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The Dynamic Landing Loads of Flying Boats with Special Reference to Measurements made on Sunderland TX.293

By

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Summary.—An account is given of a full-scale investigation into the stresses occurring in the wing members of a Sunderland flying boat during landing impacts. It is found that the main dynamic effect is caused by the wing oscillating in its fundamental mode. These dynamic loads have a spanwise distribution similar to the normal lift load and, if the level flight lift load is taken as unity, a magnitude (in the most severe impact recorded) of 1·4 upwards and 1·5 downwards. Generalizing this result, one concludes that whereas down loads in landing may be a deciding factor in design the up loads are amply covered by existing requirements.

Comparison of calculated and experimental loads found in these tests indicates that satisfactory agreement can be attained by using recently introduced modifications of standard dynamical methods.

Although the investigation is primarily a structural one some interesting results on general water load phenomena are obtained.

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1. *Introduction.*—In the past, wing strength has usually been determined by manoeuvring loads. The present trend in civil aviation towards larger aircraft has brought about a change in the character of the loads which are critical in design. Instead of the comparatively slowly applied manoeuvring loads, impact loads produced by gusts and landings tend to determine the strength of the structure.

These impact loads, which are encountered during landing and while flying in gusty air, cause certain oscillations to arise in the structure and in virtue of being sudden enough to excite oscillations they are called ' dynamic ' loads. If the rate of application of a load is too slow to excite oscillations in the aeroplane structure, it is not, by the above definition, regarded as a dynamic load.

In this report we are particularly concerned with the loads to which a flying boat is subjected in landing, and results obtained in the course of full-scale landing tests on a Sunderland V are given, analysed and discussed, and finally, so far as possible, generalized for application to other and bigger flying boats. Although the primary object was to investigate the purely dynamic effect of the landing loads, in other words the stresses induced as a result of the overswings of the oscillating wings under the suddenly applied water reaction at the hull, it will be understood that this object could not be attained without exploring the complete response, both static and dynamic, of the aircraft to the landing forces. It is to be explained that the

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static response to an applied loading system, varying with time, is obtained by considering the state of loading at any instant to have been reached infinitely slowly. The static response then consists of the succession of responses thus obtained.

Very few data, whether on the dynamic or the static forces associated with the full-scale landing of flying boats, are available for comparison with the measurements made during these tests. Probably the main reason for this is the fact that not until fairly recently has it been possible to measure transient stresses and accelerations with anything like certainty. The advent of the resistance strain-gauge and the introduction of the compact light accelerometer, both used in conjunction with the recording oscillograph, has radically changed the position, thereby enabling the investigator to analyse the details of actions that previously could only be observed in their cumulative effects, and even so only qualitatively.

This paucity of reliable information on the forces brought into play during full-scale landings made it still more desirable that as full an investigation as possible should be aimed at, consistent with the restriction of the tests to one type of aircraft. With this in view, it was arranged that not only should the overall stresses and accelerations of the main structural components be measured but that the local stresses in the hull panels should also be determined, so as to obtain design data on actual hull-plate stresses directly produced by the water pressure. This latter objective was not entirely achieved and further tests may be carried out later to supplement the results already obtained.

Acknowledgment.—The authors wish to express their gratitude to Dr. D. Williams for the continual help and guidance which he has given to them during the preparation of this report.

1.1. *Account of Experimental Work.*—A short account may be useful here of the experimental work that was carried out.

1.11. All the tests were carried out on a Sunderland Mark V at Marine Aircraft Experimental Establishment, Felixstowe, and with the co-operation of Marine Aircraft Experimental Establishment staff. The landings were made in sheltered waters, as it was thought desirable not to complicate the landing conditions by a factor so difficult to take into account as the presence of sea swell and large waves, not to mention the fact that there is a strong case for maintaining that it is unfair to expect flying boats to land under such conditions.

Subject to the above restriction, every type of landing was included in the series of tests. Fly-on as well as stalled landings were made of all degrees of heaviness from the lightest to the most violent the pilot dared make, consistent with safety, so that, so far as the Sunderland is concerned, a thoroughly representative series of landings was carried out.

1.12. As indicated above the main object of the tests was two-fold, first to determine the magnitude and time-history of the impact force of the water on the flying boat hull, and second to find the response of the wings to this impact in terms of stresses and accelerations. In order to measure these quantities and obtain a synchronous record of their variation a 12-channel Miller recording oscillograph was used in conjunction with a number of accelerometers and electrical resistance strain-gauges. Fig. 1 shows the Miller equipment installed on the navigator's table on the upper deck of the Sunderland. The accelerometers were judiciously distributed along the wings and hull (*see* Fig. 2) so as to provide as clear a picture as possible of the impact-excited oscillations. Some of the strain-gauges were located at the spar roots and others were distributed on the inner surface of the hull plating. Owing to the restricted number of channels in the recorder, only one of these two sets of gauges could however be used at the same time as the accelerometers.

1.13. As, during the landing impact, no single element of the structure has an acceleration identical with that of the centre of gravity of the flying boat as a whole, it was found necessary to deduce the centre of gravity acceleration from the values recorded at different points in the aircraft. This acceleration, being a direct measure of the water force (assuming the air load constant during the impact), can then be used as a basis for calculating the theoretical response of the wings and comparing it with the actual response. For calculating the theoretical response, the method of normal modes as adapted by Williams[1,2] for application to dynamic load problems was used. This method requires a knowledge of the frequencies and shapes of the natural modes of vibration of the structure concerned and, of course, the time-variation of the impact force concerned. In the case of the Sunderland no resonance tests have been carried out and therefore, the frequencies and modes were calculated.* The frequencies were readily checked against the values observed during the tests and proved to be in reasonably good agreement, the wing fundamental frequency being 3·6 c.p.s. and the first harmonic 8 c.p.s. The fundamental frequency is readily observed in practically all the records shown in this report but the first harmonic is much less pronounced, and still higher frequencies are practically absent.

2. *General Character of Sunderland Oscillations During Landing.*—2.1. *Method Used to Determine Vibrations.*—The amplitude and frequency of the oscillations excited in the wing and hull were determined chiefly by means of accelerometers placed at various positions on the flying boat (*see* Fig. 2). Vibrations of a frequency greater than 10 c.p.s. were partially damped out by electrical means—a justifiable operation when accelerations were required for determining wing stresses since undamped strain-gauge readings along the wing spar showed no sign of any high frequency variation. With the damping arrangement used 95 per cent of full response was obtained at 20 c.p.s. falling off to approximately 5 per cent at 100 c.p.s. Some damping had to be used in order to prevent the main structural oscillations being obscured by the engine vibrations.

2.2. *Wing Oscillations.*—Accelerometers placed at port and starboard wing tips gave very similar readings showing that the oscillations excited were mainly symmetrical (Fig. 3). Six accelerometers attached to the wing front spar showed that the predominant oscillation excited, especially in heavy landings, was the wing fundamental (Figs. 4, 5, 6); a small amount of first harmonic was also apparent both in heavy and light landings (Figs. 7, 8). Three accelerometers placed at one cross-section of the wing, on the rear spar, front spar, and forward on the outer engine mounting, showed a torsional component of the first harmonic (Fig. 3).

2.3. *Hull Vibrations.*—The chief type of vibration measured in the hull (excluding panel vibrations) was a ' tail whip ' or flexural vibration of the hull. This vibration could only be detected in the rear portion of the hull; Figs. 9 and 13 show a typical tail whip. The frequency is about 11·8 c.p.s. which agrees with the calculated value for the second harmonic. Records of accelerations along the length of the hull show that the whole hull shares in the fundamental motion (Fig. 11). Other higher frequency vibrations appear in the region of the rear step obviously caused by local water impacts.

2.4. *Effect of Hull Flexibility.*—It has been suggested from time to time that flexibility of the hull shell may be an important factor in modifying the severity of the impact transmitted to the hull superstructure and to the wings. The records taken in the course of this investigation demonstrate, however, that this notion has little foundation in fact for flying boats with hull stiffnesses comparable with that of the Sunderland. Fig. 14 gives a typical example of the almost identical character of the accelerations measured at the keelson in the region of the step and at the wing spar vertically above that point.

On the same grounds, the records dispose of the German[3,4] idea of treating the seaplane as two elastically-connected masses, the first consisting of the hull bottom and an associated mass of water, and the second of the rest of the seaplane.

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* For these calculations and other assistance during the tests the authors are indebted to the staff of Messrs. Short Bros. Ltd.

3. *Experimental and Theoretical Wing Stresses during Landing.*—3.1. *Wing Stresses Measured During Landing.*—During the series of landings on the Sunderland, measurements were made of the wing root bending moment and front and rear spar shears. In the wing root moment the fundamental frequency is very apparent and the first harmonic introduces only comparatively small moments as seen in Fig. 15. The first harmonic is more apparent in the shear measurements, as would be expected from theoretical considerations, but even there, it is small compared with the shears from the oscillation of the wing in the fundamental mode. Fig. 16 shows the bending moments and shears during a $1 \cdot 1\,g$ landing. The relative magnitudes of the fundamental and first harmonic vibrations are typical of medium to heavy landings. It is, of course, to be expected that very little first harmonic should appear in the bending moment records, having regard to the fact that recorded first harmonic accelerations were small compared with those induced in the fundamental mode. For even if the first harmonic accelerations were equal in magnitude to those in the fundamental mode, the resulting bending moments would be only about a quarter of those in the fundamental mode on account of the nodes being correspondingly closer together. For this same reason the shears in the first harmonic mode would be reduced to only about half of the fundamental shears for the same maximum accelerations.

3.2. *Comparison of Experimental Wing Root Bending Moments with Theoretical.*—It is interesting to take the centre of gravity impact acceleration time curve obtained experimentally for a particular landing*, and from it to calculate the wing root bending moment by both the static or rigid wing and dynamic methods, in order to compare the results with those actually measured by strain-gauges during the landing. Figs. 17 and 18 show the results of such calculations made for three landings. The agreement between the dynamic and the experimental bending moment is good for the heaviest landing, but the rigid wing method naturally always badly under-estimates the wing root bending moment. Only the fundamental vibration is included in the dynamic calculations since this is the predominant mode excited.

3.3. *Wing Lift Values During Landing.*—The bending moments discussed above, both experimental and calculated, consist of the component due to the impact loading alone; they must be superimposed on that due to air lift. At the instant before touch-down the wing bending moment is due solely to air lift; its value, however, is less than that in level flight, since the sinking speed of the flying boat is accelerating due to its partially stalled condition. The lift falls off, still further, while the flying boat is in the water, owing to loss of forward speed: although this may be partly counteracted by increase in wing incidence due to change of attitude. Values of the order of $0 \cdot 85$ times the wing lift in level flight are normal at touch-down but if the flying boat bounces clear of the water, values as low as $0 \cdot 70$ may be found on re-entering the water.

The value of the wing bending moment due to lift during the landing is of importance, since its sign is the reverse of that caused initially by the impact loads, and hence the greater it is, the more will it alleviate the bending moment due to impact. For this reason bounces subsequent to the initial touch-down may produce the greater wing stresses.

3.4. *Conditions for the Landing to Provide a Design Case.*—The question naturally arises, ‘ Does a landing produce a design case for the wings ? ’ The root bending moments in the present series of landings tend to lie between the positive bending moment of level flight and the negative moment due to the weight of the wing alone. It is only when the bending moments due to impact exceed these wing bending moments, that the stresses can possibly become critical. The swing back of the wings after impact seldom produces root bending moments greater than those of level flight. In the heaviest landing recorded the maximum positive bending moment is only 40 per cent greater at the root than the level flight bending moment (Fig. 15). In view of the design requirements for flight manoeuvres and gusts it is evident that critical loads are not caused by the upwards overswing of the wings on landing. A point of interest is that the second upswing is more severe than the first despite the decrease in amplitude

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* As found indirectly from the combined records of the various accelerometer readings.

of the fundamental oscillation due to aerodynamic damping. The reason for this is that the oscillation takes place about a varying level which is governed by the magnitude of the impact load applied at the instant in question (this point is clearly shown in Fig. 15). During the first upswing the impact loading is still sufficiently great to counteract the effect of the upswing, but during the second the impact loading is normally reduced to zero.

The negative bending moment on the other hand caused by the first downward overswing is not likely to be covered by the stressing requirements for negative g in flight (except in the case of planes stressed for aerobatical manoeuvres), and it is in this respect (negative g) that the possibility exists for the landing case to provide a design criterion for the wings. Final recommendations on this subject are made in section 5.3.

3.5. *The Presence and Effect of Torsion.*—The important normal modes of vibration excited in a landing are the wing flexure-torsion modes. Torsion and flexure of the wings are not independent, and any natural mode consists of an amount of flexure with an associated amount of torsion. The fundamental wing mode is, in general, mainly flexural but the first and higher harmonics may contain an element of torsion which, although not altering the total bending moment or shear at any cross-section (except for secondary effects due to taper), introduces extra shear stresses in the wing spars and skin. Further investigation is required to determine the amount of these stresses as the data gathered during these tests are too meagre to enable reliable estimates to be made.

4. *The Impact Acceleration-time Curve.*—4.1. *Definition.*—This is the curve defining the variation of the acceleration of the centre of gravity of the aircraft due to the vertical impact with time. Another way of arriving at the same curve is to plot the total vertical impact force divided by the aircraft weight against time, since the centre of gravity acceleration (in terms of g) due to impact at any instant equals the vertical impact force divided by the aircraft weight (changes in air load neglected). In the following sections the impact acceleration-time curves are often referred to merely as impact curves for the sake of brevity. Time is measured from the instant of entry into the water and the time of build-up is defined as the time taken for the impact acceleration to reach its maximum.

Different impact curves are obtained for different conditions of landing and in order to compare curves it is convenient to reduce them to their ' basic shape.' This is done by smoothing the curves and then reducing them to a non-dimensional form by dividing the impact acceleration at any instant by the maximum impact acceleration and the time by the time of build-up. By smoothing is meant the elimination of the irregularities discussed in section 4.6 by drawing the best mean curve. It is then possible to compare the responses to unit impacts of various shapes, for a range of natural frequencies. Fig. 19 shows twelve impact acceleration-time curves obtained during the Sunderland landings first of all smoothed and then plotted in a non-dimensional form.

4.2. *Theoretical Determination.*—The shape of the impact curves depends on a large number of parameters: these include the attitude of the flying boat and its horizontal and vertical velocities at touch-down, the geometry of the bottom of the boat, and the weather conditions and state of the sea. With these conditions specified, it is theoretically possible to calculate the impact acceleration-time curve. The methods at present available[5 to 10] are, however, still in process of development, and are known to contain coefficients that require confirmation from full-scale experimental landings.

4.3. *Experimental Determination.*—It is not an easy matter to obtain experimentally the centre of gravity acceleration due to impact. An accelerometer fixed to any part of the flying boat records, not only the centre of gravity acceleration, due to impact and change of wing lift, but also the acceleration of that part due to vibrations excited by the impact. At the beginning of the experimental work on the Sunderland it was hoped that the chief mode of vibration excited would be the fundamental, and that it would be possible to fix an accelerometer at a fundamental node, which would then indicate only centre of gravity acceleration. Unfortunately the presence of first harmonic vibration at the fundamental node made determination of the centre of gravity acceleration by this means too difficult. Two other methods were then employed, both requiring a number of accelerometer readings at different parts of the flying boat. In the first, a mean acceleration was found by associating appropriate masses with accelerometers at nine points along the wing and down the hull (positions shown in Fig. 2, *see* Appendix I). This method was found somewhat laborious and good results were obtained by means of an alternative method (given in Appendix I) whereby certain chosen modes of vibration were eliminated. It will be appreciated that, in the absence of modes higher than the second, readings from only three accelerometers are required to eliminate the fundamental and first harmonic and thus obtain the centre of gravity acceleration. If the higher harmonics are too pronounced to be neglected their presence is easily detected by their high frequencies which moreover allow a mean curve to be drawn.

Fig. 20 shows, for several landings, the centre of gravity accelerations obtained by elimination of the fundamental and first harmonic accelerations compared with acceleration readings at the front-spar centre-span position. Fig. 21 shows a centre of gravity acceleration compared with acceleration readings on the front spar at the centre-span position, half-way between the engines and at the outer wing. These graphs emphasise the necessity of calculating the centre of gravity acceleration from a combination of accelerometer readings, and show the error in estimating the maximum centre of gravity acceleration from a single acceleration reading. For example maximum readings on the centre-span give an over estimation of very nearly 26 per cent in the majority of cases while at the outer wing an over-estimation of the centre of gravity impact acceleration of as much as 160 per cent may be obtained.

The centre of gravity acceleration as found above still contains a component due to fall off of wing lift. This, however, is small during the time of build-up of the impact loading and in analysing the experimental results the whole of the centre of gravity acceleration is assumed to be due to the impact.

4.4. *Types of Landings.*—Figs. 22 and 23 show examples of centre of gravity, *i.e.*, impact, acceleration-time curves obtained from experimental readings. They represent the heaviest landings selected from a large number made in the Sunderland on different days by different pilots. The records are classified as stalled or fly-on, and are obtained from measurements made at the first touch-down or during subsequent bounces, since it was found that very often the flying boat bounced clear of the water two or three times after the first touch-down (*see* Appendix II, which discusses this point at more length in relation to experimental results showing the variation of attitude and height with time). The subsequent bounces, when occurring in the course of a fly-on landing, should more properly be classed as stalled, since the flying boat is generally in a partially stalled condition when bouncing. The bounces are in general heavier than the initial touch-down, which is contrary to the behaviour predicted in Ref. 9 which is based on the assumption that the attitude remains constant. Fig. 24 shows the variation of attitude, height, and impact acceleration, with time, for the first 10 secs of a fly-on landing, in which two bounces occurred. A rough synchronisation between the acceleration and ciné-camera records has been obtained by matching the start of impact build-up with the initial contact of keel and water. As can be seen there is a considerable variation in attitude during the course of the landing. The methods used to measure the attitude, height and ground speed of the flying boat during landing are given in detail in Appendix III.

It is difficult to define the heaviness of a landing: but it can be said that the landings that gave rise to some of the impact acceleration-time curves recorded here are the heaviest that could be made under moderately good weather and sheltered sea conditions without seriously damaging the bottom of the flying boat. In actual fact the bottom of the flying boat was damaged, probably in the course of the experiments, while in one landing the starboard float was completely torn off !

The following table shows the number of landings made for each of the ranges of acceleration covered in the course of the experiments.

TABLE 1

Analysis of Centre of Gravity Accelerations Obtained During Sunderland Landings

Range of acceleration (Incremental—add 1*g* to obtain absolute accelerations)	*Number of landings*
0 to 0·25*g*	3
0·25 to 0·5 *g*	9
0·5 to 0·75*g*	9
0·75 to 1·0 *g*	8
1·0 to 1·25*g*	9
1·25 to 1·5 *g*	3
1·5 to 1·75*g*	1
1·75 to 2·0 *g*	3

4.5. *Effect of Damping.*—It might be thought that there would be a danger of the repeated bouncing of the flying boat tending to build up large oscillations, owing to the possibility of the oscillations excited by a particular bounce being superimposed additively on the oscillations excited by the previous bounce, thus causing a much more serious vibration of the wing to occur than would be predicted theoretically if the bounces were treated as independent impacts. This build-up, however, cannot take place in practice, because the time between bounces allows vibrations from a previous bounce to be effectively damped out before the next occurs.

Values for damping obtained on the Sunderland are of interest in this respect. Estimates of the aerodynamical damping obtained from the records of the wing root bending moment, which show very clearly the die-away of the fundamental vibration (*see* Fig. 15), give a figure of the order of 0·07 times the critical damping. (This value is obtained on the assumption that only the fundamental mode is excited; *i.e.*, dynamic coupling between modes due to damping is neglected). A damping of 0·07 of critical damping is sufficient to reduce the amplitude of the fundamental by 90 per cent in 1·5 sec and by 99 per cent in 3 sec. Measured times between bounces give a minimum value of 1·5 sec and an average of 2·2 sec corresponding to a damping out of 90 per cent and 97 per cent respectively of the fundamental. Estimates of damping for the first harmonic vibration, obtained from wing root shear measurements such as are shown in Fig. 8, again give a value of the order of 0·07 critical corresponding to a decrease in amplitude of 75 per cent in 0·4 sec. This figure is of interest in that it shows to what extent the first harmonic vibrations caused by impact with small waves at the beginning of a landing are damped out by the time maximum deceleration is attained (*i.e.*, in about 0·4 sec).

Another important effect of damping is to lessen the amplitude of the upward overswing of the wing in the fundamental oscillation. It is the second overswing which produces the most severe stresses but by the time it occurs the amplitude of the fundamental oscillation has, owing to damping, dropped to about 50 per cent of its value in the first downswing (Fig. 15).

4.6. *Irregularities of the Experimental Impact Acceleration-time Curves.*—The impact acceleration-time curve appears to consist of a smooth basic curve on which certain irregularities occur. It is difficult to decide whether these irregularities are genuine changes of impact load or denote inaccuracies in the elimination of the modes. Records obtained showing strain readings on the bottom plating give however some indication of the possible iregularities occurring in landing. Fig. 12 shows strain-gauge readings on the bottom plating and the acceleration at the wing front spar centre-span position. At a time 0·26 sec before the flying boat enters the water the keel has made transient contact with the top of a wave. This wave causes a bump on the acceleration record, such as is found at the beginning of the landings of Fig. 22. The hitting of small waves or ' chop ' when entering the water is thought to cause irregularities. Other irregularities in the impact curve occur because the hull itself is moving up and down at the fundamental frequency, so that the water reaction (and hence the impact acceleration) also varies at fundamental frequency. The effect is most noticeable after the impact force has reached its peak since not until then is the fundamental fully excited. The record shown in Fig. 12 illustrates the variation of strain in the hull plating and adjacent frames at the fundamental frequency. It is interesting to note the phase difference between the centre-span acceleration and the hull bottom strains due to the variation of water pressure with velocity as well as with displacement.

To sum up: there appear to be two classes of irregularities imposed on the smooth impact acceleration-time curve,

(a) Those caused by hitting small waves and chop;

(b) Those due to the oscillation of the hull in the fundamental mode causing a variation in water load; such irregularities are most marked after the maximum value of the impact has been reached.

4.7. *Comparison of Theoretical and Experimental Impact Acceleration-time Curves.*—In order to calculate the value of the centre of gravity impact acceleration at any instant of time during the landing of a particular flying boat it is necessary to know the angle and velocity of approach to the water. Given these initial conditions, an estimate of the centre of gravity impact acceleration may be obtained by various methods all based on the assumption that no pitching occurs during the landing. In order, therefore, to compare theory and experiment, photographic records were made of some of the landings from which the vertical velocity and angle of approach could be measured. (Details of the methods used are given in Appendix III). The following table compares experimental with theoretical maximum accelerations and times of build-up for these landings. The theoretical values are calculated from approximate formulae due to Monaghan[10], based on the best available methods. The maximum experimental and theoretical accelerations for the first impact of each landing are seen to be in reasonable agreement, but the theoretical accelerations tend to be lower than the corresponding experimental accelerations for the second impacts and the theoretical times of build-up are in all cases shorter than the experimental. It is possible that these discrepancies are due to changes of pitch occurring during the landings (of which the theory takes no account), and it is of interest to note that similar discrepancies have been observed in America[11].

TABLE 2

Landing Number		Experimental Results		Calculated Results	
				Monaghan	
		Max. impact acceleration g	Time of build-up to max. centre span acceleration sec	Max. impact acceleration g	Time of build-up to max. impact acceleration sec
42	1st impact	0·56	0·42	0·78	0·27
	2nd impact	1·67	0·38	0·96	0·25
44	1st impact	0·46	0·40	0·54	0·33
	2nd impact	0·29	0·60	0·26	0·48
45		1·72	0·36	1·93	0·17
49	1st impact	0·48	0·62	0·49	0·37
	2nd impact	1·33	0·45	0·63	0·31
	3rd impact	1·11	0·51	0·48	0·38
54		0·96	0·44	0·52	0·37

5. *The Dynamic Factor and its Application.*—5.1. *Dynamic Factor for Sunderland.*—Measurements made during experimental landings on the Sunderland show that the increase in wing stresses due to structural flexibility is appreciable and that the initial overswing of the wings may produce downloads of a critical nature. For example the heaviest landing recorded in the Sunderland shows a maximum bending moment at the wing root of twice the wing dead weight bending moment, whereas had there been no overswing, the wing root bending moment would have been only 0·8 times the wing dead weight bending moment. It appears then that it is necessary for the designer to make an allowance for the increase in wing stresses due to flexibility. This he can do by means of standard methods available[1,2] for calculating the dynamic loads. Considerable labour, however, can be saved by the direct use of an approximate dynamic factor by which the static or rigid wing bending moments and shears must be multiplied to get the resultant dynamic effect.

From measurements obtained on the Sunderland it is evident that the wing oscillations excited during heavy landings are predominantly in the fundamental mode with only small amounts of the first harmonic. It is the first downswing of the wing in the fundamental which produces the greatest downloads and it is at the wing root that the resulting stresses are most likely to be critical. This is due to the comparatively greater alleviation obtained in the outer wing from the wing lift. The point is illustrated in Fig. 25 which shows how, in the heaviest Sunderland landing, it is only at and near the wing root that the bending moment exceeds that due to the dead weight of the wing itself. In view of the relative unimportance of the outer wing stresses induced by landing impacts, attention hereafter is confined to dynamic factors at the wing root, and no values are given for dynamic factors further outboard.

Analysis of the heaviest Sunderland landings gives values for the dynamic factor of 1·54, 1·70 and 1·73 for the wing root bending moment and 1·27 for the wing root shear. These figures are the ratios of the bending moments and shears measured in the landings to the corresponding calculated static or rigid wing values. (The latter depend directly on the maximum centre of gravity acceleration which is found for each landing from a number of experimental acceleration measurements as explained in section 4.3). From these landings it appears that a dynamic factor of 1·8 covers the increase in wing root bending moments and shears due to wing overswing.

It is thought unlikely that impact landing loads on the Sunderland will produce wing stresses greater than those covered by a factor of 1·8. The reason for this is that:

1. The impact acceleration-time curves obtained in experimental landings can be reduced to very similar basic shapes (Fig. 19b).
2. The calculated dynamic factors for these basic shapes never exceed 1·5.
3. The increase in the experimental figure 1·8 over the calculated figure of 1·5 is due to irregularities in the impact curves caused by small waves. Provided landings are confined to sheltered waters, calculations show that irregularities will not increase the dynamic factor for the basic shape of impact curve to more than 1·8.

5.2. *Application of Dynamic Factor to Other Flying Boats.*—It can be shown by simple dimensional theory (Appendix IV) that for flying boats of different sizes but similar proportions both the periodic time of the fundamental wing oscillation and the time of build-up of the landing impact vary inversely as the linear dimensions and hence as the cube root of the flying boat weight. It can, therefore, be inferred that, as flying boats get larger, the predominant mode excited by the landing impact will still be the fundamental and the dynamic factors will remain unchanged.

It is recognised that future large flying boats will most likely have different water characteristics from those of the Sunderland, but in view of the unreliability of present methods of prediction of the water reaction in landing, it is considered that a simple argument based on dimensional theory offers the best means of extrapolating to larger sizes.

5.3. *Recommendations for the Landing Design Case of Flying Boats.*—It is therefore recommended that the design case for the main-step landing of a flying boat should be as follows:—

(i) A down-loading of $(1 + 1 \cdot 8n)$ times the wing weight, together with
(ii) An up-loading of 0·80 times the level flight lift,

where n is the maximum incremental centre of gravity acceleration, expressed in number of g, and is appropriate to the flying boat and the conditions under which it is required to land.

6. *Conclusions.*—Among the results obtained and the conclusions reached the following may be mentioned.

(1) *Wing Modes Excited.*—Although traces of first harmonic excitation were found they were not significant from a stressing point of view, and still higher modes were absent. The fundamental mode was the dominant mode excited in these tests and the stresses directly due to this mode are important.

(2) *Maximum Bending Moments Obtained.*—Account has to be taken of three distinct bending moment distributions, those due to:—

(a) aerodynamic lift,
(b) wing weight and wing inertia loads due to the wing sharing the acceleration of the centre of gravity and referred to as static inertia loads,
(c) wing inertia loads due to wing oscillation in the fundamental mode.

The bending moment rises most steeply towards the root in (b) with (c) next and—least peaky—(a). Thus, in comparison with (a), the bending moments from (b) and (c) are somewhat exaggerated by quoting only their root values. Root values however are taken as a basis for presenting the resultant effect.

With root bending moment in level flight taken as unity (air loads minus wing weight), the resultant bending moment may be split up as follows:—

(i) Bending moment just before water impact (reduction from unity to 0·8 due to loss of lift). $= + 0 \cdot 8$.
(ii) Maximum experimental bending moment (static and fundamental). $= - 1 \cdot 53$.
(iii) Static bending moment at instant of maximum (ii) $= - 1 \cdot 14$.
Fundamental bending moment at instant of maximum (ii) $= - 1 \cdot 19$.
(iv) Maximum static (occurring earlier than maximum (ii)) $= - 1 \cdot 39$.

Thus a maximum downward root bending moment is obtained about 50 per cent greater than the level flight upward bending moment. Another way of putting this is to give the maximum downward root bending moment as 1·99 times the wing weight bending moment with the boat floating stationary.

(3) *Calculated Bending Moments.*—Agreement between measured resultant bending moment and that calculated from the accelerometer-deduced impact was not unsatisfactory.

(4) *Effect of Bounces.*—Some of the bounces in fly-on landings gave very heavy impacts due to loss of lift and unfavourable pitch changes.

(5) *Damping of Wing Oscillations after Impact.*—Damping was found to be about 7 per cent of critical and heavy enough to reduce wing oscillations practically to zero between bounces in spite of a minimum interval of only 1·5 sec between bounces.

(6) *Estimate of Water Impact from Hydrodynamical Considerations and Sinking and Forward Speeds.*—Measured values have been compared with those obtained from the latest theoretical methods of estimating the magnitude and time-history of the water reaction. Agreement is not altogether satisfactory and it is concluded that these methods cannot yet be relied upon to give a good approximation to the water impact.

(7) *Hull Vibration.*—Apart from the hull movement associated with the fundamental mode and local high frequency panel vibrations, the only important hull oscillation was a type of tail whip at about 12 c.p.s.

(8) *Effect of Hull Flexibility.*—Any effect of hull flexibility in modifying the water impact seems to be negligible as the accelerations at keelson and spar root are practically identical.

(9) *Hull Water Pressures.*—The method of measurement did not prove accurate enough to give reliable quantitative values. Some interesting qualitative characteristics were recorded but these have not yet been fully analysed.

The experiments described in this report also lead to several interesting conclusions, rather more general than those listed above.

A simple and reasonably accurate, if somewhat laborious, method of measuring the height, ground speed and attitude provides interesting data on the behaviour of a flying boat during landing. It is evident that changes of attitude, usually of about 1 deg, take place during the build-up of the water reaction. This is contrary to the assumption of constant attitude made in theoretical treatments of the landing problem.

Coming now to the main purpose of the tests, the investigation of the wing inertia loads due to impact, the experiments described in this report show that the oscillations excited in the wings of flying boats by landing loads seriously affect the stresses induced in the structure. If, as is likely to be the case for large civil types (which are not intended to indulge in violent manoeuvres) landing or gust loads provide design cases then it becomes important that the effects of these impact loads should be accurately predictable. So far as landing in sheltered waters is concerned, the present investigation amply shows that a flying boat wing strong enough to meet present gust requirements is unlikely to be troubled by landing forces, but for landing in rough waters the forces may become critical.

The methods suggested by Williams for estimating, given a knowledge of the impact curve, the internal actions due to impacts[1, 2] are shown to be reliable, reasonably good agreement having been obtained between the theoretical estimates and experimental results.

Owing to the unreliability of theoretically obtained impact curves it is suggested that a dynamic factor of 1·8 be used in the design of flying boat wings to allow for the increase in wing stresses due to oscillation during landings. The inclusion of this factor, which is based on results obtained from the Sunderland landings, lead immediately to the proposed design case quoted in section 5.3.

The attempt here made to generalize the results obtained so as to apply to larger flying boats is based on the strict application of dimensional theory. The indications are that even when there is some departure from strict similarity the overall dynamic factor above suggested may still be a reasonable one. This may form the subject of a further note.

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APPENDIX I

Two Methods of Obtaining the Centre of Gravity Acceleration from the Records of Accelerometers in the Wings and Hull

An accelerometer record shows not only the overall acceleration experienced by the flying boat as a whole, but also the accelerations in every mode of vibration which is excited appropriate to the point at which the accelerometer is attached.

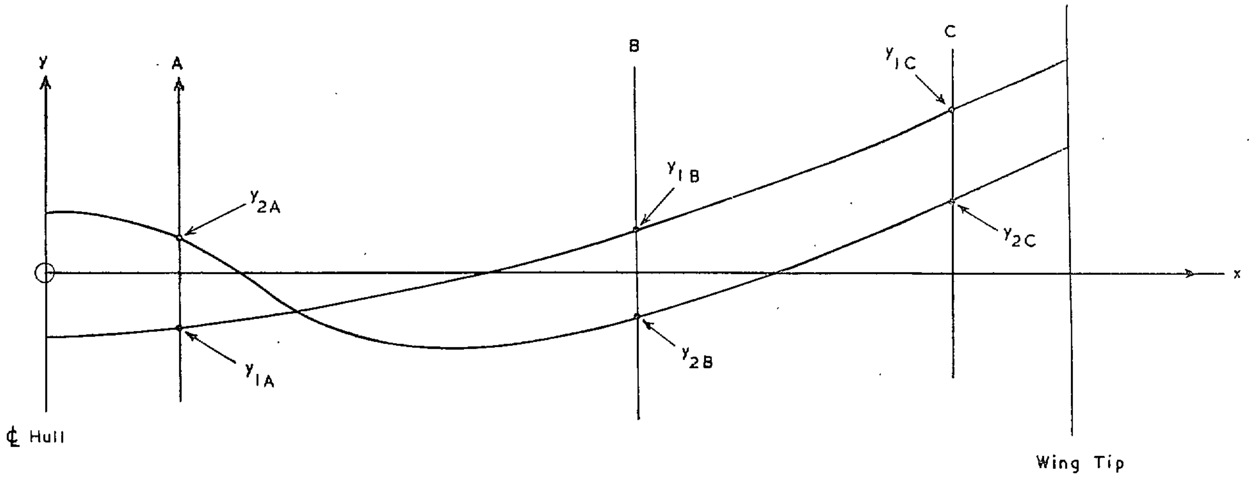
The first method of discovering the centre of gravity acceleration from accelerometer records is simply to associate every mass element (m) in the wings and hull with the acceleration ($\ddot{y}$) shown on a particular accelerometer record. The acceleration of the centre of gravity is then given by

$$\ddot{y}_{c.g.} = \frac{\Sigma m\ddot{y}}{M}$$

where M is the mass of the flying boat.

This method gives good results but is very laborious and is therefore not recommended.

A second and simpler method which depends upon the fact that only the first two modes are sensibly excited is as follows:—



Let the above diagram represent the shapes of two natural modes of vibration of the wing and let the displacements at stations A, B and C in these modes be as shown.

Since the modes are normal modes of vibration we can write

$$\frac{y_{1A}}{y_{1B}} = \frac{\ddot{y}_{1A}}{\ddot{y}_{1B}} = K_1, \text{ say. Also } \frac{\ddot{y}_{1A}}{\ddot{y}_{1C}} = K_2; \ \frac{\ddot{y}_{2A}}{\ddot{y}_{2B}} = K_3; \ \frac{\ddot{y}_{2A}}{\ddot{y}_{2C}} = K_4$$

where all the K's are constants.

Accelerometers at stations A, B and C will record accelerations

$$a_A = \ddot{y}_{c.g.} + \ddot{y}_{1A} + \ddot{y}_{2A} + r_A,$$

$$a_B = \ddot{y}_{c.g.} + \ddot{y}_{1B} + \ddot{y}_{2B} + r_B,$$

$$a_C = \ddot{y}_{c.g.} + \ddot{y}_{1C} + \ddot{y}_{2C} + r_C, \text{ respectively,}$$

where the r's are the sums of accelerations in all modes other than the two being considered. By using the K ratios it is clear that, if r_A, r_B, r_C are negligible we can, with a knowledge of a_A, a_B and a_C, solve for $\ddot{y}_{c.g.}$, $\ddot{y}_1$ and $\ddot{y}_2$. By solving for successive instants the negligibility or otherwise of the r's may be shown.

The sum $a_A + \beta a_B + \gamma a_C$ contains only centre of gravity acceleration and the r's if

$$\beta = \frac{(K_2 - K_4)\, K_1 K_3}{K_1 K_4 - K_2 K_3} \text{ and } \gamma = \frac{(K_3 - K_1)\, K_2 K_4}{K_1 K_4 - K_2 K_3}.$$

If the r's can be neglected, we can thus obtain the centre of gravity acceleration.

A point worth noting is the self-checking character of the process—in that accelerations found for successive instants should lie on a smooth curve.

In practice, at any rate for hull landings in the Sunderland, it was found that by eliminating accelerations in the fundamental and first harmonic modes very little of higher frequency variations remain in the resulting curve, thus showing that, for this case, the r's in the above expressions are not important. Most of the curves of centre of gravity acceleration shown in this report have been obtained by this second method. The two methods have been checked against one another and agreement is extremely good.

Fig. 29 shows for landing number 17 the results of eliminating in turn fundamental and first harmonic accelerations, first harmonic and centre of gravity accelerations, fundamental and centre of gravity accelerations using the accelerometer records from three wing stations. The recorded centre-span acceleration is included for comparison with the centre of gravity acceleration obtained by elimination.

Fig. 30 shows centre-span, mid-engine and wing-tip accelerations and the resulting centre of gravity acceleration obtained by the elimination method for landing number 8 (first bounce). The completeness with which oscillations at fundamental and first harmonic frequencies have been excluded from the result is a measure of the success of the elimination.

It must be emphasised that in order to use this method the shapes of the modes in which accelerations are to be eliminated must be known very accurately otherwise the modes will not be completely eliminated.

APPENDIX II

The Variation of Flying-boat Attitude and Height Measured During the Sunderland Landings

Figs. 27a to 27d show the variation of attitude of the flying boat, as measured by a pitch recorder, for two fly-on and two stalled landings on the rear step. In Figs. 28a to 28f the variation of attitude and height of the flying boat as measured from the ciné-records for four fly-on and two stalled landings is shown.

The stalling speed of the Sunderland V landing with one-third flap (which was the flap condition in all the experimental landings) is approximately 125 ft/sec. With the wind encountered in the landings this corresponds roughly to a ground speed of between 110 and 125 ft/sec. 'Stalled' landings appear to be slow-speed gliding approaches followed by touchdown in a partially stalled condition.

The technique of making fly-on and stalled landings varies considerably. In the fly-on landing the boat approaches the water in a shallow glide and as the speed drops off the incidence is gradually increased to maintain lift. Touchdown normally takes place at a ground speed of approximately 135 ft/sec. In the stalled landing the ground speed at touchdown is generally much lower, being about 115 ft/sec and, as can be seen from the figures, the incidence is increasing rapidly during the last few seconds before touching the water.

It will be seen from the records of the landings that the flying boat often bounces clear of the water one or more times. The boat more often bounces clear in the fly-on landings owing to the speed at touchdown being higher and the attitude smaller than in the stalled landings.

It can be seen from Figs. 27 and 28 that an increase in attitude during impact tends to lift the aircraft out of the water whilst a decrease in attidude, such as occurs during a stalled landing on the rear step, has the opposite effect.

The landings shown in the figures may be considered as typical of those made in the Sunderland.

APPENDIX III

Methods of Measuring Rate of Descent, Ground Speed and Attitude of Aircraft During Landing

The rate of descent, ground speed and attitude of the Sunderland flying boat in the landings which are the subject of this report were measured from 35-mm ciné-film records of the landings.

The records were obtained in a theodolite camera which measured azimuth and elevation angles, to an accuracy of approximately ± 7 minutes of arc, by means of two notched bars, mechanically linked to the horizontal and vertical tracking motions of the camera. These notched bars formed the right- and left-hand edges of each frame of the ciné-record and the up-and-down position of the notches in the frame determined the azimuth and elevation angles. It was found that the change of elevation needed to follow the flying boat during a landing was so small that the rate of descent of the flying boat could not be determined from the movement of the elevation notch. The azimuth notch, however, operated very satisfactorily with the result that a good estimate of ground speeds during landings was obtained.

Rate of descent and attitude of the flying boat were ascertained by means of readings taken from optical projections of the ciné-record, using as a plane of reference for measurements the plane through the camera lens, and the ' horizon ' appearing on the ciné-record. This horizon consisted of a straight shoreline, something over a mile from the camera, parallel to the direction along which the flying boat was supposed to land. Time marks, at 1/50 sec intervals, were recorded on the ciné-film by means of a sparking mechanism, thus enabling a definite time of occurrence to be ascribed to each exposure in the record.

It should be noted that vertical or nearly vertical distances only should be measured; horizontal distances appear on the photograph, of course, foreshortened by various amounts depending on whether the boat is photographed nose-on, tail-on or side-view. Since the boat pitches and rolls through only a few degrees, measurements which are at some stage vertical are negligibly affected by foreshortening when they become slightly out of vertical.

Measurement of Rate of Descent.—To measure rate of descent of the flying boat the following measurements were taken from the projection of the ciné-record exposures (*see* Fig. 26):—

(a) The vertical distance between any two points on the flying boat, the actual distance between which (*i.e.*, measured on the flying boat) is known.

(b) The vertical distance between a point on the flying boat and the horizon appearing on the film record.

Measurement (b) was scaled up to an actual height above the plane defined by the camera lens and the horizon by means of measurement (a) and the known distance between the two points used in measurement (a).

Such measurements were made on each frame of the ciné-record. The height of the point on the flying boat used for measurement (b) above the plane of reference was then plotted against time and the slope of this curve gave the rate of descent through the reference plane at any time.

Since the plane of reference was not quite horizontal the rate of descent obtained as above is in error, unless the flying boat is flying parallel to the horizon, for otherwise an apparent constant rate of descent would be recorded with the boat flying straight and level. In landings involving more than one touch-down this error can be eliminated, as, assuming the boat to be flying straight (this assumption was confirmed for several landings by further ciné-camera measurements) and at a constant speed, the error in rate of descent is constant. This means that the several points on a height above reference plane-time plot corresponding to the times at which touch-downs occurred must lie on a straight line. This straight line being drawn in, a height above water-time curve can be drawn by taking measurements between the line and the height above reference plane-time curve. If only one touch-down occurs the error in rate of descent cannot be eliminated as above. It is thought, however, that in all the landings made in the Sunderland the error was small.

Measurement of Attitude.—To measure the attitude of the flying boat the following measurements were taken from the projection of the ciné-record exposures (*see* Fig. 26):—

(c) The vertical distances between two points (one forward on the boat and one aft) and the horizon appearing on the film record.

Measurements (c) were scaled up to actual measurements above the plane defined by the camera lens and the horizon by means of measurement (a) above and the known distance between the two points used in measurement (a).

From these two scaled-up measurements and the known actual horizontal distance between the points used for measurements (c) the angle between the horizontal and the line joining the two points used for measurements (c) was determined.

From a knowledge of the geometry of the flying boat this angle can be altered to refer to any line on the flying boat, *e.g.*, hull datum.

From a knowledge of rate of descent and forward speed—and hence of flight path angle to the horizontal—the attitude measurement can be referred to the flight path rather than to the horizontal.

The measurements being made on each frame of the ciné-record and reduced to a convenient angular measure, an attitude-time curve can be drawn using the known time of photographing of each frame.

A quite negligible error in the measurement of attitude occurs if during the landing the flying boat is not flying parallel to the horizon.

Measurement of Ground Speed.—To measure the ground speed of the flying boat the following measurements were taken from the projections of the ciné-record exposures (*see* Fig. 26):—

(d) The height, H, of the frame. This was kept constant during the analysis of a particular landing by not altering the focus of the projector.

(e) The distance, x, of the azimuth notch from either top or bottom of the frame.

(f) The horizontal distance, y, between the centre of the frame and a chosen point on the flying boat.

Applying the usual lens formulae to the camera lens we have

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{F} \quad \text{and} \quad \frac{v}{u} = \frac{i}{o} = \frac{1}{f},$$

where u is distance of flying boat from the lens,

v ,, distance of film in camera from the lens,

o ,, a vertical dimension on the flying boat,

i ,, the same dimension on the film record,

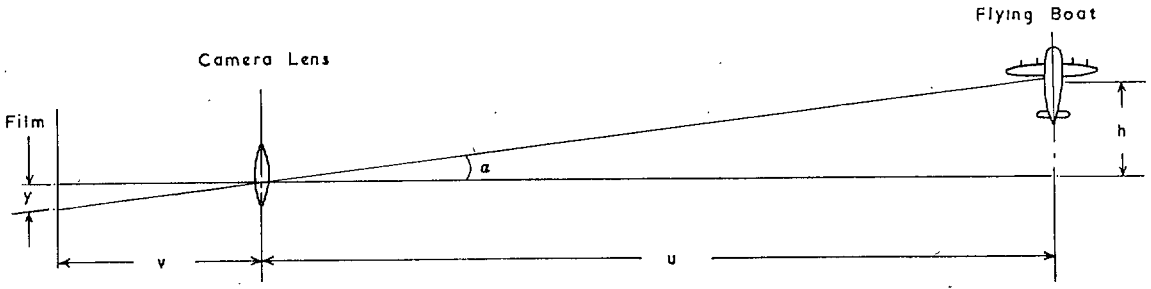
f ,, a size factor defined as $f = o/i$,

F ,, focal length of the camera lens

and hence $u = F\,(1 + f)$.

Unity is negligible in comparison with f so we may write

$$u = Ff.$$



Referring to the above diagram, h and y are horizontal displacements, of a point on the flying boat and the corresponding point on the film record respectively, from the line through the centre of the lens and the centre of the frame on the record. Azimuth angles, as measured by the notch, are referred to this line. The angle α is thus the correction to be applied to the azimuth angle as measured by the notch.

We have, since α is always small,

$$\alpha \simeq \frac{h}{u} = \frac{fy}{u} = \frac{y}{F}.$$

This is more conveniently written as

$$\alpha = \frac{y_1}{Ff_1}$$

where $f_1 = \dfrac{\text{a dimension on the projection of the film record}}{\text{the same dimension on the film record}}$

and y_1 is the projected equivalent of the measurement y.

The azimuth angle, as given by the notch from an arbitrary reference line is given for the camera used in the Sunderland landings by

$$A = \frac{x}{H} \times 38{\cdot}233 \text{ deg.}$$

The corrected azimuth angle is therefore given by

$$(A + \alpha) = \frac{x}{H} \times 38{\cdot}233 \pm \frac{180}{\pi} \frac{y_1}{Ff_1}.$$

The ambiguity of sign is easily determined in a particular case and depends on whether A is measured as an increasing or a decreasing angle and on whether the flying boat is ahead of or behind frame centre.

If now, choosing any point as origin, we set off $u \cos (A + \alpha)$ along and $u \sin (A + \alpha)$ at right-angles to the arbitrary reference line for all the frames in the record, we obtain a series of points, each having a definite time of occurrence associated with it showing the line of flight, in plan, of the flying boat. If now, we measure along the line of flight curve to each point in turn we can plot horizontal distance along flight path against time. The slope of this curve is the ground speed.

It will be noted that to obtain the ground speed the slope of a curve has to be measured. This is unsatisfactory and means that any curve showing ground speed against time is necessarily inaccurate. Very good estimates of the mean ground speed over a period (*e.g.*, the one or two seconds immediately prior to touch-down) during which it is not likely to alter appreciably can however be obtained.

Fig. 26 shows an enlargement of a frame from a ciné-record of one of the Sunderland landings. All the measurements mentioned above are clearly indicated thereon.

It will be obvious from the foregoing that the fact that the camera used was equipped to traverse in a vertical plane was more of a hindrance than a help—the notch system for measuring elevation was not sufficiently accurate to be useful and recourse had to be had to referring readings to an imaginary and very arbitrary plane.

It is therefore suggested that in any future use that is made of this method the plane of reference should be fixed as the horizontal plane by using a camera, fitted with a notch system to measure azimuth angle, which is mounted on a horizontal base and which can traverse only in the horizontal plane. Height and attitude would then be measured in a very similar way to that described above, the only difference being that no reference would then be made to the horizon—in fact no horizon would be needed.

APPENDIX IV

An Estimate of the Effect of Flying Boat Size on the Landing Impact Curve

Let

l be a linear dimension (L),
V ,, speed of approach (LT^{-1}),
v ,, kinematic viscosity (L^2T^{-1}),
σ ,, density of the flying boat hull (assuming all mass concentrated in the hull) (ML^{-3}),
ϱ ,, density of water (ML^{-3}),

then, assuming the above to be the only variables affecting the impact we may write,

$$\text{Water reaction } (MLT^{-2}) = l^a V^b v^c \sigma^d \varrho^e.$$

Equating powers we have

$$d + e = 1,$$
$$a + b + 2c - 3d - 3e = 1,$$
$$b + c = 2,$$

therefore, $a + c = 2.$

Hence

$$\text{Water reaction} = l^{2-c}\, V^{2-c}\, v^c \sigma^d \varrho^{1-d}$$
$$= \varrho l^2 V^2 \cdot f\left(\frac{v}{lV}, \frac{\sigma}{\varrho}\right).$$

Similarly it may be shown that

$$\text{Time to reach maximum reaction} = \frac{l}{V} f\left(\frac{v}{lV}, \frac{\sigma}{\varrho}\right).$$

If we neglect scale effect v/lV and assume that we are dealing with scale models so that σ/ϱ is constant we may say, roughly speaking

$$\text{Reaction} \quad \propto l^2V^2$$

$$\text{Time to maximum} \propto \frac{l}{V}\,.$$

Since the mass of the boat, assuming scale models, is proportional to l^3, the acceleration experienced by the boat is proportional to V^2/l

$$\left.\begin{array}{l} i.e., \text{ Acceleration } \propto \dfrac{V^2}{l} \\[2ex] \text{Time to maximum} \propto \dfrac{l}{V} \end{array}\right\} \begin{array}{l} \text{also since } W, \text{ the weight of} \\ \text{the boat, } \propto l^3 \end{array} \left\{\begin{array}{l} \text{Acceleration} \\ \quad \propto \dfrac{V^2}{W^{1/3}} \\[2ex] \text{Time to} \\ \text{maximum} \propto \dfrac{W^{1/3}}{V} \end{array}\right.$$

Thus, for landings at the same speed, with of course non-dimensional quantities such as attitude and angle of flight path kept the same, roughly speaking the acceleration is inversely proportional to and the time to maximum acceleration proportional to the linear dimensions of the boat, *i.e.*, to (Weight of the boat)$^{1/3}$. The periodic time of oscillation of the wings is proportional to (Mass/Stiffness)$^{1/2}$. For scale models:—Mass is proportional to l^3 and Stiffness to l. Thus periodic time is proportional to l, *i.e.*, $W^{1/3}$.

Obviously, for actual flying boats of different sizes, which are by no means scale models, these results will not hold but they are useful in that they enable an idea to be obtained of how the relations between maximum deceleration, time of build-up and periodic time will alter with size.

It can be said from the above that little change with size of flying boat is to be expected in the basic shape of the impact curve, although its proportions may alter, and also that the ratio of periodic time to time of build-up will remain approximately constant.

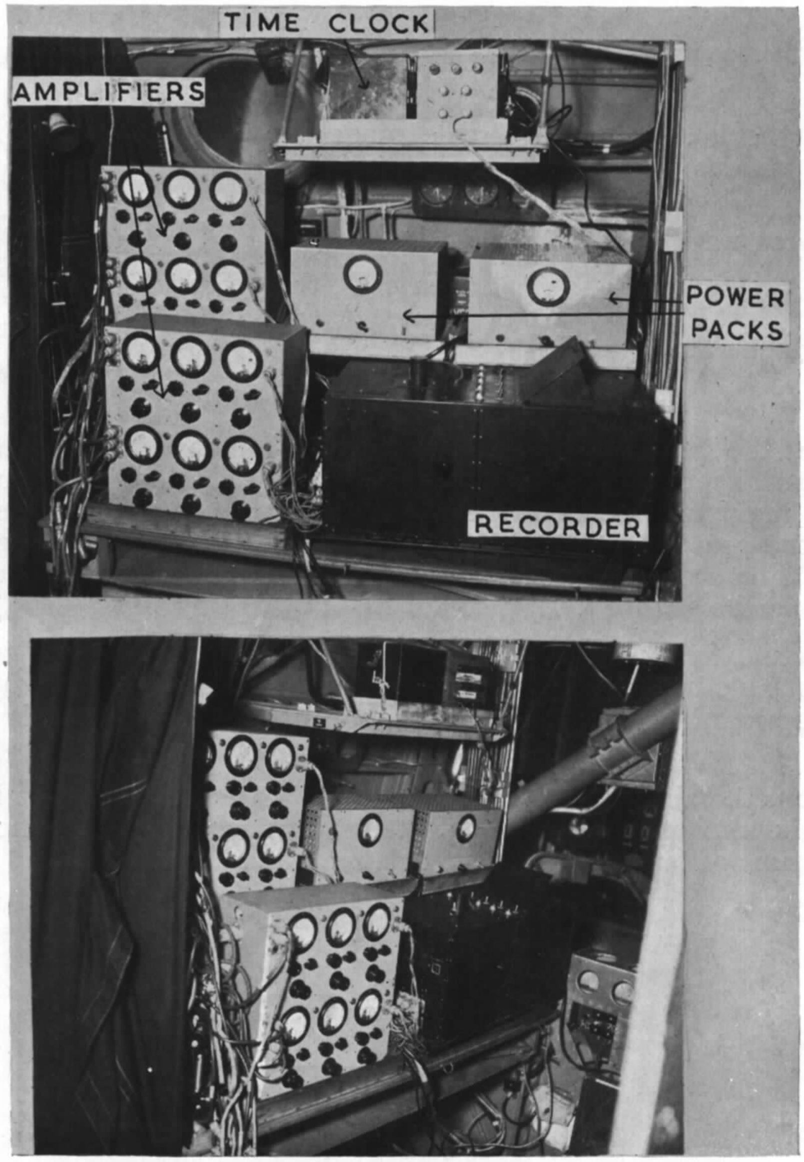


FIG. 1. Miller equipment installed in the Sunderland.

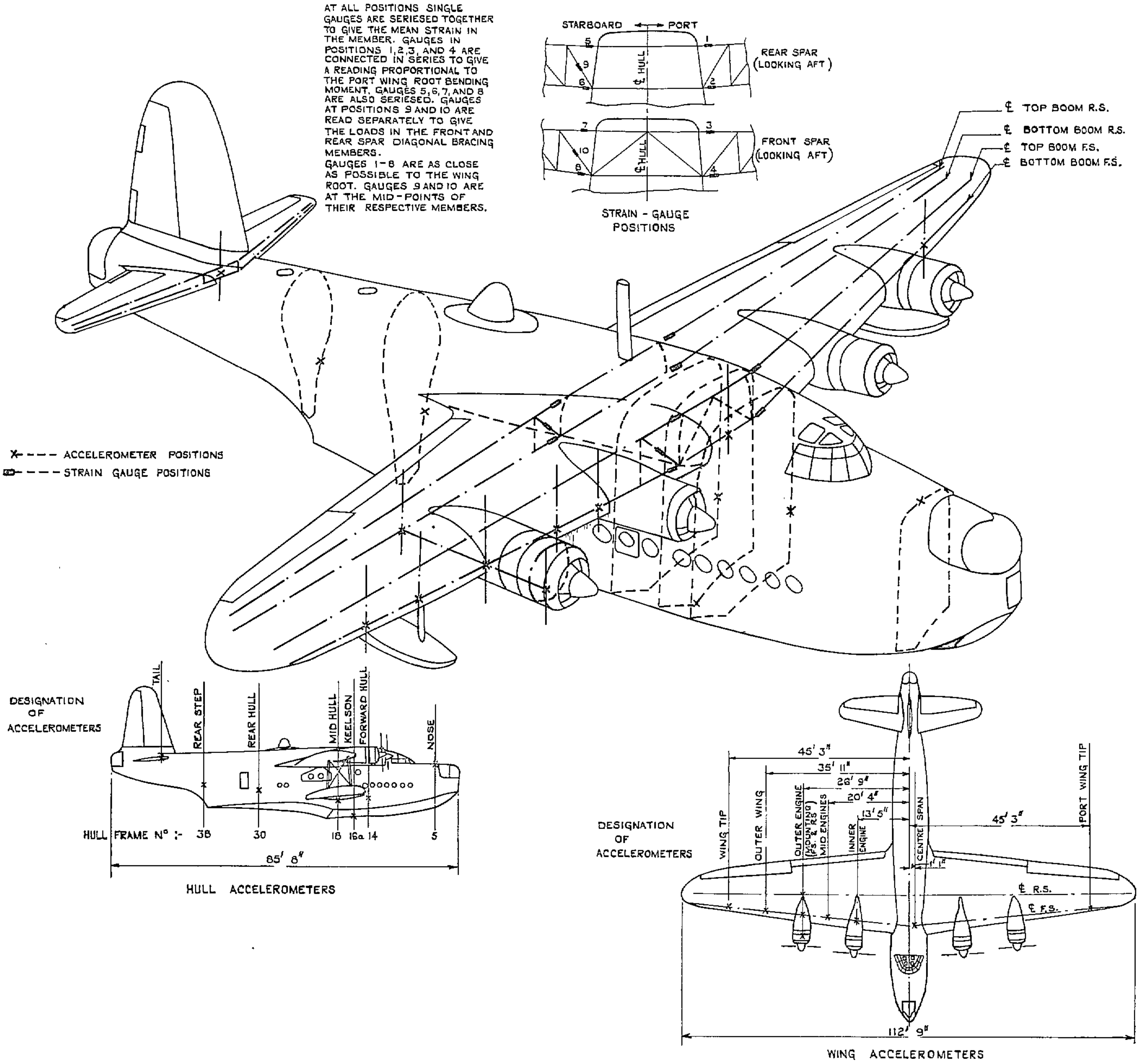


FIG. 2. Sunderland Mk. V. TX 293.—Accelerometer and strain-gauge positions.

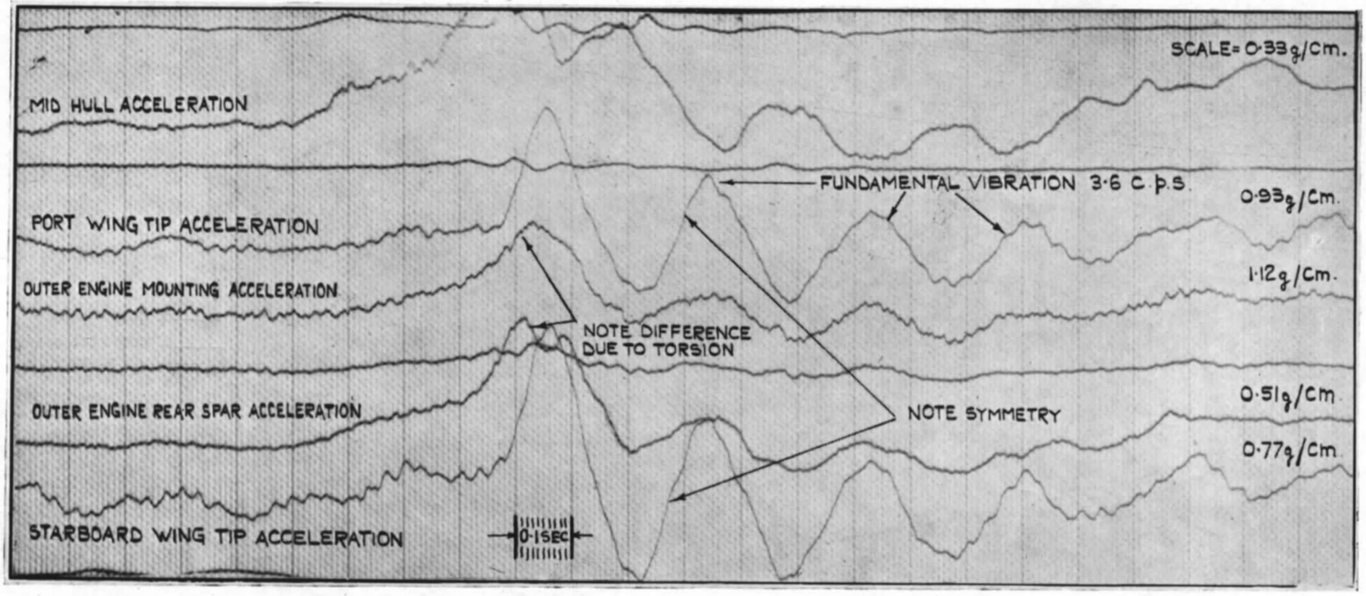


FIG. 3. Accelerations recorded for stalled landing number 3 (second bounce), showing symmetry of port and starboard wing tip vibration and difference between outer engine mounting and outer engine rear spar acceleration due to torsion.

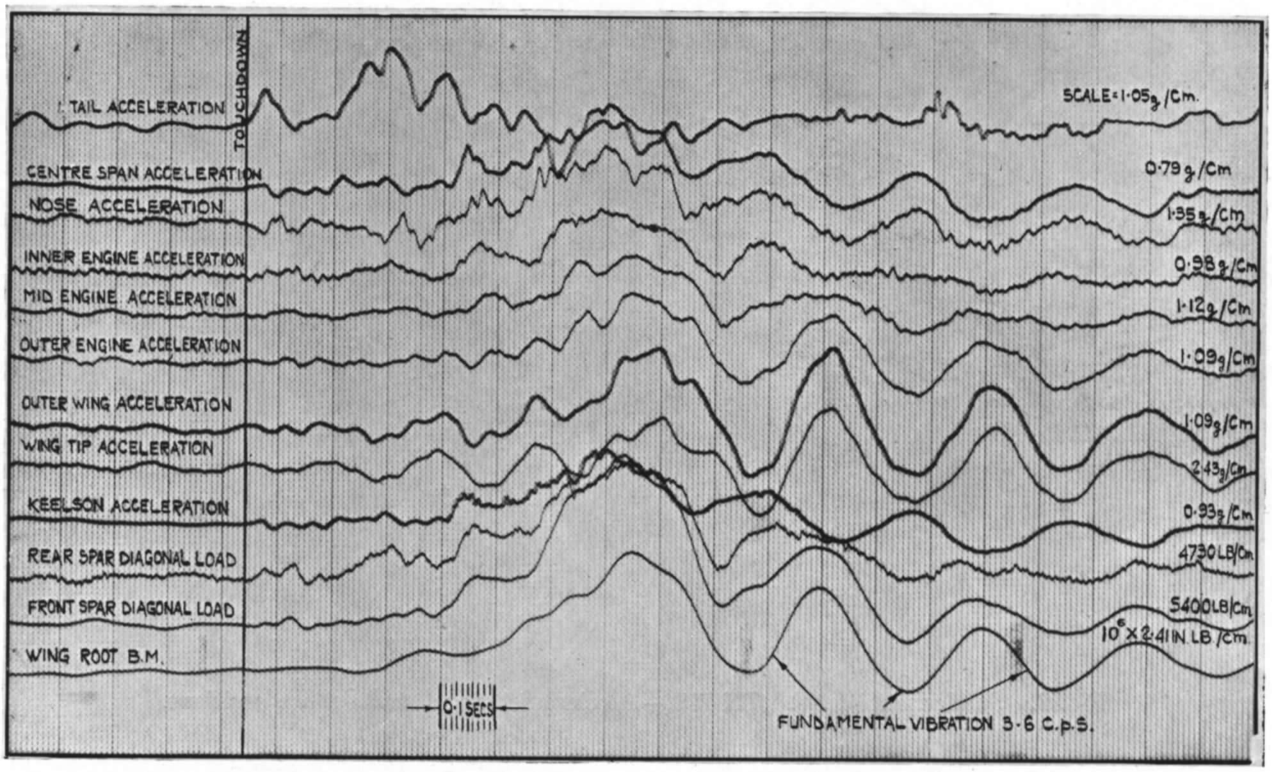


FIG. 4. Strains and accelerations recorded for stalled landing number 27 (first bounce). Example of fundamental vibration of wing (amplitudes adjusted as shown for convenience of presentation).

Note: For FIGS. 3 to 12, multiply scales at right-hand side by 3/2 to allow for the reduction of the originals.

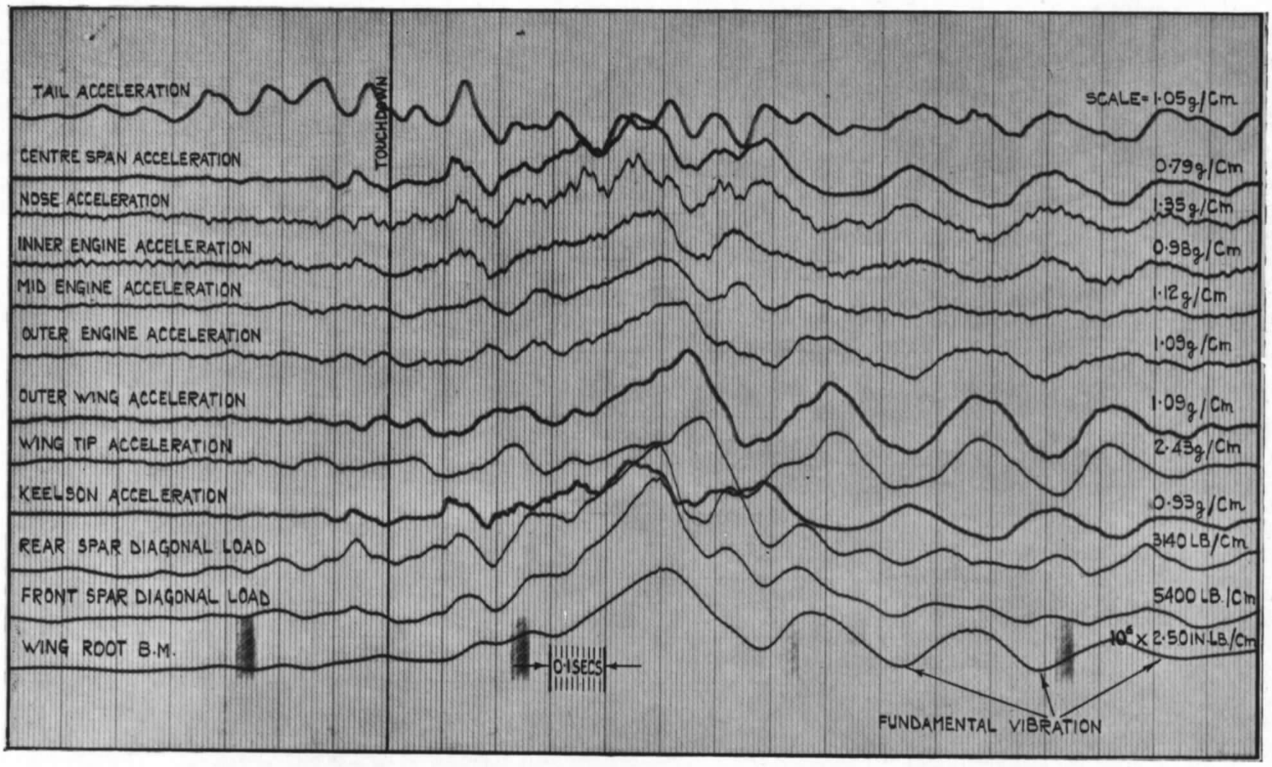


FIG. 5. Strains and accelerations recorded for stalled landing number 23 (first bounce). Example of fundamental vibration of wing (amplitudes adjusted as shown for convenience of presentation).

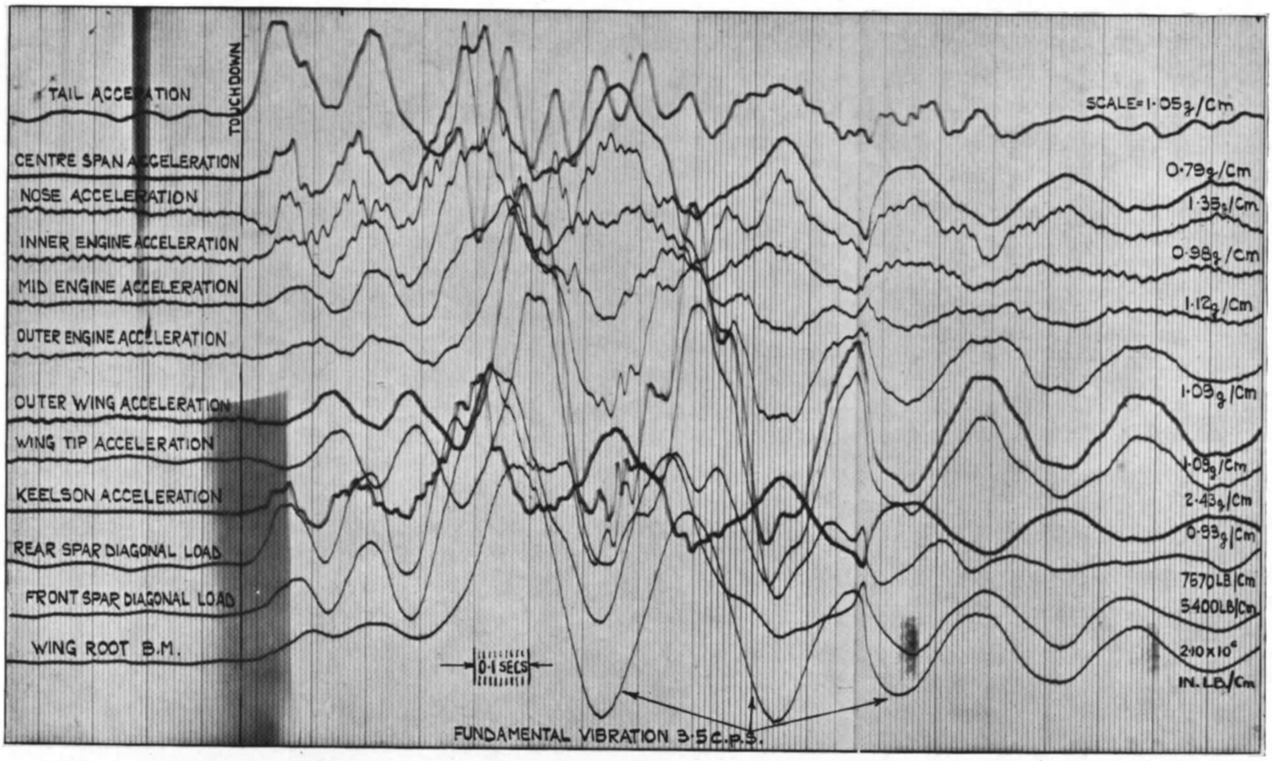


FIG. 6. Strains and accelerations recorded for stalled landing number 22 (first bounce). Example of a very heavy stalled landing showing wing fundamental vibration (amplitudes adjusted as shown for convenience of presentation).

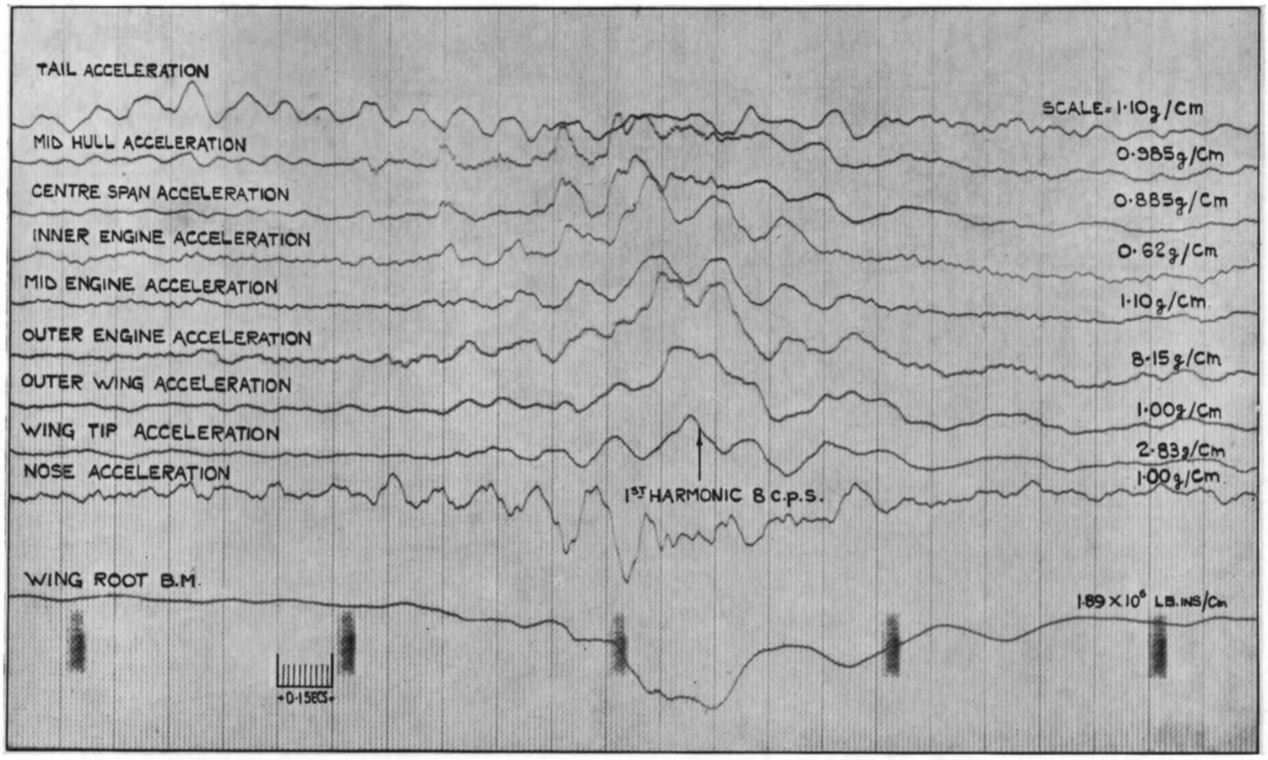


FIG. 7. Strains and accelerations recorded for stalled landing number 14 (first bounce—rear step landing). Example of light stalled landing showing first harmonic wing vibration.

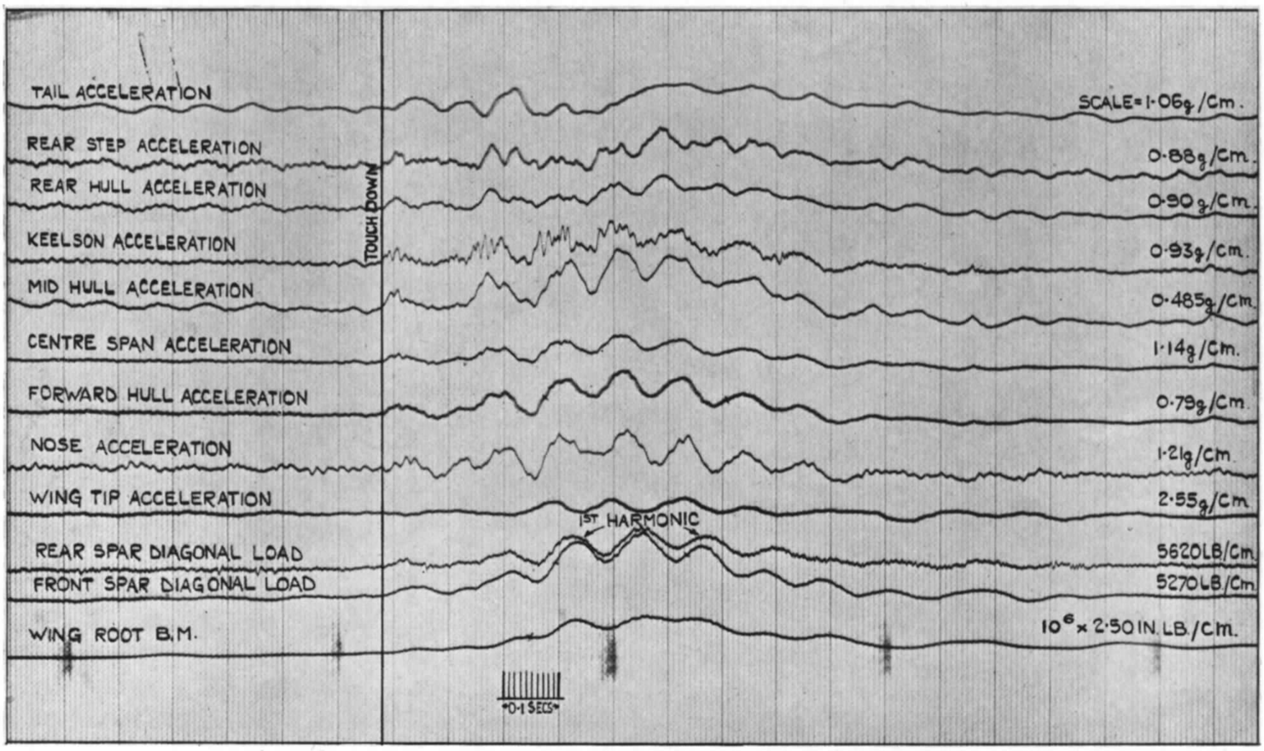


FIG. 8. Strains and accelerations recorded for fly-on landing number 31 (first bounce). Record of hull accelerations and wing strain-gauges showing first harmonic present in light landings.

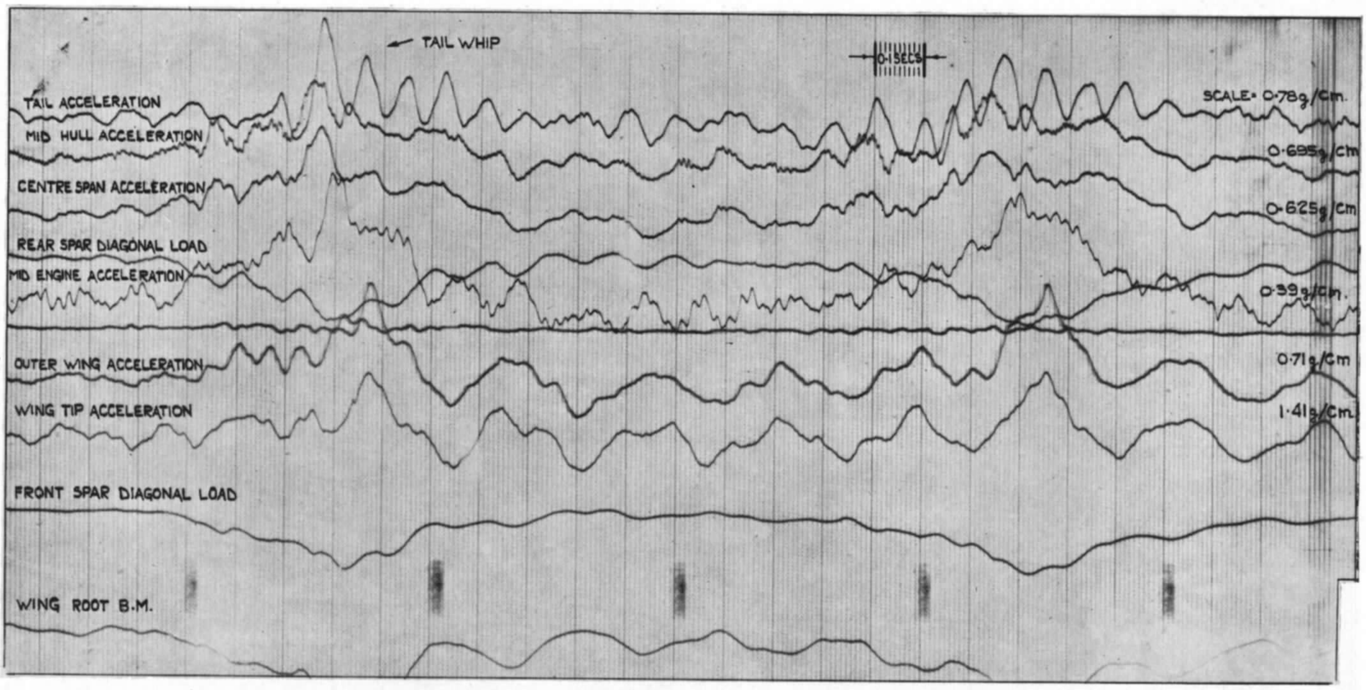


Fig. 9. Strains and accelerations recorded for fly-on landing number 10 (second and third bounces). Example of ' tail whip '.

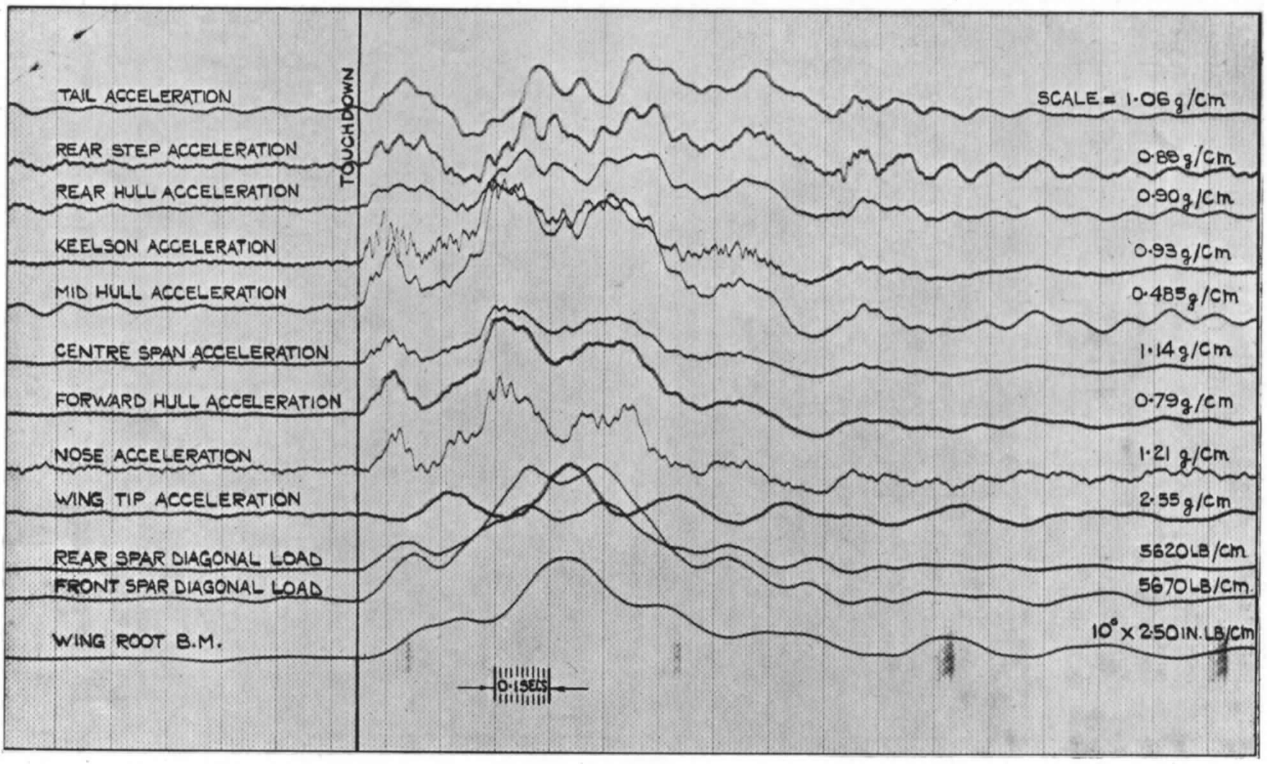


Fig. 10. Strains and accelerations recorded for fly-on landing number 32 (first bounce). Record of hull accelerations and wing root strain-gauge measurements.

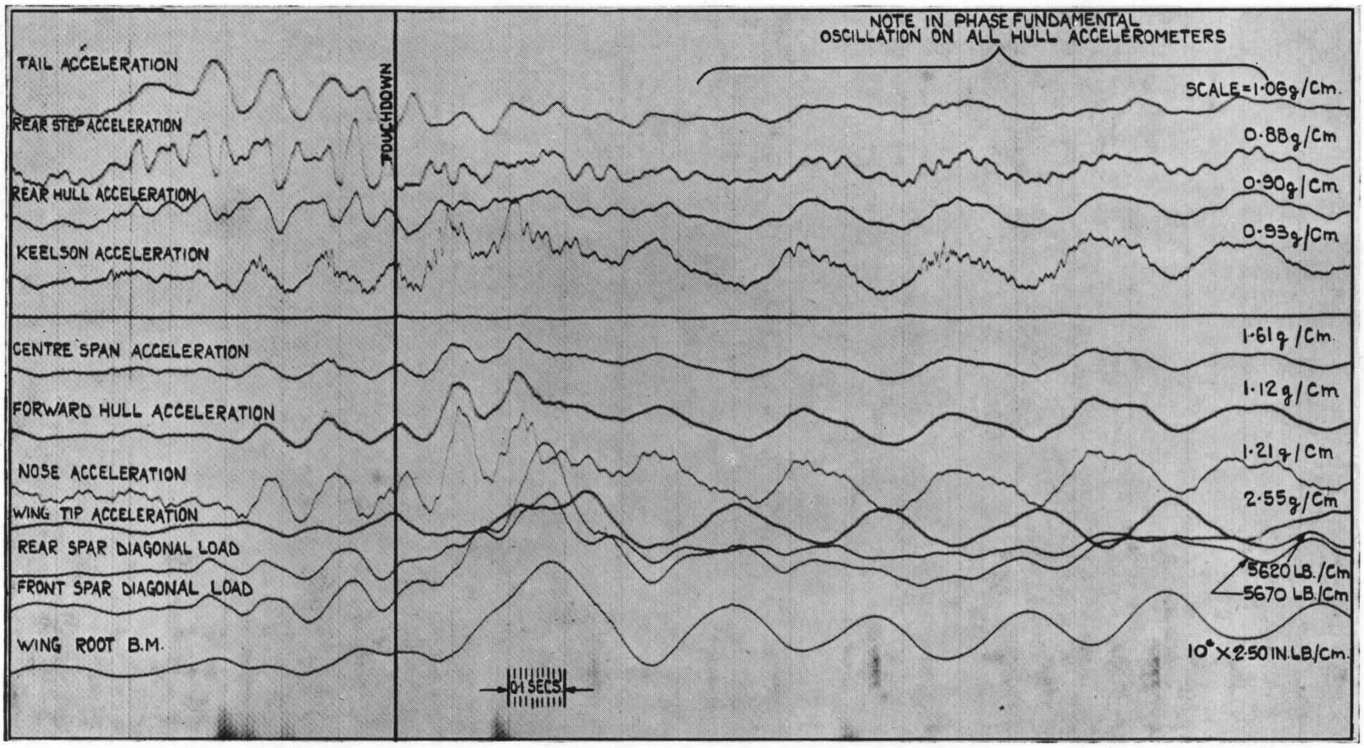


FIG. 11. Strains and accelerations recorded for stalled landing number 29 (second bounce). Record of hull accelerations and wing root strain-gauge measurements.

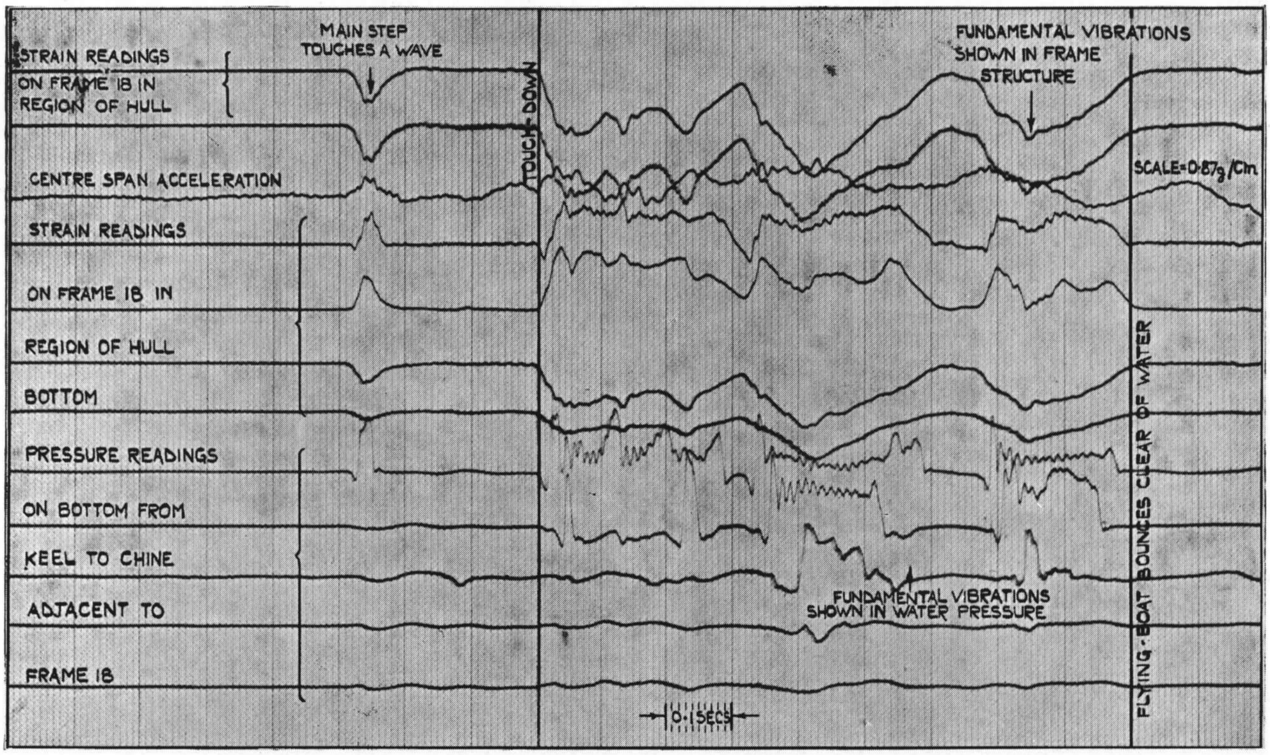


FIG. 12. Strains and accelerations recorded for fly-on landing number 40 (second bounce). Example of strain-gauge readings on hull bottom and frame 18 showing effect of hitting a wave on entry and pressure on hull bottom due to motion of hull in wing fundamental vibration.

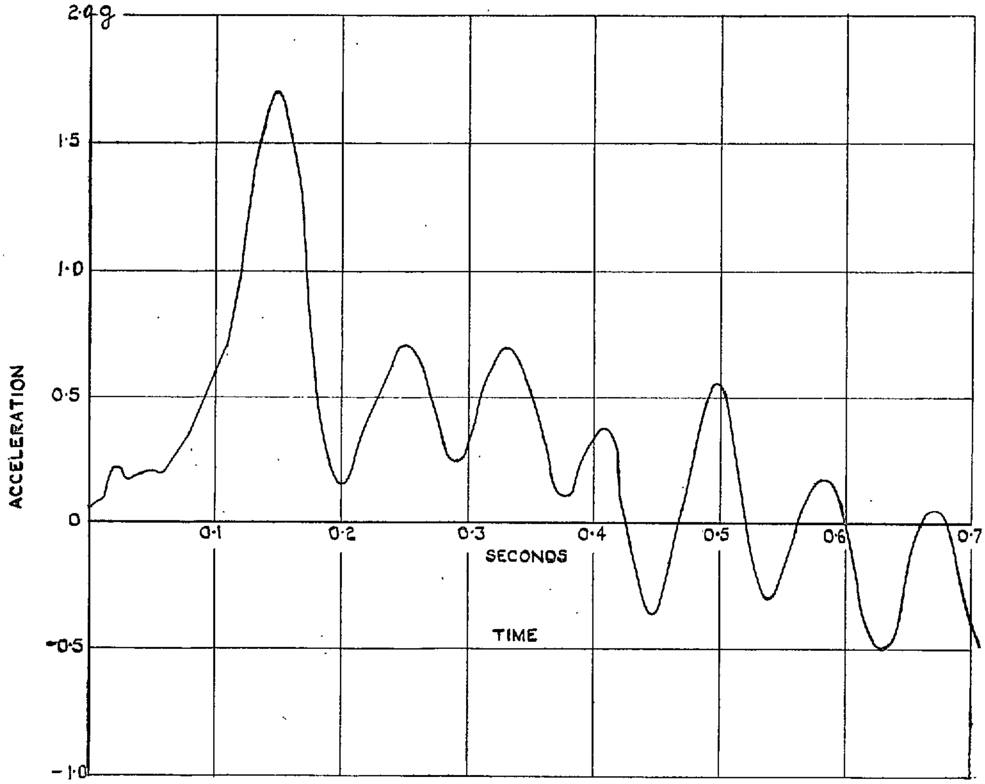


FIG. 13. Typical ' tail whip '.
Note: All accelerations are incremental, *i.e.*, 0*g* corresponds to level flight.

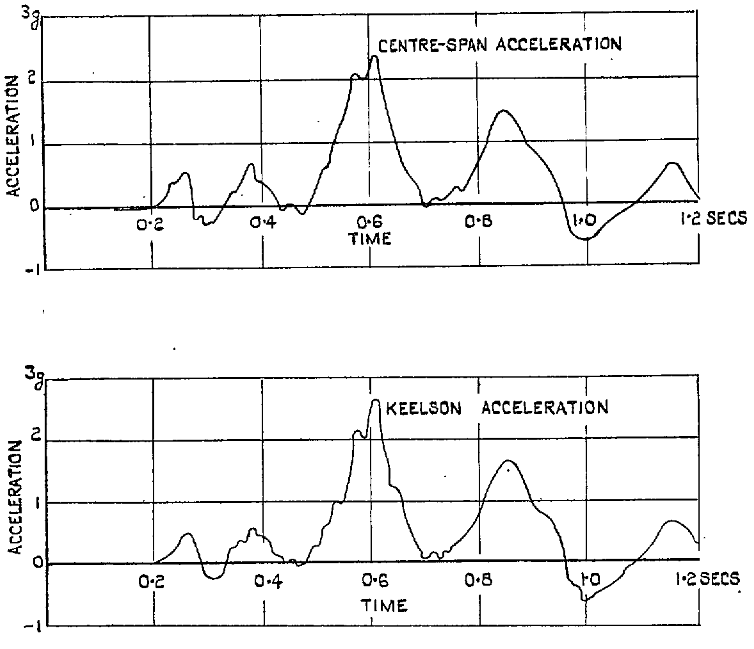


FIG. 14. Similar accelerations obtained on front spar centre-span and keelson (landing number 22).
Note: All accelerations are incremental, *i.e.*, 0*g* corresponds to level flight.

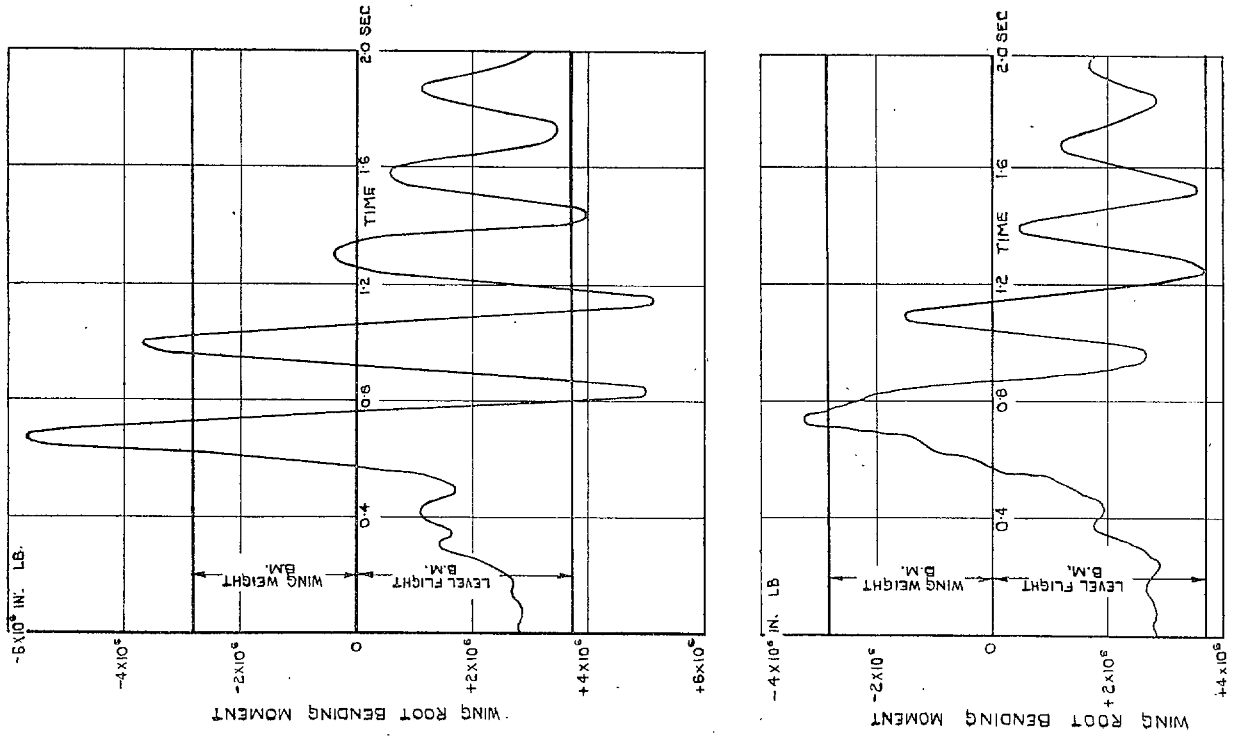


FIG. 15. Wing root bending moments during a 1·75 and a 1·25g landing—examples of fundamental vibration.
Note: The above accelerations are incremental and 1g must be added to obtain absolute accelerations.

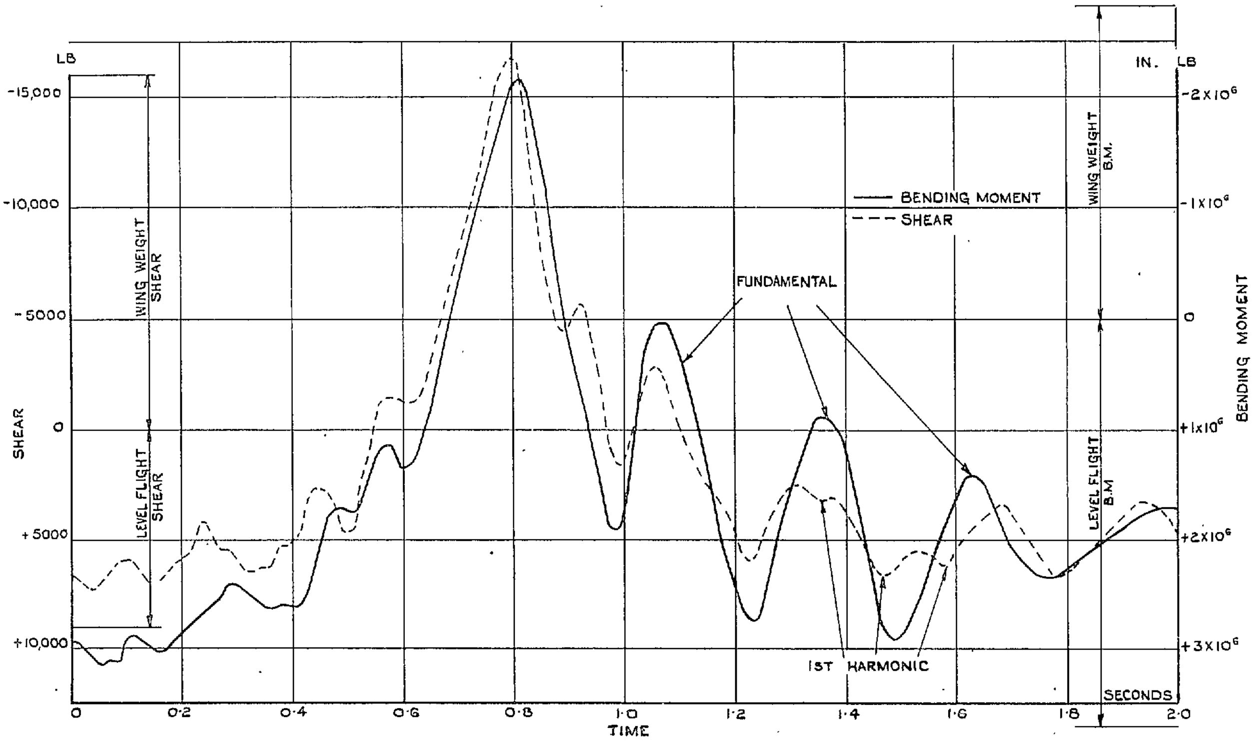


FIG. 16. Wing root bending moment and shear during a 1·1g landing.

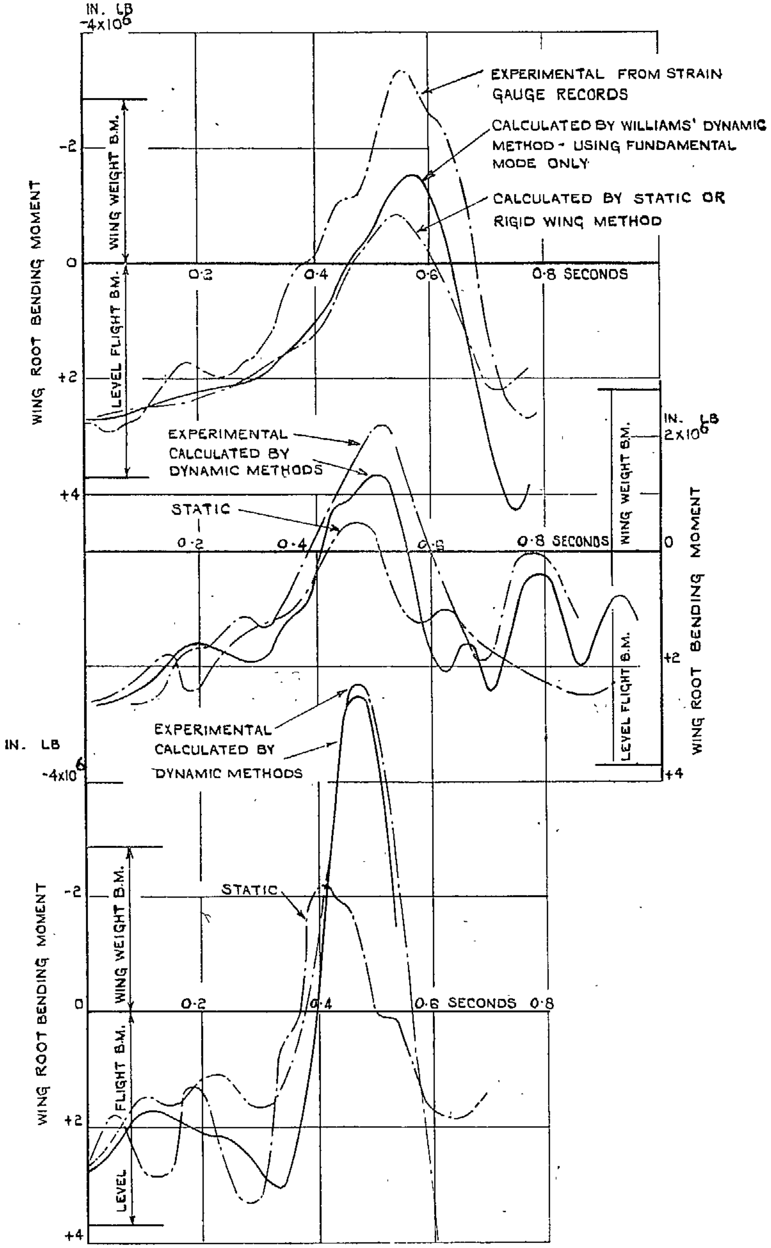


FIG. 17. Comparison of experimental and calculated wing root bending moments (stalled landings numbers 27, 23 and 22).

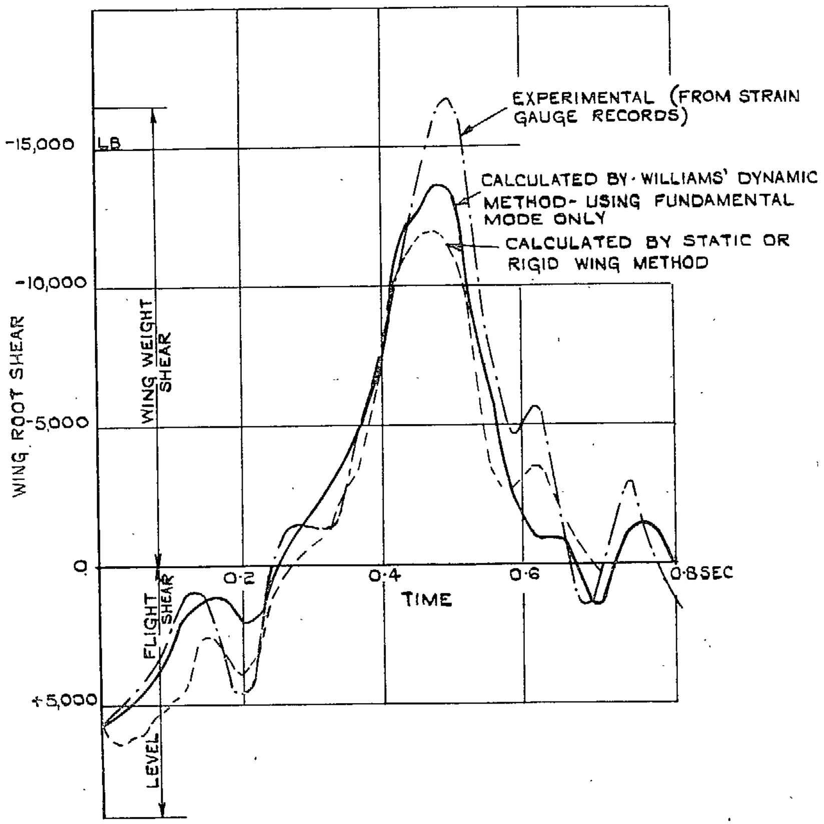


FIG. 18. Comparison of experimental and calculated wing root shears (stalled landing number 23).

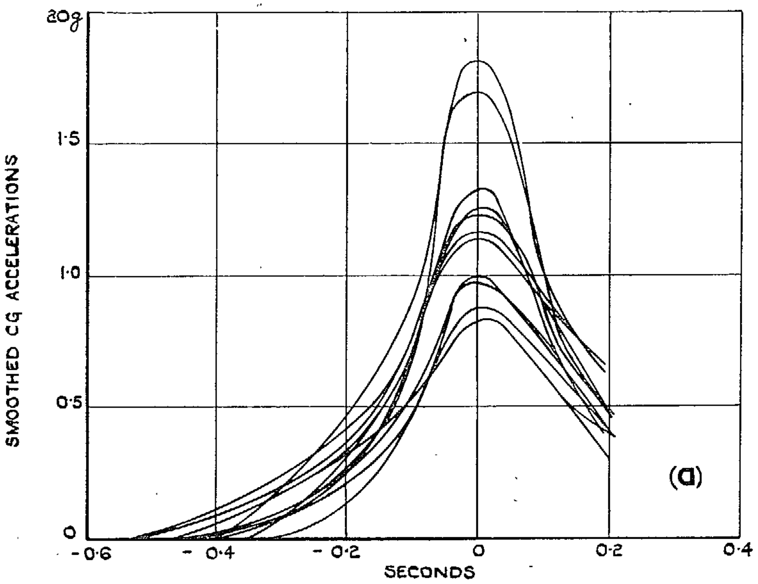


FIG. 19a. Smoothed impact acceleration-time curves from Sunderland landings.

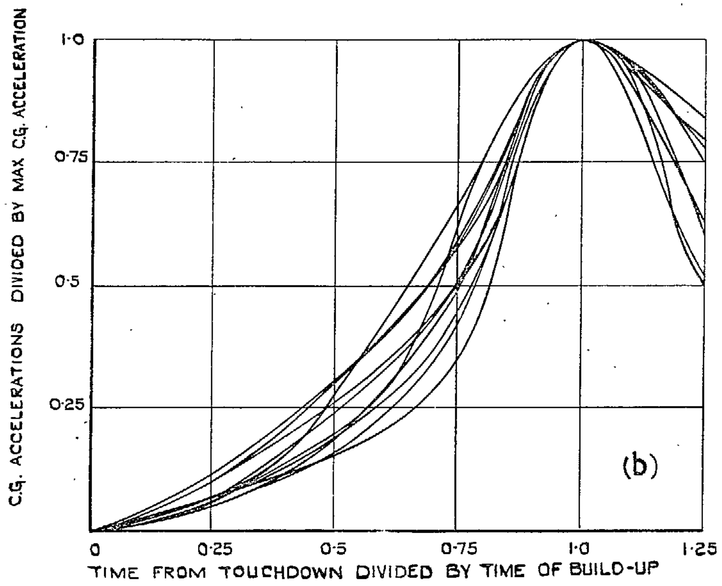


FIG. 19b. Derived non-dimensional curves showing similarity of basic shapes.

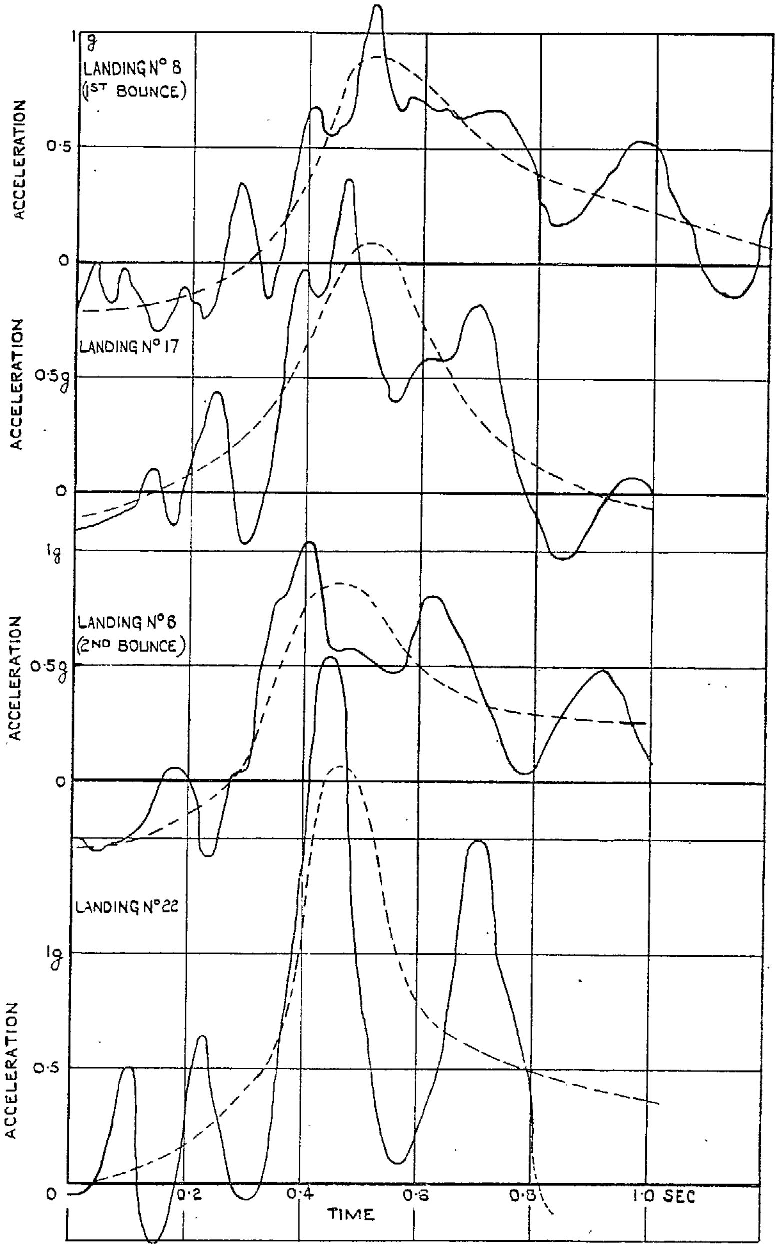


FIG. 20. Comparison of c.g. acceleration (obtained by elimination of normal modes) with centre-span acceleration for landings numbers 8 (first bounce), 17, 8 (second bounce), and 22.

Note: All accelerations are incremental, *i.e.*, 0g corresponds to level flight.

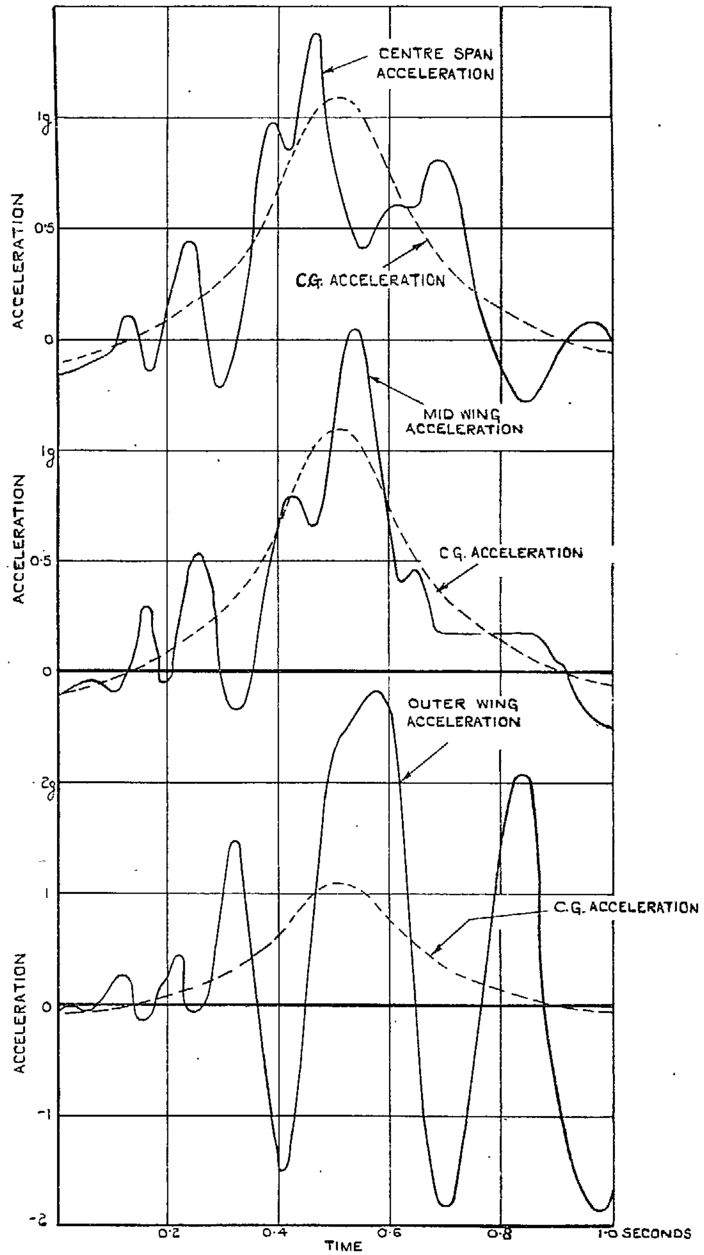


FIG. 21. Comparison of c.g. acceleration with centre-span, mid-wing and outer-wing accelerations for landing number 17. Note: All accelerations are incremental, *i.e.*, 0*g* corresponds to level flight.

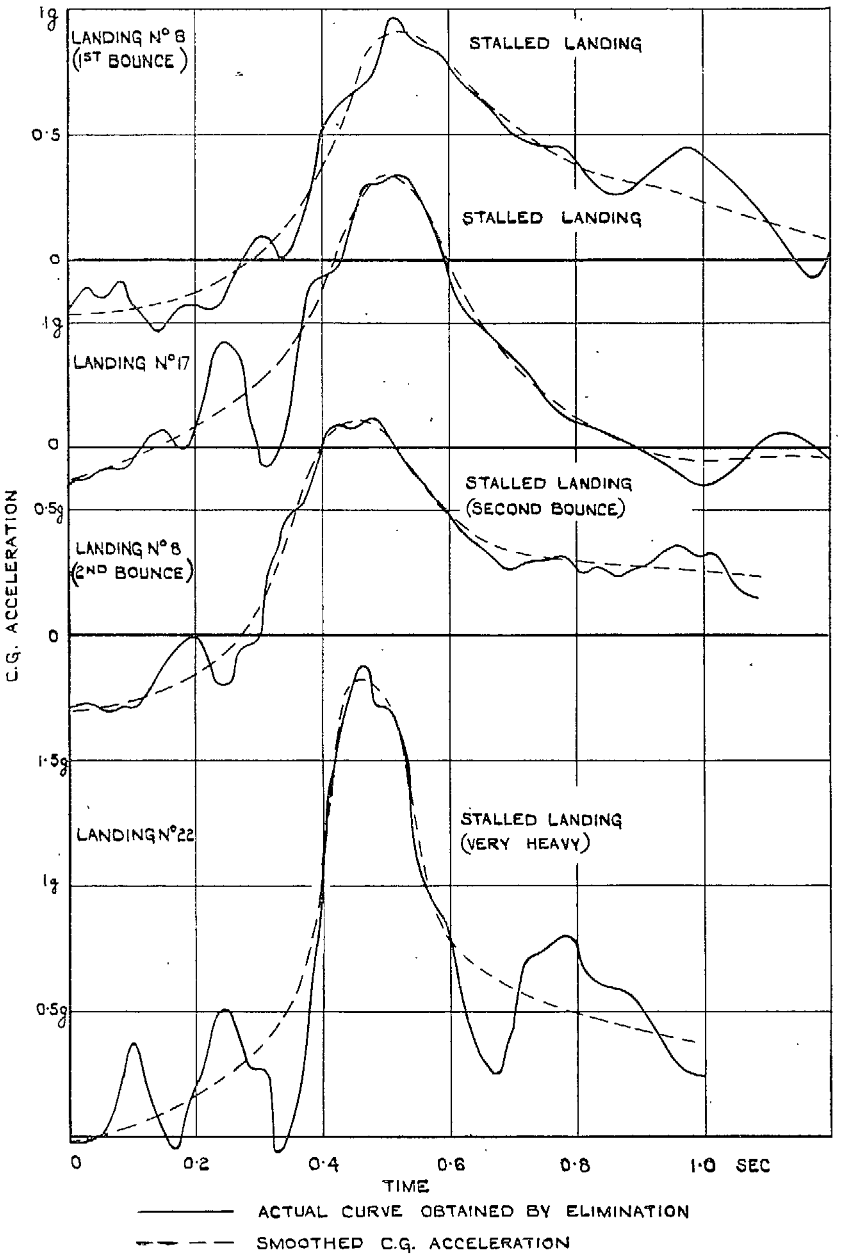


FIG. 22. C.G. accelerations obtained by elimination of normal modes, landings numbers 8 (first bounce), 17, 8 (second bounce), and 22. Note: All accelerations are incremental, *i.e.*, 0*g* corresponds to level flight.

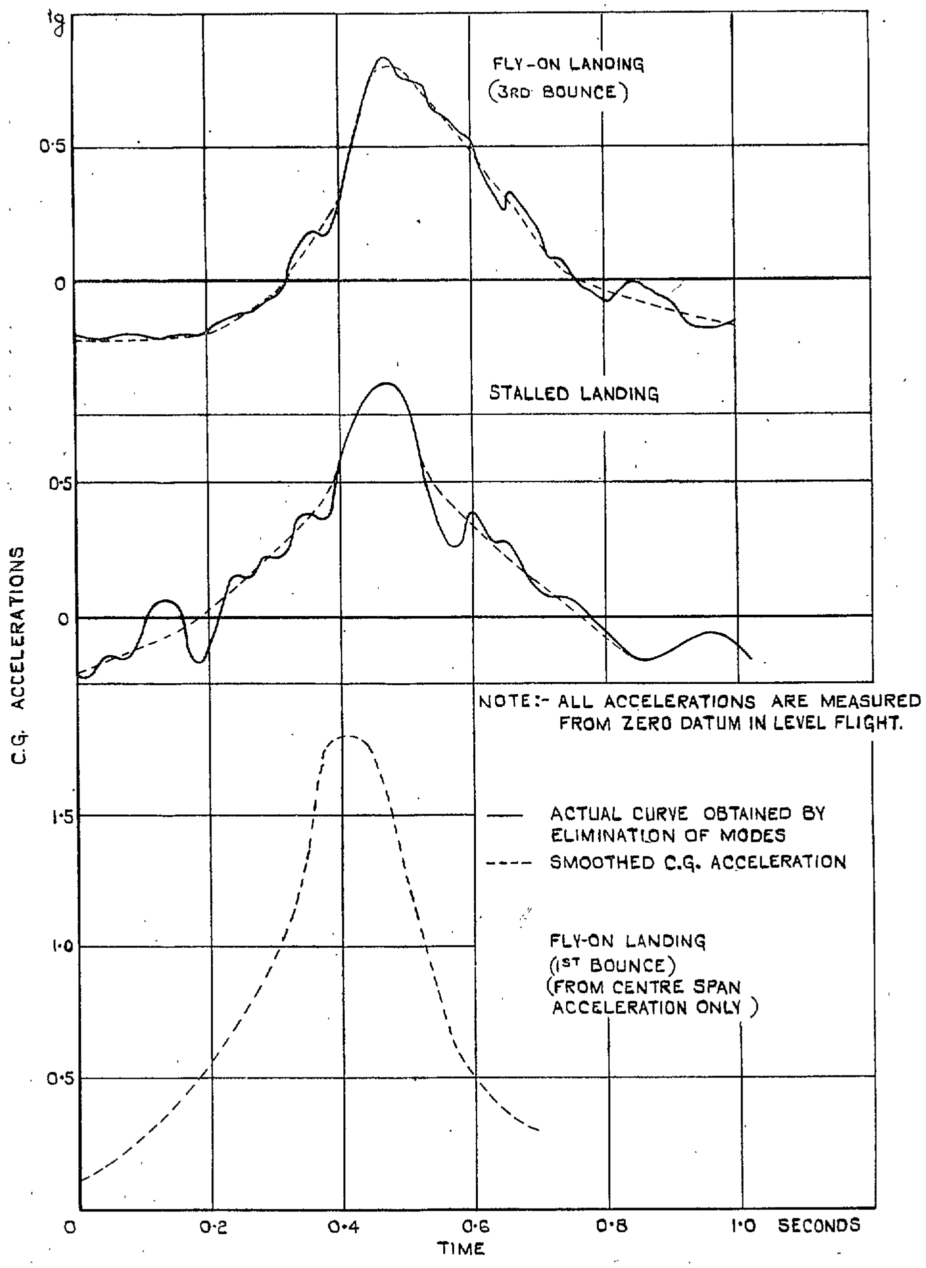
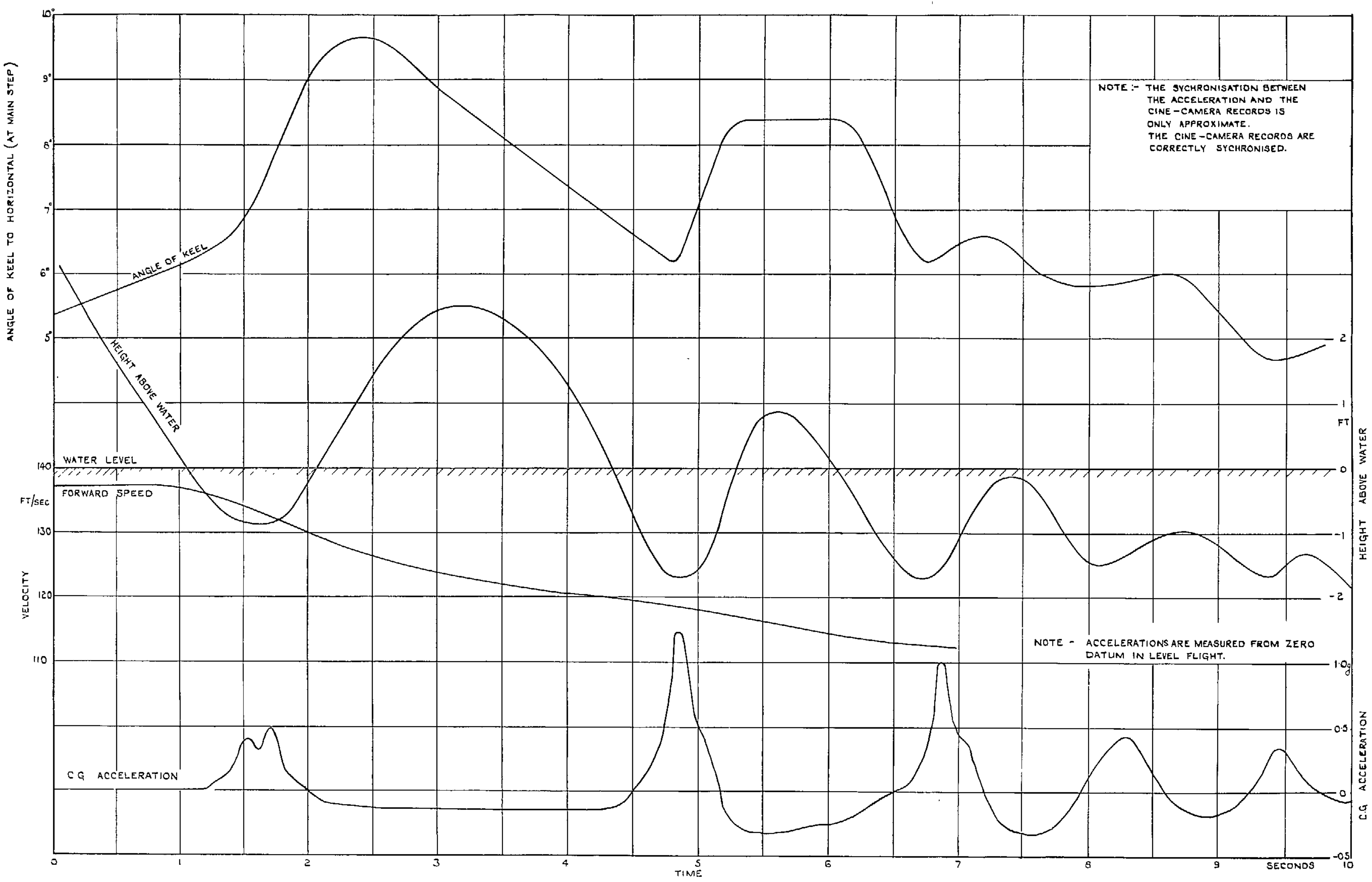


FIG. 23. C.G. accelerations obtained by elimination of normal modes.



NOTE :- THE SYCHRONISATION BETWEEN THE ACCELERATION AND THE CINE-CAMERA RECORDS IS ONLY APPROXIMATE. THE CINE-CAMERA RECORDS ARE CORRECTLY SYCHRONISED.

NOTE - ACCELERATIONS ARE MEASURED FROM ZERO DATUM IN LEVEL FLIGHT.

FIG. 24. Analysis of fly-on landing number 49.
Pitch, height above water level, and forward speed from ciné-camera records.
C.G. acceleration from Miller equipment.

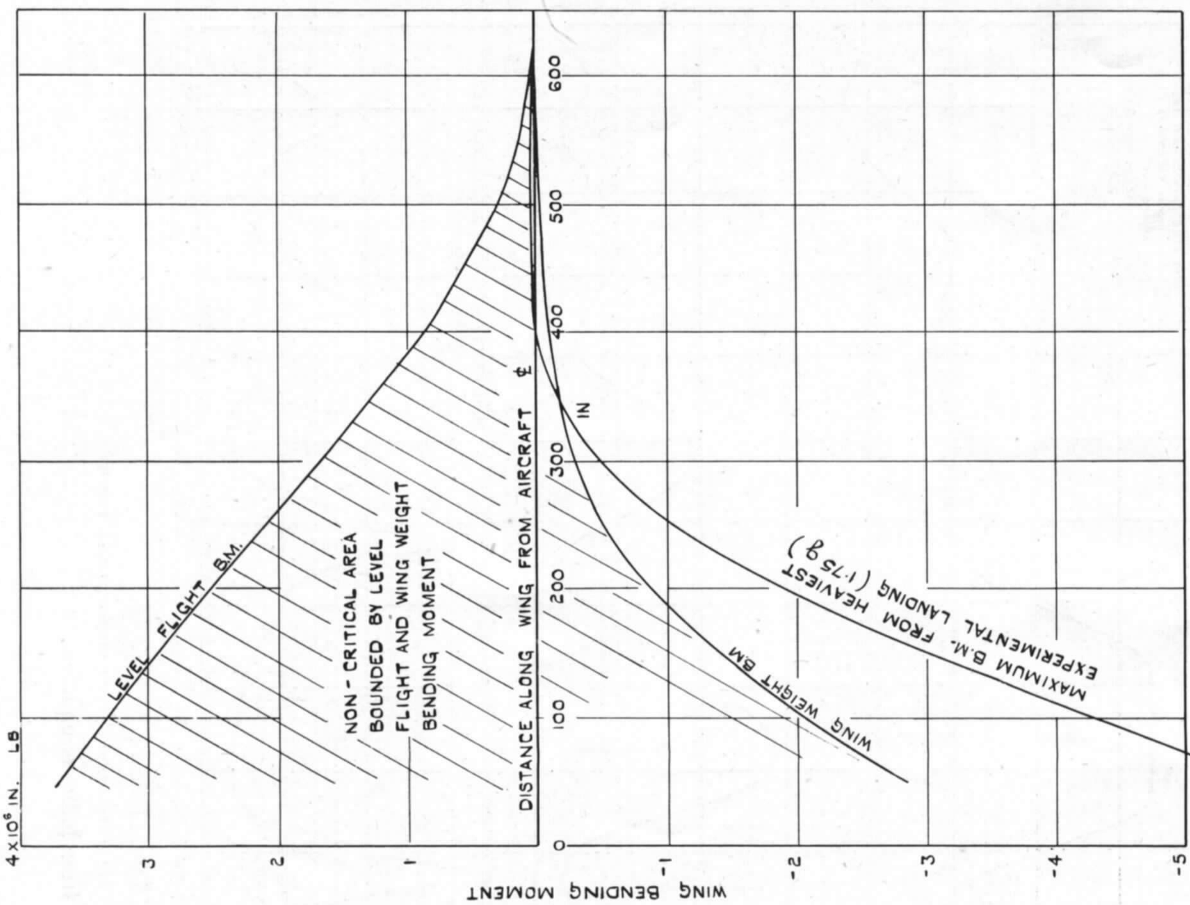
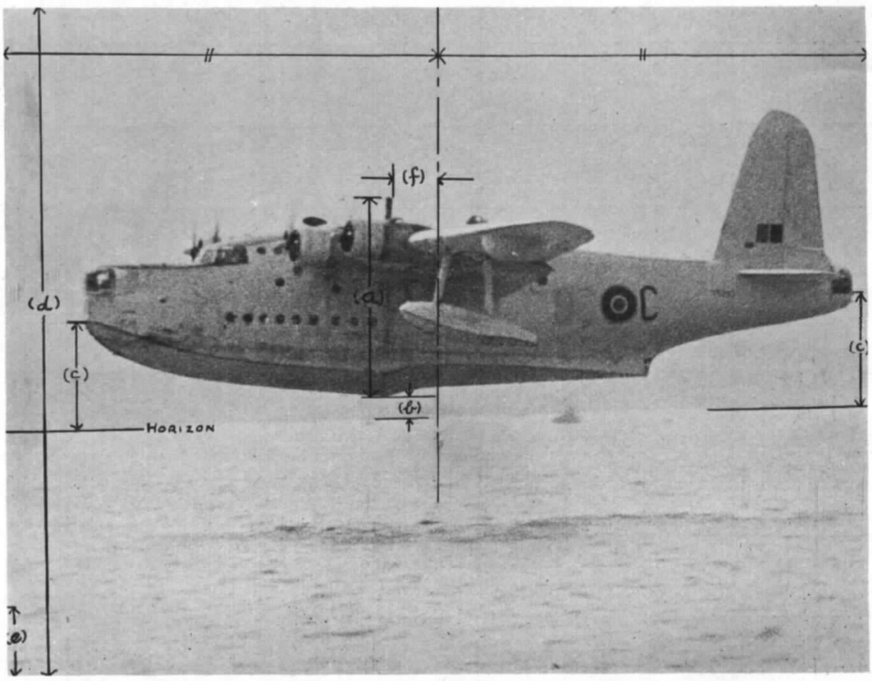


FIG. 25. Comparison of the greatest wing bending moment obtained during experimental landings with the level flight and wing weight bending moments.



Timing notch on film→

FIG. 26. Measurements taken from ciné-camera records of the Sunderland landings (enlargement of a frame from the records).

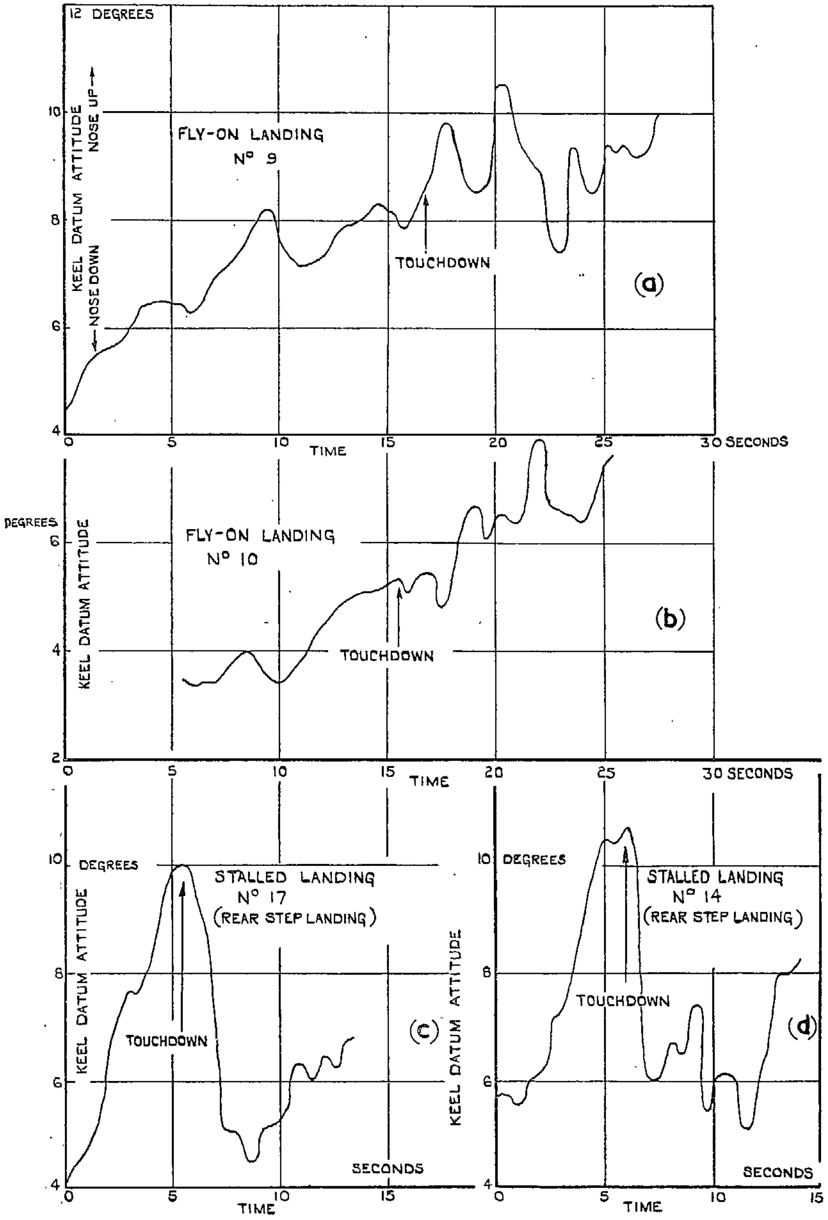


Fig. 27. Variation of attitude in fly-on and stalled landings (obtained from gyroscopic pitch recorder).

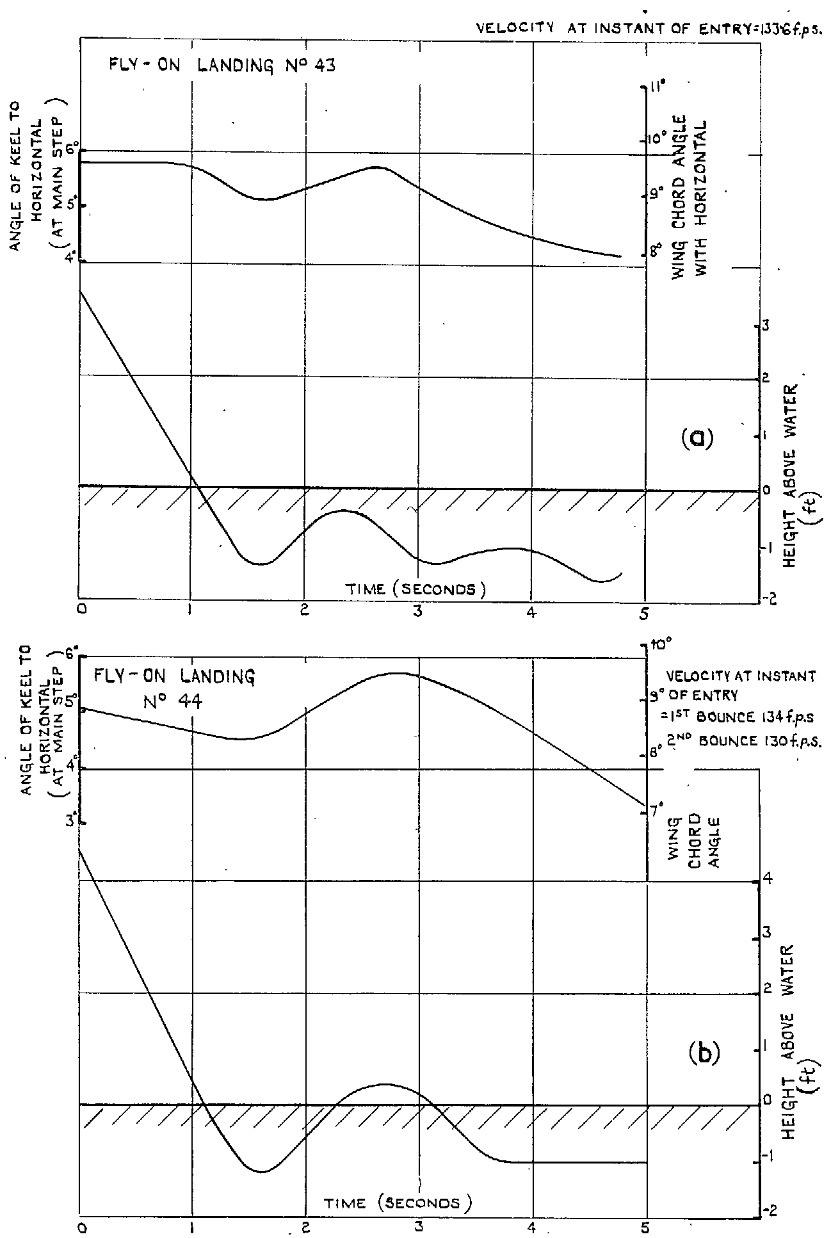
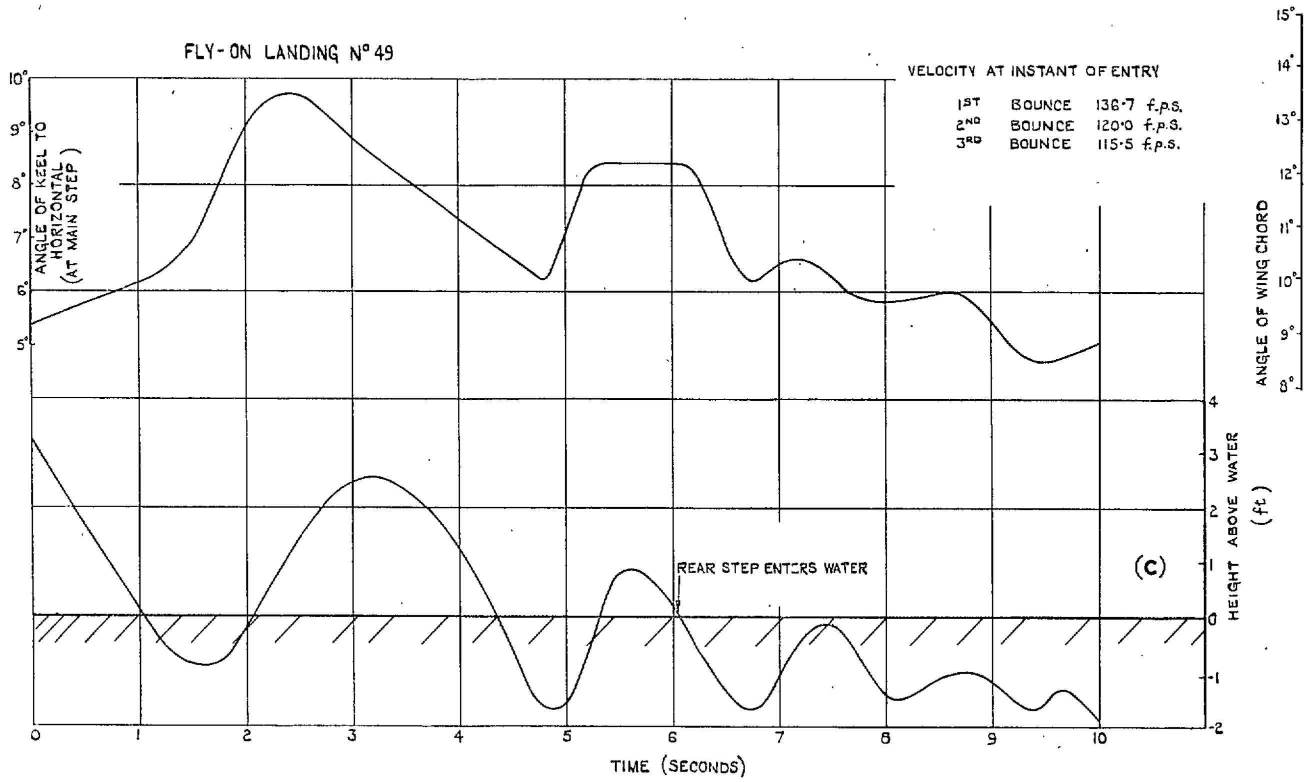


Fig. 28. Variation of attitude and height in fly-on and stalled landings (from ciné-camera records).



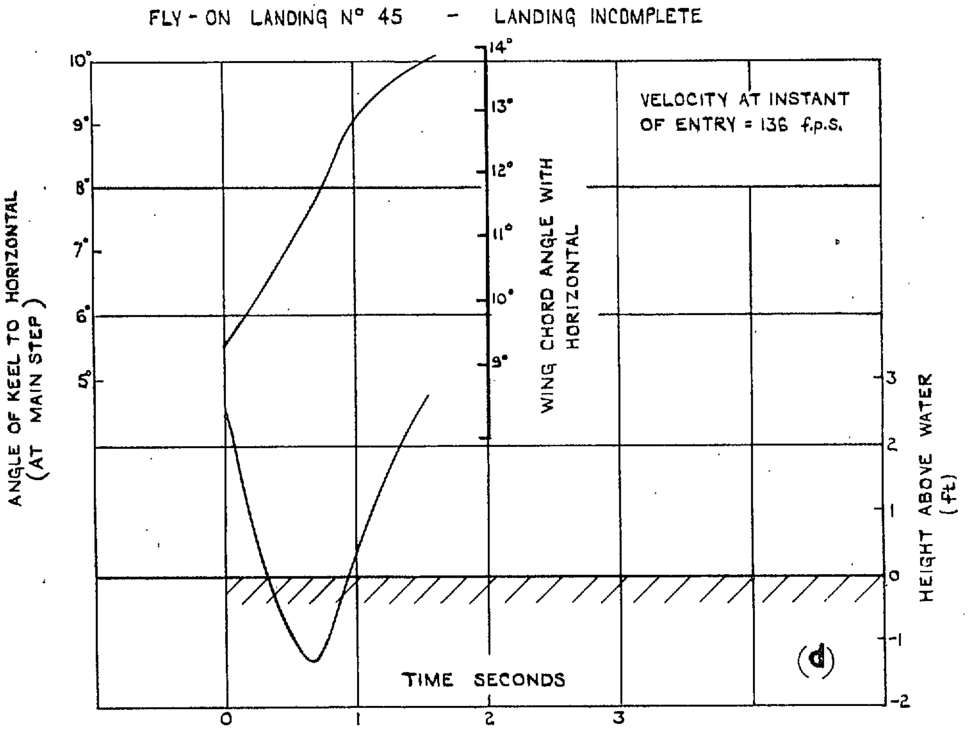
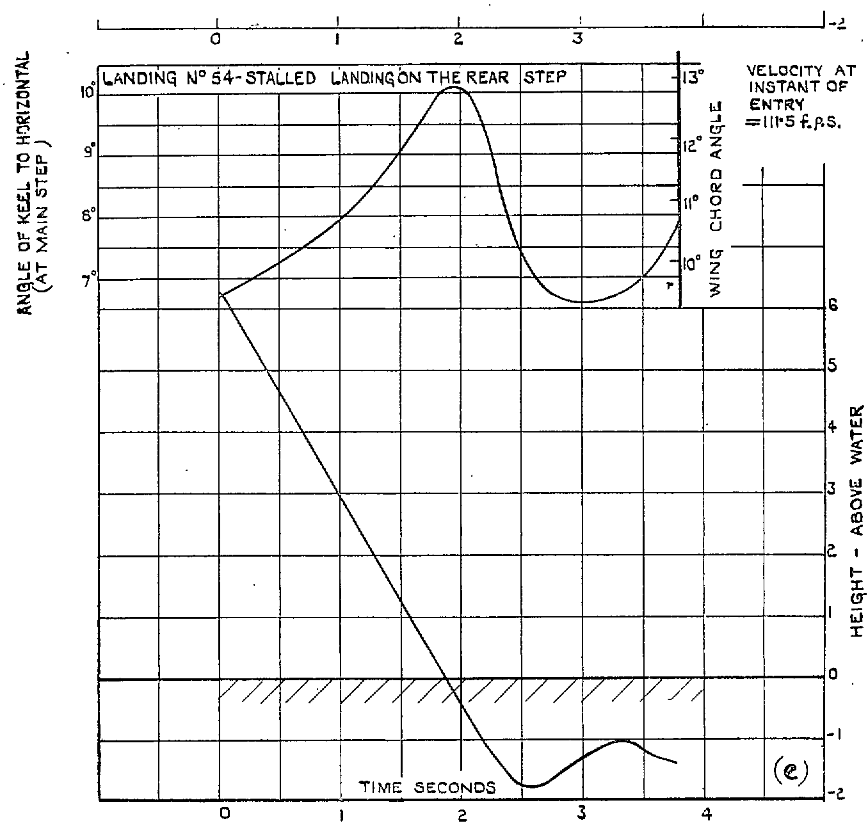


FIG. 28. Variation of attitude and height in fly-on and stalled landings (from ciné-camera records)—continued.



STALLED LANDING N° 42

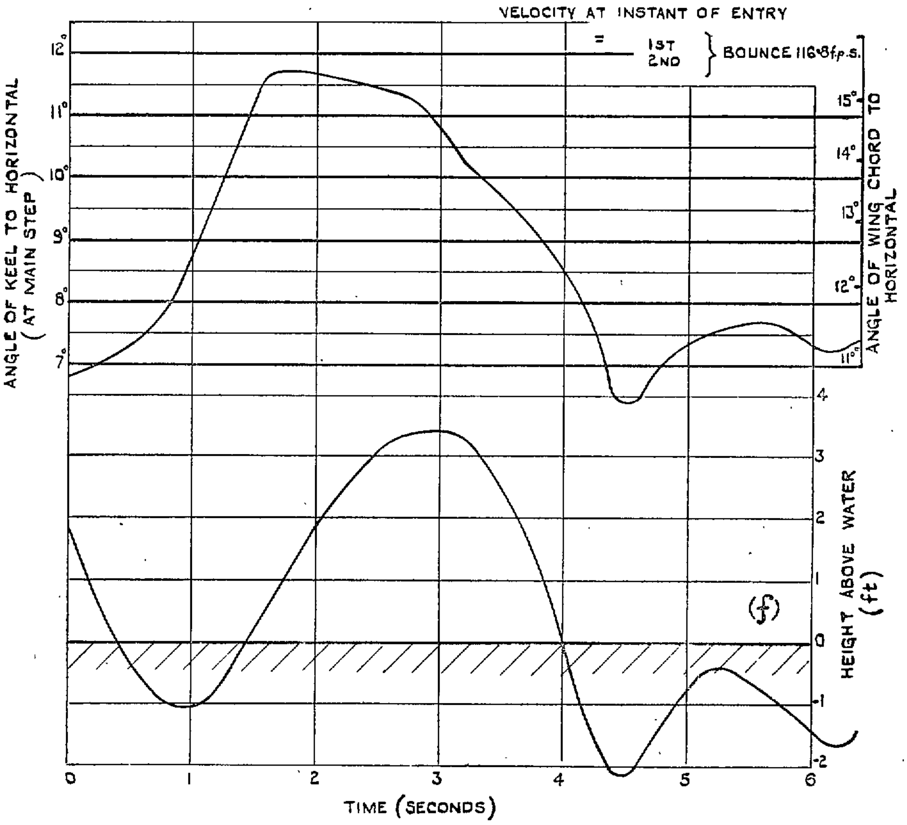


FIG. 28. Variation of attitude and height in fly-on and stalled landings (from ciné-camera records)—continued.

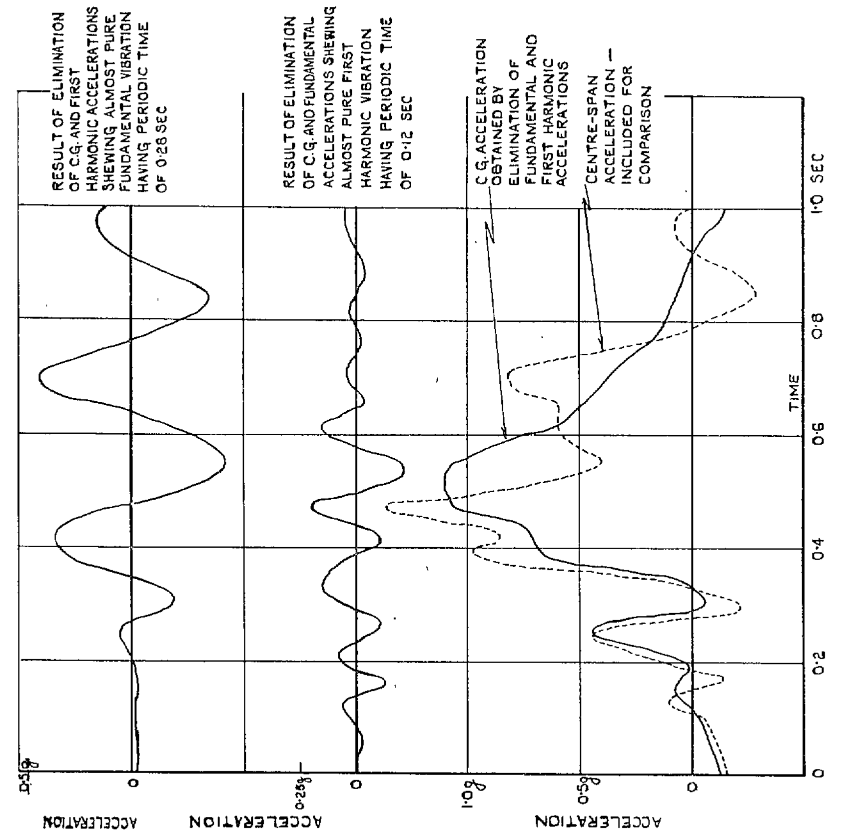


FIG. 29. C.G., fundamental and first harmonic accelerations obtained by elimination for landing number 17.

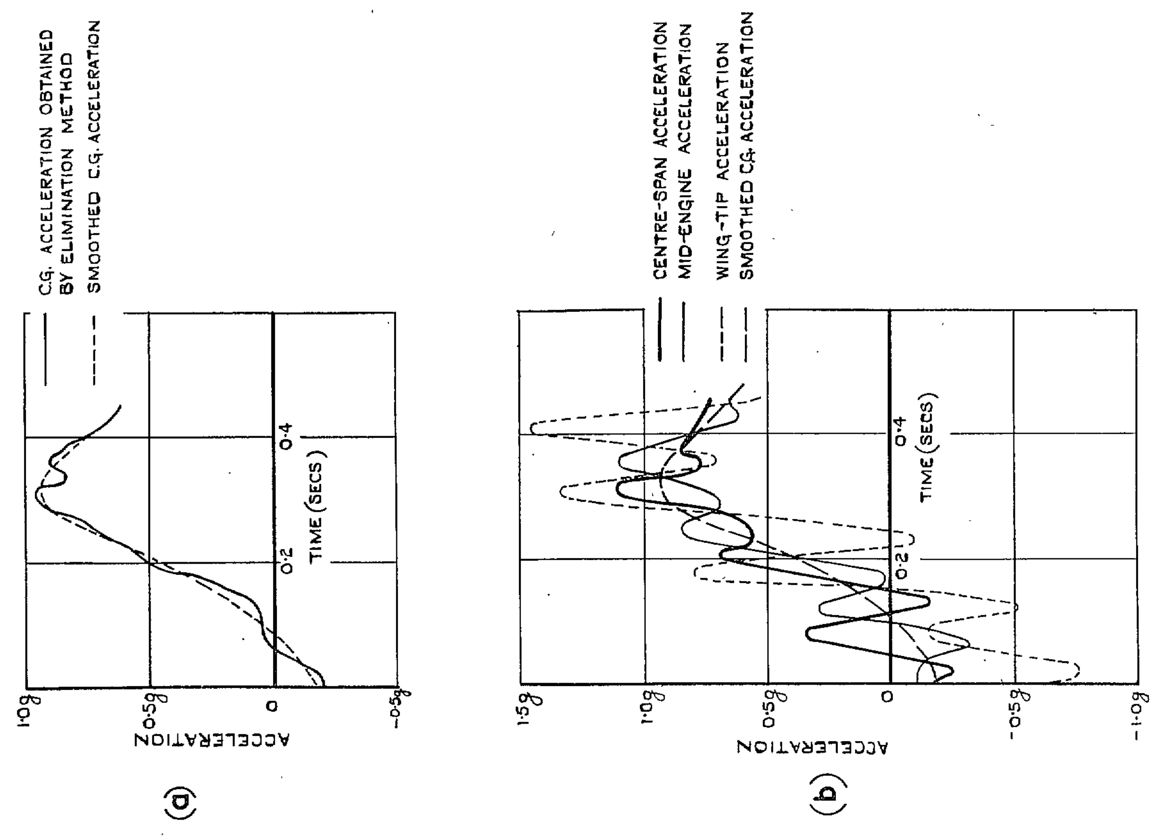


FIG. 30. Landing number 8 (first bounce).

(a) C.G. acceleration obtained by elimination using centre-span, mid-engine and wing-tip accelerations.

(b) Centre-span, mid-engine, wing-tip and C.G. accelerations.

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