	5 914	9 548
t_2	5·104	4 358	0 936
F_{s_1}	1·90	1 90	1 91
F_{s_2}	1 35	0 77	0 54

τ = - ⅔

PH	13 93	10 08	-0 34
t_{PH}	3 775	3 557	0 718
VV_2	11 090	9 369	2 262
VA_2	5 168	4 103	8 821
t_2	6 216	5 586	0 956
F_{s_1}	1 90	1 89	1 90
F_{s_2}	1 94	1 53	0 53

τ = 0

PH	14 28	10 68	-0·15
t_{PH}	3 539	3·285	0 836
VV_2	11 41	9 046	2·158
VA_2	6 237	4 705	6 582
t_2	6·253	5 609	1 154
F_{s_1}	1 86	1 86	1 87
F_{s_2}	2 03	1 48	0 45

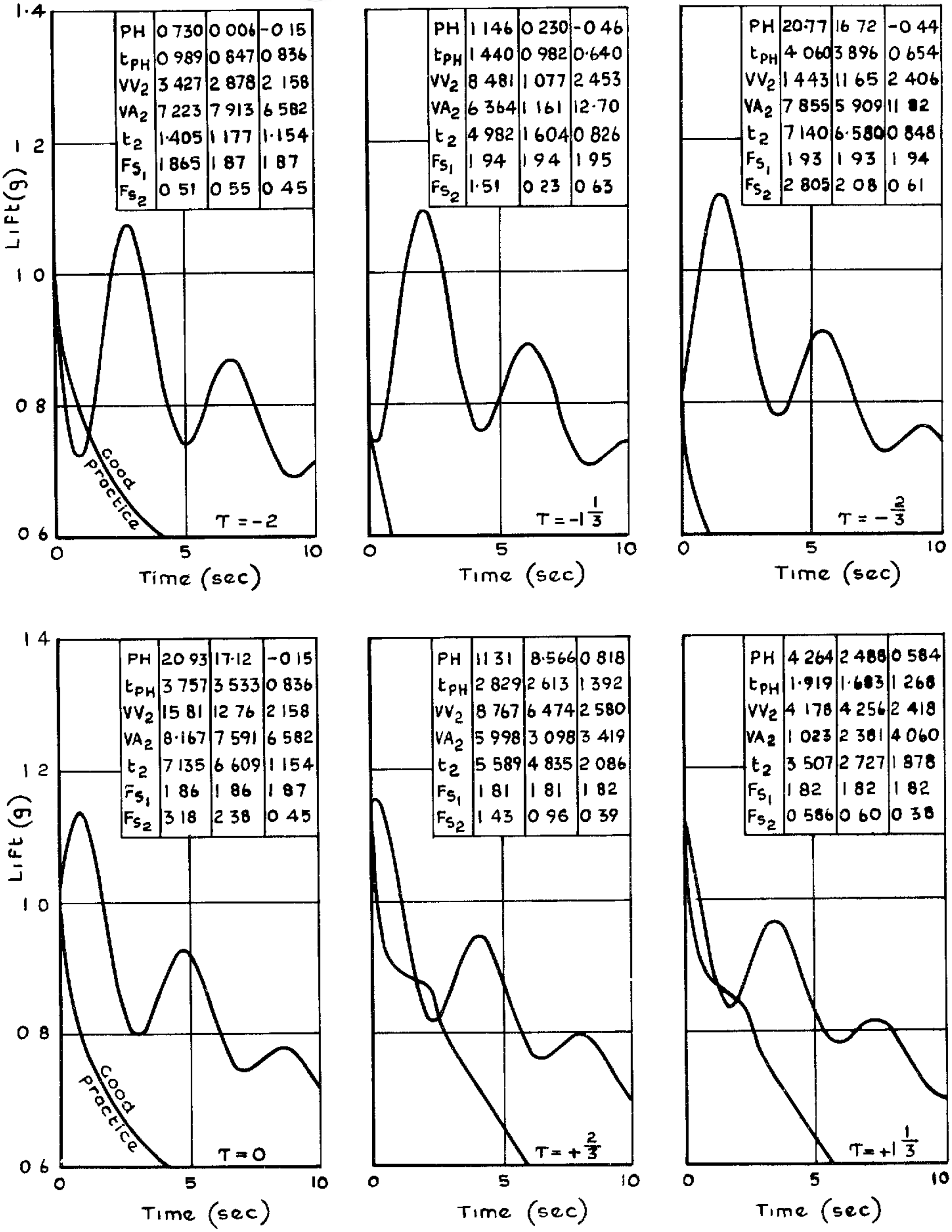
τ = + ⅔

PH	9 521	6 588	0·110
t_{PH}	2 965	2 663	1·016
VV_2	8 454	6 327	2·222
VA_2	5 245	3 460	4·551
t_2	5 413	4 649	1·462
F_{s_1}	1 84	1 84	1 82
F_{s_2}	1 36	0 94	0·38

τ = + 1⅓

PH	5 374	3 103	0 097
t_{PH}	2 409	2 031	0 986
VV_2	5 531	3 828	2 181
VA_2	4 032	2 210	5·142
t_2	4 499	3 523	1 406
F_{s_1}	1 84	1 84	1·84
F_{s_2}	0 81	0·54	0 40

Fig.13 Type B lift decay
Basic amplitude 0·1g
Vertical velocity at initial touchdown 11ft/sec



T = -2

PH	0 730	0 006	-0 15
t_{PH}	0 989	0 847	0 836
VV_2	3 427	2 878	2 158
VA_2	7 223	7 913	6 582
t_2	1·405	1 177	1·154
Fs_1	1 865	1 87	1 87
Fs_2	0 51	0 55	0 45

T = -1 1/3

PH	1 146	0 230	-0 46
t_{PH}	1 440	0 982	0·640
VV_2	8 481	1 077	2 453
VA_2	6 364	1 161	12·70
t_2	4 982	1 604	0 826
Fs_1	1 94	1 94	1 95
Fs_2	1·51	0 23	0 63

T = -2/3

PH	20·77	16 72	-0 44
t_{PH}	4 060	3 896	0 654
VV_2	1 443	11 65	2 406
VA_2	7 855	5 909	11 82
t_2	7 140	6·580	0 848
Fs_1	1 93	1 93	1 94
Fs_2	2 805	2 08	0 61

T = 0

PH	20 93	17·12	-0 15
t_{PH}	3 757	3 533	0 836
VV_2	15 81	12 76	2 158
VA_2	8·167	7 591	6 582
t_2	7 135	6 609	1 154
Fs_1	1 86	1 86	1 87
Fs_2	3 18	2 38	0 45

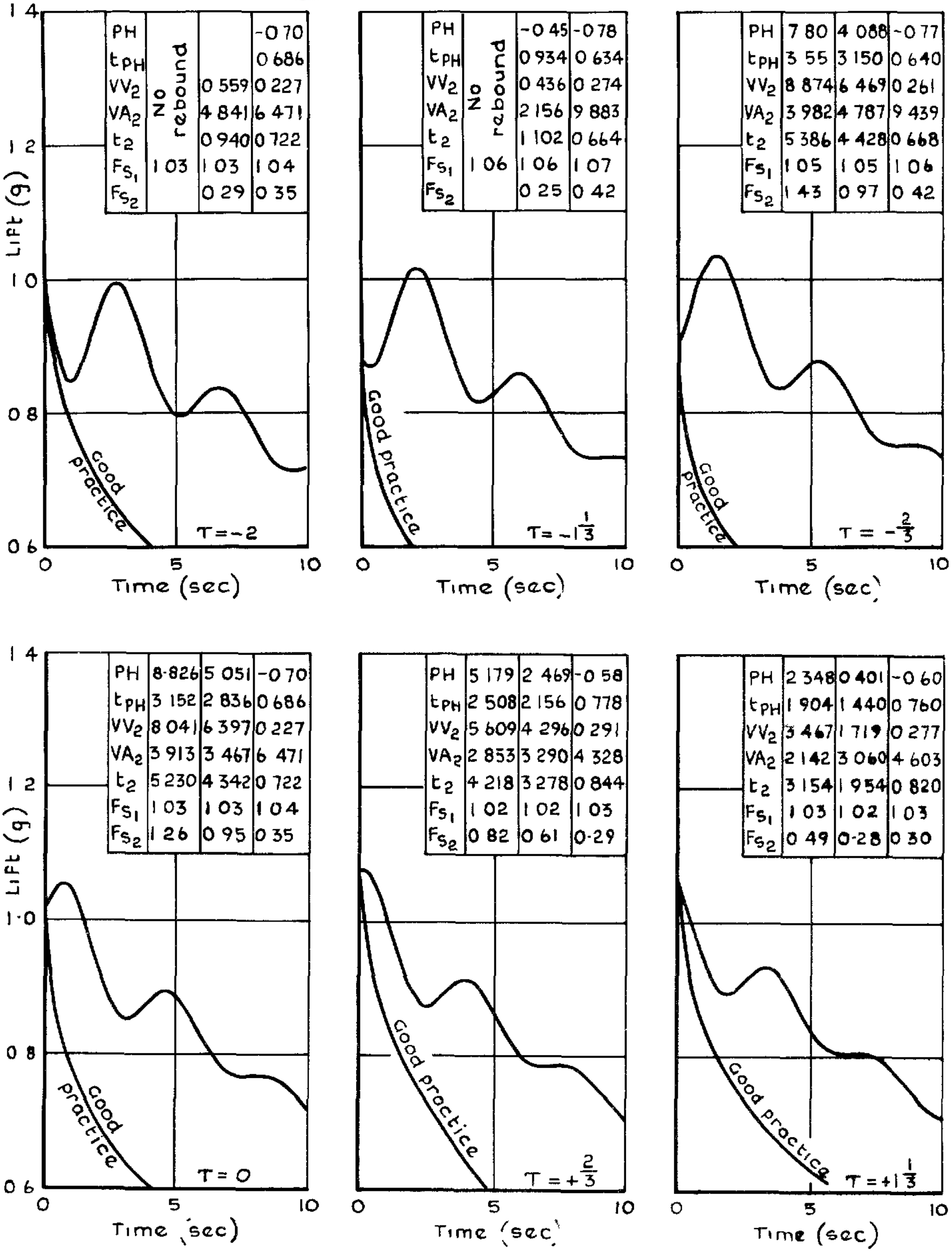
T = +2/3

PH	11 31	8·566	0 818
t_{PH}	2 829	2 613	1 392
VV_2	8 767	6 474	2 580
VA_2	5 998	3 098	3 419
t_2	5 589	4 835	2 086
Fs_1	1 81	1 81	1 82
Fs_2	1 43	0 96	0 39

T = +1 1/3

PH	4 264	2 488	0 584
t_{PH}	1·919	1·683	1 268
VV_2	4 178	4 256	2 418
VA_2	1 023	2 381	4 060
t_2	3 507	2 727	1 878
Fs_1	1 82	1 82	1 82
Fs_2	0 586	0 60	0 38

Fig. 14 Type B lift decay
Basic amplitude 0 2g
Vertical velocity at initial touchdown 11ft/sec



PH	No rebound		-0 70
t_{PH}			0 686
VV_2		0 559	0 227
VA_2		4 841	6 471
t_2		0 940	0 722
Fs_1	1 03	1 03	1 04
Fs_2		0 29	0 35

PH	No rebound	-0 45	-0 78
t_{PH}		0 934	0 634
VV_2		0 436	0 274
VA_2		2 156	9 883
t_2		1 102	0 664
Fs_1	1 06	1 06	1 07
Fs_2		0 25	0 42

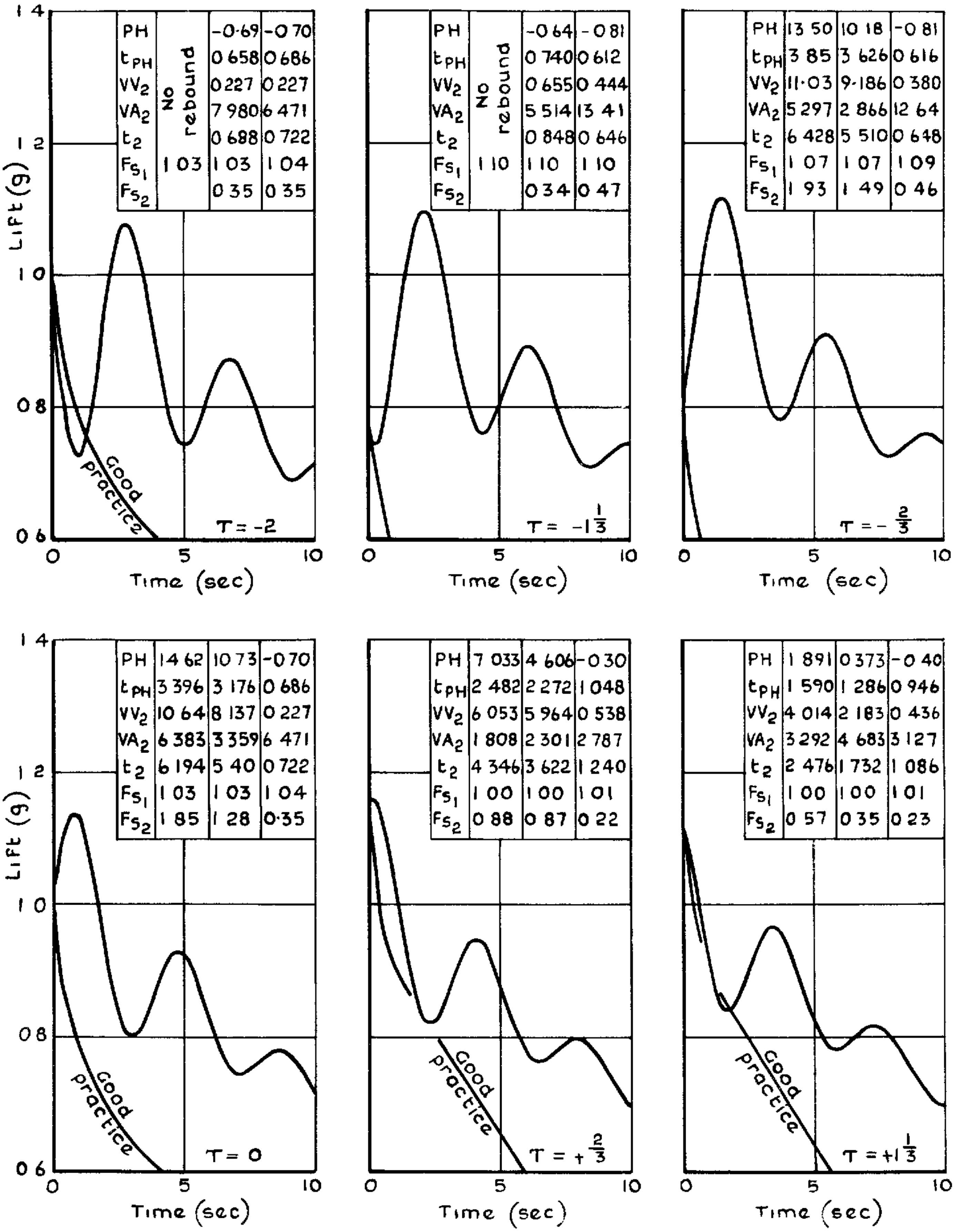
PH	7 80	4 088	-0 77
t_{PH}	3 55	3 150	0 640
VV_2	8 874	6 469	0 261
VA_2	3 982	4 787	9 439
t_2	5 386	4 428	0 668
Fs_1	1 05	1 05	1 06
Fs_2	1 43	0 97	0 42

PH	8-826	5 051	-0 70
t_{PH}	3 152	2 836	0 686
VV_2	8 041	6 397	0 227
VA_2	3 913	3 467	6 471
t_2	5 230	4 342	0 722
Fs_1	1 03	1 03	1 04
Fs_2	1 26	0 95	0 35

PH	5 179	2 469	-0 58
t_{PH}	2 508	2 156	0 778
VV_2	5 609	4 296	0 291
VA_2	2 853	3 290	4 328
t_2	4 218	3 278	0 844
Fs_1	1 02	1 02	1 03
Fs_2	0 82	0 61	0-29

PH	2 348	0 401	-0 60
t_{PH}	1 904	1 440	0 760
VV_2	3 467	1 719	0 277
VA_2	2 142	3 060	4 603
t_2	3 154	1 954	0 820
Fs_1	1 03	1 02	1 03
Fs_2	0 49	0-28	0 30

Fig. 16 Type B lift decay
Basic amplitude 0·1g
Vertical velocity at initial touchdown 7ft/sec



T = -2

PH	No rebound	-0·69	-0 70
t_{PH}		0 658	0 686
VV_2		0 227	0 227
VA_2		7 980	6 471
t_2		0 688	0 722
Fs_1	1 03	1 03	1 04
Fs_2		0 35	0 35

T = -1 1/3

PH	No rebound	-0 64	- 0 81
t_{PH}		0 740	0 612
VV_2		0 655	0 444
VA_2		5 514	13 41
t_2		0 848	0 646
Fs_1	1 10	1 10	1 10
Fs_2		0 34	0 47

T = - 2/3

PH	13 50	10 18	-0 81
t_{PH}	3 85	3 626	0 616
VV_2	11·03	9·186	0 380
VA_2	5 297	2 866	12 64
t_2	6 428	5 510	0 648
Fs_1	1 07	1 07	1 09
Fs_2	1 93	1 49	0 46

T = 0

PH	14 62	10 73	-0 70
t_{PH}	3 396	3 176	0 686
VV_2	10 64	8 137	0 227
VA_2	6 383	3 359	6 471
t_2	6 194	5 40	0 722
Fs_1	1 03	1 03	1 04
Fs_2	1 85	1 28	0·35

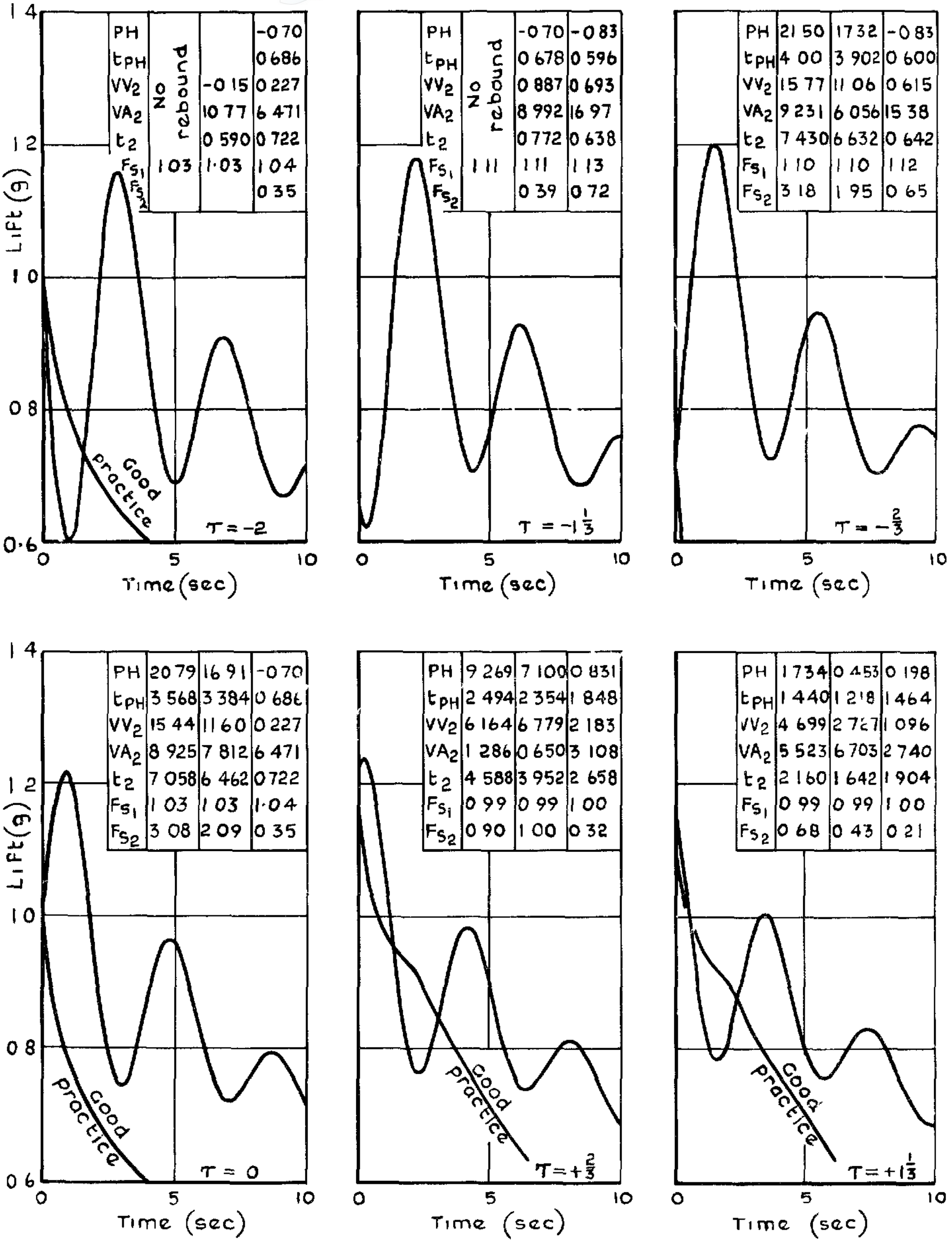
T = + 2/3

PH	7 033	4 606	-0 30
t_{PH}	2 482	2 272	1 048
VV_2	6 053	5 964	0 538
VA_2	1 808	2 301	2 787
t_2	4 346	3 622	1 240
Fs_1	1 00	1 00	1 01
Fs_2	0 88	0 87	0 22

T = +1 1/3

PH	1 891	0 373	-0 40
t_{PH}	1 590	1 286	0 946
VV_2	4 014	2 183	0 436
VA_2	3 292	4 683	3 127
t_2	2 476	1 732	1 086
Fs_1	1 00	1 00	1 01
Fs_2	0 57	0 35	0 23

Fig. 17 Type B lift decay
Basic amplitude 0·2g
Vertical velocity at initial touchdown 7ft/sec



PH	No rebound		-0 70
t_{PH}			0 686
VV_2		-0 15	0 227
VA_2		10 77	6 471
t_2		0 590	0 722
F_{S_1}	1 03	1·03	1 04
F_{S_2}			0 35

PH	No rebound	-0 70	-0 83
t_{PH}		0 678	0 596
VV_2		0 887	0 693
VA_2		8 992	16 97
t_2		0 772	0 638
F_{S_1}	1 11	1 11	1 13
F_{S_2}		0 39	0 72

PH	21 50	17 32	-0 83
t_{PH}	4 00	3 902	0 600
VV_2	15 77	11 06	0 615
VA_2	9 231	6 056	15 38
t_2	7 430	6 632	0 642
F_{S_1}	1 10	1 10	1 12
F_{S_2}	3 18	1 95	0 65

PH	20 79	16 91	-0 70
t_{PH}	3 568	3 384	0 686
VV_2	15 44	11 60	0 227
VA_2	8 925	7 812	6 471
t_2	7 058	6 462	0 722
F_{S_1}	1 03	1 03	1·04
F_{S_2}	3 08	2 09	0 35

PH	9 269	7 100	0 831
t_{PH}	2 494	2 354	1 848
VV_2	6 164	6 779	2 183
VA_2	1 286	0 650	3 108
t_2	4 588	3 952	2 658
F_{S_1}	0 99	0 99	1 00
F_{S_2}	0 90	1 00	0 32

PH	1 734	0 453	0 198
t_{PH}	1 440	1 218	1 464
VV_2	4 699	2 727	1 096
VA_2	5 523	6 703	2 740
t_2	2 160	1 642	1 904
F_{S_1}	0 99	0 99	1 00
F_{S_2}	0 68	0 43	0 21

Fig. 18 Type B lift decay
Basic amplitude 0·3g
Vertical velocity at initial touchdown 7ft/sec

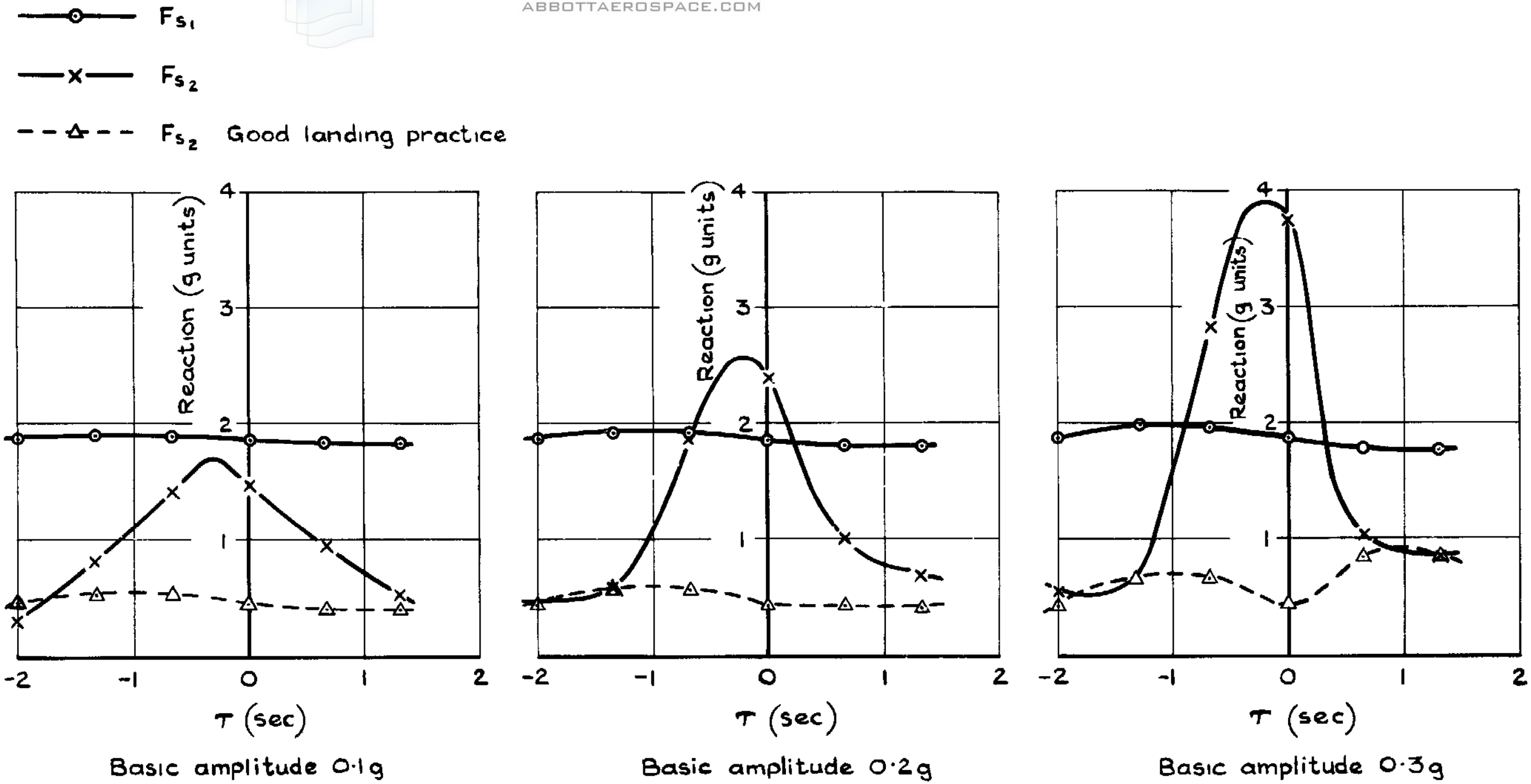


Fig. 19 Type A lift oscillation decay
50:1 Oleo damper
Vertical velocity at initial touchdown 11ft/sec

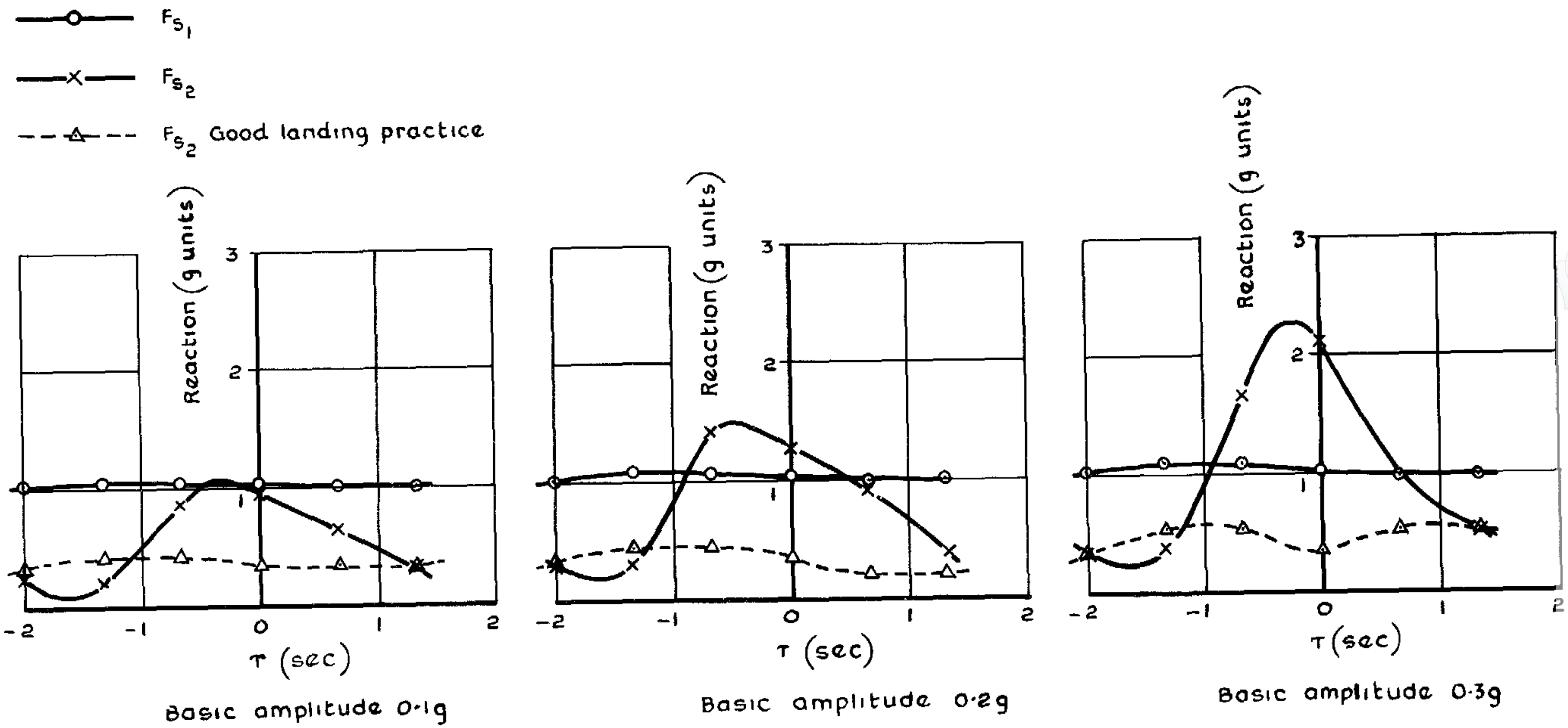


Fig. 20 Type A lift oscillation decay
50:1 Oleo damper
Vertical velocity at initial touchdown 7ft/sec

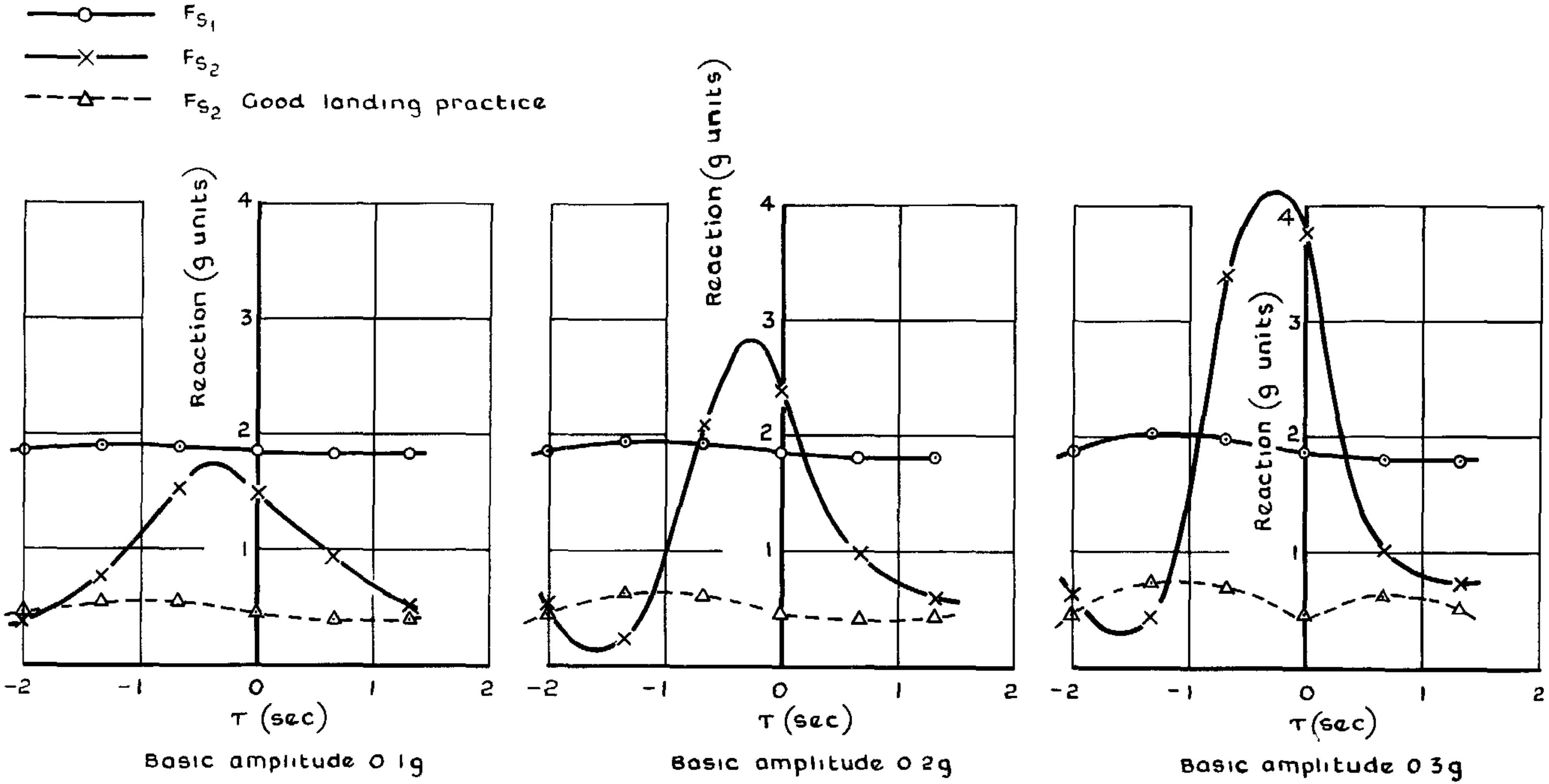
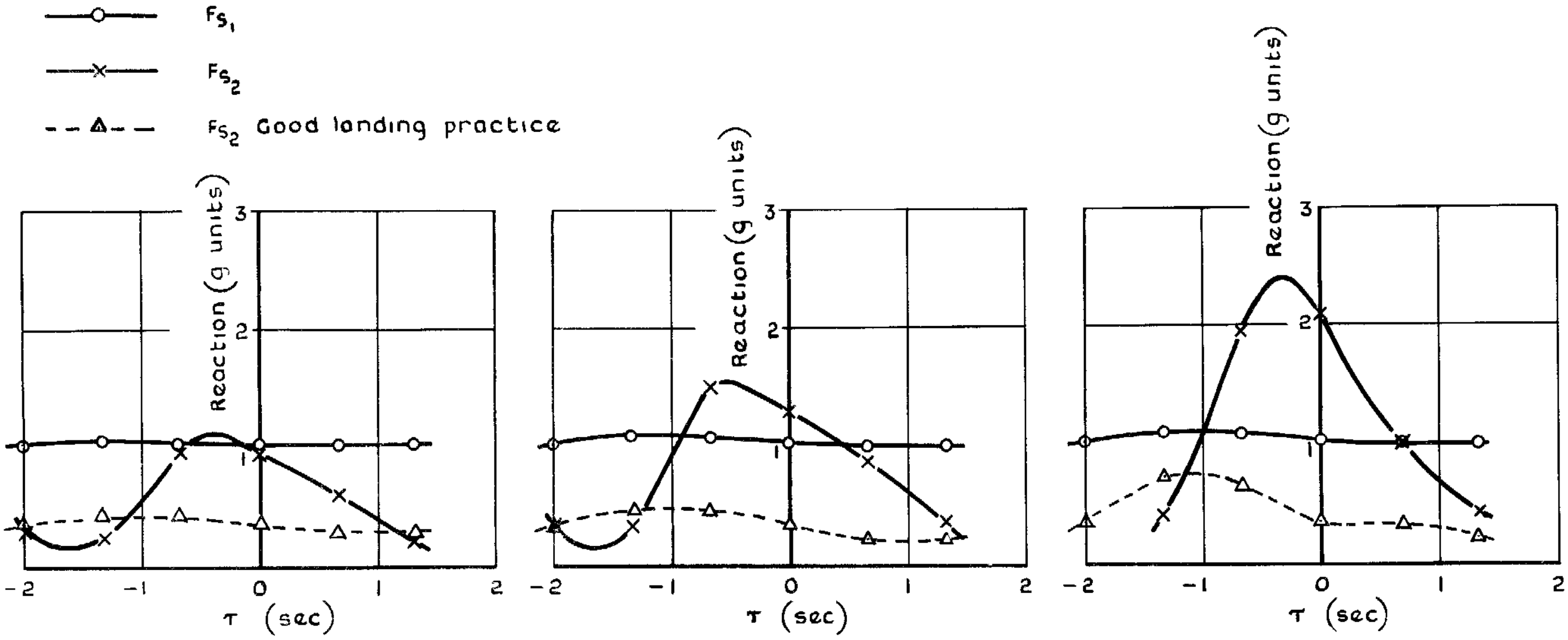


Fig. 21 Type B lift oscillation decay
50·1 Oleo damper
Vertical velocity at initial touchdown 11ft/sec



Basic amplitude 0·1g

Basic amplitude 0·2g

Basic amplitude 0·3g

Fig. 22 Type B lift oscillation decay
50:1 Oleo damper
Vertical velocity at initial touchdown 7ft/sec

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Hutton, G. B.

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