DEVELOPMENT OF AN AUTOMATIC RECORDING ACCELEROMETER

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DEVELOPMENT OF AN AUTOMATIC RECORDING ACCELEROMETER

SUMMARY

This paper describes an automatic recording accelerometer which was developed for the purpose of determining accelerations experienced by aircraft while in flight, or while landing, taxiing, or taking-off The device consists of a bank of classifying accelerometer elements which are arranged to indicate the maximum acceleration reached. The recording element utilizes electrically marked paper so that a permanent record is obtained immediately Further, the device is constructed so as to operate only when actual shocks are being experienced, thus providing for automatic operation Results of laboratory and flight tests which were performed on the automatic recording accelerometer are given in detail

It is concluded that the automatic recording accelerometer will indicate accurately accelerations having a duration as short as 0 02 seconds Therefore, it could be used in the measurement of landing accelerations, since the flight tests indicated that the minimum duration of the latter was of this order of magnitude

INTRODUCTION

As a result of the war emergency a large number of light planes have been used to train pilots for the Armed Forces In general, this means that these aircraft have been subjected daily to the rough and inexperienced handling of novice pilots, and that all too frequently they have experienced severe shocks which might seriously affect the strength of the various structural components

In order to obtain data on the magnitude and frequency of occurrence of the accelerations experienced by light planes, it was considered desirable to develop a recording accelerometer having the following characteristics.

1. The device should be capable of automatically recording the maximum acceleration experienced during each shock
2. The record should be readable immediately, without the necessity for processing the recording medium
3. The recorder should be energized only when an actual shock is taking place, thus allowing a large number of records to be obtained with a minimum of recording paper
4. The design should be simple, and the device should be light-weight, easy to maintain, and require no servicing after being installed in the airplane.
5 Speed of response of the device should be such that accelerations of short duration, similar to those which are experienced as a result of landing impacts or of gusty weather, should be recorded
6. Accelerations resulting from engine vibrations should not be recorded

The primary reason for undertaking the development of an instrument of this nature was to obtain statistical data relative to the number of times an aircraft component experienced accelerations of various predetermined magnitudes If, for example, the accelerometer were to be mounted on the landing gears of a number of training planes of similar make, data would be obtained which would give the designer a knowledge of the frequency of occurrence of various loads Armed with this information he could design landing gears in the light of the load factors which had been obtained under service conditions with novice pilots in control.

One further application of this type of device relates to its use as a training instrument. If the device were to be made small enough, it could be used to check the performance of a pilot on landing and take-off runs over a period of time Thus a quantitative measure of his normal piloting skill could be obtained[1].

In preliminary studies of the design of this device it was decided to make it of the classifying[2] type Accordingly, specifications were drawn up covering the development of a device which would be in accordance with the requirements previously mentioned The actual design and fabrication was undertaken by the Electrical Research Products Division of Western Electric Co. The laboratory and flight tests described in this report were conducted by the Civil Aeronautics Administration

Further work is now under way on the development of an accelerometer based upon the results and conclusions contained in this report The objective of the continued development is to obtain an instrument which will be much lighter in weight and smaller in size, and that will be capable of measuring and recording accelerations having a duration of 0 02 second or longer with intervals as short as 0 1 second between successive shocks This will be described in a subsequent Technical Development report

DESCRIPTION OF THE AUTOMATIC RECORDING ACCELEROMETER

The complete accelerometer unit containing a bank of 10 classifying accelerometer elements is shown in figure 1 Figure 2 is a view of the recording unit of the device which is connected to the accelerometer unit by means of a multi-conductor cable indicated in figure 1 Figure 3 shows a single accelerometer element

The operation of the accelerometer element is as follows

When the acceleration acting on the mass is equivalent to a force sufficient to operate the push button of the Micro Switch[3], closure of an electrical circuit including one of the recording stylii is effected. This operation applies a voltage difference across the Teledeltos[4] recording paper, and the resulting current marks the surface of the paper The marks are similar to those shown in figure 19 With the aid of the tension adjusting screw it is possible to adjust the amount of preloading on the spring so that a number of these elements can be arranged in a classifying order such that they will trigger at a graded series of accelerations The circuit which accomplishes this is shown in figure 4.

In the accelerometer element case are mounted 10 accelerometer elements which have been adjusted to trigger at accelerations of 1 5 g, 2 0 g, 2 5 g, 3 0 g, 3 2 g, 3.4 g, 3 6 g, 3.8 g, 4.0 g, and 5 0 g for vertical upward accelerations Each element actuates one of the 10 switches labeled D_1, D_2, D_{10} The first element will trigger when 1 5 g is exceeded, closing switch D_1 and introducing the 90-volt battery into the time-delay relay circuit REL_1 The function of the time-delay relay will be explained below. Subsequently, the paper advance solenoid SOL_1 is energized and remains energized until switch D_1 opens, at which time the solenoid claw engages the paper-advance ratchet, thereby preparing the paper for the next recording. Switch D_{11} inserts the current limiting resistor R_9 in the circuit, when the solenoid is in the energized position in order to reduce the battery drain

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[1] In this connection, compare the effect of a rough technique on load factors given by Ryder, E I , "Load Factors Obtained on Civil Airplanes in Acrobatic Maneuvers," J Aeronautical Sciences, 9, 195 (April 1942)

[2] F H. Norton & E. P Warner, "Accelerometer Design," N A C A T R #100, 1920.

[3] This switch is a snap-action type switch manufactured by the Micro Switch Corporation, Freeport, Ill.

[4] Teledeltos is an electrosensitive recording paper manufactured by the Western Union Telegraph Co

When D_1 is closed, the circuit through time-delay relay circuit REL_2 is also closed so that current flows through the recording paper, thus marking it at a position corresponding to the first recording stylus.

Operation of the automatic recording accelerometer for accelerations greater than 1 5 g is explained best by an example Suppose that an acceleration of 3 0 g is experienced Switches D_1, D_2, D_3, and D_4 will be in the closed circuit position so that current flows through point 6 and the paper is marked at stylus 4 Thus, the arrangement of the circuit is such that only the maximum acceleration which is exceeded will be indicated, provided the rate of application of the acceleration is fast enough so that the time-delay relays for the other recording stylii do not have time to operate If the force is applied at a sufficiently slow rate, all of the intermediate points also will be marked, but these will appear along the same line on the recording, indicating that these points are intermediate values for the same maximum acceleration After removal of the force the paper advance ratchet is operated by the return of the solenoid claw and the paper is advanced slightly, ready for the next measurement. There is no battery drain unless an actual shock greater than 1.5 g is being measured and paper is advanced as required, making for economy of operation

The time-delay relays provide a means for filtering out accelerations arising from engine vibrations Circuits REL_1 to REL_3 have a time delay of 1/15 second, while REL_4 to REL_{11} have delay times of 1/40 second, i e , 1/15 second is required before the voltage applied to the relay in REL_1 builds up to a value sufficient to operate the relay armature, and similarly 1/40 second is required for the relay armature to close in REL_4 Since engine frequencies are of the order of 10 c p s or higher, whereas pertinent landing shocks were presumed to be much longer in duration than 1/15 second, it was assumed that these time delays would filter out engine vibration The validity of this assumption will be discussed under the section devoted to flight test results

As a source of power the automatic recording accelerometer utilizes two 45-volt storage batteries of the Burgess M-30 type The current drain and length of recording paper are such that approximately 1,000 records of landing shocks may be obtained The recorder has the approximate dimensions of 7" x 8" x 9" and weighs 14 lbs The accelerometer unit has the dimensions of 5" x 6" x 7" and weighs 5 5 lbs

LABORATORY TESTS

Static Load Tests

In order to calibrate the accelerometer unit and adjust the elements to the desired triggering acceleration, it is necessary to hang known loads on the calibrating hook of the accelerometer element and adjust the tension screw until closure of the switch occurs The stop adjustment, which is obtained by rotating the forward screw on the element, is not critical since its only purpose is to prevent the mass from chattering The combined weight of the leaf spring and mass is 23 3 gms The spring is a very minor part of this total weight Furthermore, as a first approximation, it may be assumed that one-half the distributed weight of the leaf spring is effective in operating the switch Hence, for calibration purposes the figure of 23 3 gms. per g acceleration is sufficiently accurate The validity of this figure also was checked by utilizing the centrifugal-force method of calibration described in a following section

During the course of the static load tests it was ascertained that there existed a range of critical loading values for which the switch could be in either a closed or open-circuit condition In other words, as the weight (which was hung on the accelerometer element) was increased gradually, a minimum load was found, for which it was possible to obtain closure of the switch However, by disturbing the element with the finger or in any other suitable manner, the element restored itself to its open-circuit position and remained in this position of equilibrium indefinitely For loads greater than this minimum value, it was possible to have the accelerometer element in equilibrium in either the open-circuit or closed-circuit position Finally a load was reached for which the element remained in a closed-circuit position and could not be made to open This is the maximum value referred to previously

This unstable behavior of the element was attributed to the fact that in the region of critical loading the Micro Switch, because of its snap action, has two positions of equilibrium One position results from the deformation or bending of the tension member[5] of the switch, while the other position is that corresponding to the undeformed condition For actuating forces in the critical region, it is possible for the tension member to be either flexed or not flexed Evidently this would appear to be an inherent property of all snap-action type switches

In table I are data obtained on a number of different elements with various tension adjustments, for determining the spread between the maximum and minimum static triggering loads The average spread was 9.6 gms , corresponding to 0.41 g

TABLE I

MAXIMUM AND MINIMUM STATIC TRIGGERING LOADS

Minimum Load Grams	Maximum Load Grams	Spread Grams
15.4	27 3	11 9
35 9	46 7	10.8
47 3	56 8	9 5
48 6	60 0	11.4
12 2	22 4	10.2
18 6	26 0	7 4
29 6	38 6	9.0
41 7	49 5	7 8
46 9	57 3	10.4
51 5	59 2	7 7
53 4	66 0	12 6
60 8	68 4	7 6
66 5	74 7	8 2
88 8	98 7	9.9
		Average 9 6

When adjusting the elements to the correct triggering accelerations for putting the accelerometer in operation, all of the elements were calibrated so that average static load, which is taken as one-half of the sum of the maximum and minimum loads, corresponded to the desired triggering acceleration That is, if it was necessary to adjust an element to 2.0 g, the element was calibrated so that it would trigger for an average static load of 23.3 gms. added to the calibrating hook of the element Thus, the tension screw was adjusted for a minimum load of (23 3 - 9 6/2) = 18 5 gms

Centrifugal Force Calibration

In this method of calibration, the accelerometer unit was mounted on the rotating turntable at the Aeronautic Instruments Section of the National Bureau of Standards and was subjected to centrifugal forces, the magnitude of which could be computed from the speed of rotation and the distance from the axis of rotation This table was supplied with slip rings which were connected to the terminals of the switch for the purpose of determining when the elements were being actuated. The same instability observed in the static load calibrations also were observed here, that is, the

5 See Micro Switch Aircraft Catalog No 70 for description of the construction of the switch

switch closed for accelerations larger than those for which it opened The data obtained on the turntable (on previously unadjusted elements) are in table II

TABLE II

CENTRIFUGAL FORCE CALIBRATION DATA

Element No	Maximum g	Minimum g	Average g	Spread in g
1	2 21	1 65	1 93	0 56
	2 20	1 65	1.93	0 50
2	2 48	2 25	2 36	0 23
	2.50	2 22	2 36	0 28
3	3 08	2 59	2 84	0 49
	3 12	2 58	2 85	0 54
4	3 07	2 60	2 84	0 47
	3 10	2 60	2 85	0 50
			Average Spread	0 45

To simulate the effect which the vibration of an airplane might have on the unstable region between minimum and maximum g, a buzzer was fastened to the accelerometer unit As was anticipated, the vibration reduced the range between the maximum and minimum values (see table III) The spread was reduced from 0 45 g to 0 23 g, so that the vibratory excitation of an airplane would have the general effect of increasing the accuracy with which the elements might be set from ± 0 22 g to ± 0 12 g In addition, it should be noted that the average value as given in tables II and III remained unchanged, within the limits of observational precision

TABLE III

EFFECT OF VIBRATION ON CENTRIFUGAL FORCE CALIBRATION

Element No	Maximum g	Minimum g	Average g	Spread in g
1*	2 04	1 76	1 90	0 28
2*	2 42	2 29	2 35	0 13
3	2 91	2 71	2 81	0 20
4**	3 64	2 85	3 25	0 79
5*	3 53	3 20	3 36	0 33
			Average Spread	0 23

* Average of 2 measurements

** In this measurement difficulty was experienced in determining the minimum value, since the vibration tended to cause chattering, and hence only partial closure was indicated on the test meter which was used to check circuit closure This value therefore has been excluded from the average spread figure

A comparison of the results of static load tests with those obtained from centrifugal loading is shown in table IV Thus, the calibration constant as determined from centrifugal force tests is in excellent agreement with that obtained previously by considering the weight of the mass and spring as the equivalent of 1 g

TABLE IV

DETERMINATION OF CALIBRATION CONSTANT FROM STATIC AND CENTRIFUGAL LOADING

Element No	Av (1)Static Load (gm)	Av Centrifugal Acceleration (g)	Grams per g
1	44 7	1 90	23 6
2	55 1	2 35	23 5
3	64 6	2.81	23.0
4	75 3	3 25	23 2
5	77.6	3.36	23 1
			Av 23 3

(1) The 23 3 gms weight of element is included in this figure

The tests described in this section have been referred to in a rather ambiguous fashion as "centrifugal" force tests However, since the acceleration acting on the accelerometer base is directed radially inward toward the center of the turntable, in reality the force is a centripetal one (figure 5) Under equilibrium conditions, when the base is moving with a constant rotational speed, there can be no relative motion between the accelerometer mass, m, and the base Therefore, m also has the acceleration a_c The force ma_c acting on the mass m can only arise from the action of the restoring force of the accelerometer spring and, hence, the deflection of m (as indicated in figure 5) must be radially outward, since deflection and spring-restoring force are in opposite directions With respect to a coordinate system fixed in the switch or base of the accelerometer element, the deflection of the mass is such as would occur from an external force acting downward (directed from mass to switch) so that the effective force on the switch could be considered as a centrifugal force from this point of view

Evidently, this same situation also holds where the accelerometer element is used to measure accelerations occurring in the vertical plane In this case, accelerations applied to the base of the accelerometer in a vertically upward direction deflect the mass on the spring downward so that force is exerted on the switch In this connection, it is to be noted that if the accelerometer case has an upward acceleration of 1 g, the actual acceleration acting on the unit caused by external forces (other than gravity) is 2 g upward, since 1 g is required to overcome the effect of gravity

Frequency Response of Accelerometer Element

An important advantage in using a preloaded element arises from the fact that no dynamic motion of the mass occurs until the exciting force reaches a magnitude which overcomes the preloading of the element Therefore, it should be possible to measure shocks of very short duration without dynamic errors arising because of the duration of the shocks and the nature of their wave shape This will be true if any motion of the mass of the element which may be involved in operating the switch is kept to a minimum

The resonant frequency of the mass leaf-spring system, when fastened at one end of the spring in cantilever fashion but free in all other respects, was measured to be 14 c p s When restrained in a manner similar to that caused by the button on the switch, the resonant frequency was approximately 15 c p s Since very little damping exists in the free element, a frequency response characteristic of the element should show considerable deviation from a flat response if dynamic errors are present Accordingly, a frequency response characteristic in the range of 12 to 22 c p s was determined

An accelerometer element was mounted on the vibrating plate of a vibration-pickup calibrator The latter is a mechanical device which produces an essentially sinusoidal vibration having both adjustable amplitude and frequency The tension on the accelerometer spring was adjusted so that different static loads would be required to close the switch The frequency of vibration at which closure of the switch occurred was observed on a cathode ray oscillograph. This was accomplished by placing the oscillograph in series with the switch so that the current surge which occurred when the switch first closed could be observed readily The acceleration amplitude which actuated the accelerometer was computed from the frequency and amplitude of displacement of the vibration. In table V a comparison between the average static g and the dynamic g is made

TABLE V

COMPARISON BETWEEN THE AVERAGE STATIC g AND DYNAMIC g

Frequency(c p s)	Average Static g	Dynamic g	Dynamic g - Average Static g
11 6	1 90	1 70	−0 20
12 8	1 82	1.83	+0 01
13 8	1 97	1 98	+0 01
15 1	2 30	2.16	−0 14
16 9	2.54	2 47	−0 07
16 9	2 33	2.48	+0 15
18 1	2 77	2 67	−0 10
19 3	3 13	2 90	−0 23
21 4	3 53	3 35	−0 18
		Average Difference	−0 083

The average difference indicates that on the average the dynamic g agrees with the average static g to within 0 1 g Furthermore, over the range of frequencies measured, there is no demonstrable frequency error, so that the accelerometer element will respond faithfully under both static and dynamic conditions Since a 20 c p s vibration corresponds to an acceleration which goes from zero to a maximum back to zero in 1/40 second, and since the dynamic tests show that during the greater part of the vibration cycle the accelerometer element behaves in a static manner (inasmuch as the mass does not move until its static triggering acceleration is reached) one can state that the accelerometer element will follow sinusoidal single pulses having a duration which may be as short as, or possibly shorter than $\frac{1}{2 \times 21\ 4}$ (=0 023) seconds Actual tests in which the element and recorder were subjected to transient shocks will be described in a following section

It is of interest to note that in the dynamic tests it was observed that the switch is closed and opened at the same magnitude of the vibratory acceleration amplitude irrespective of whether this amplitude is increasing or decreasing Evidently the dynamic effect is such as to overcome the instability of the Micro Switch Since the average static g agrees well with the dynamic g, and since actual shocks are dynamic in nature, it follows that the adjustment of the elements so that their average static g agrees with the desired triggering accelerations is an accurate and convenient procedure

Frequency-Response Measurements of Recorder Components

There are several components in the recording unit of the automatic recording accelerometer which limit the frequencies at which the device will respond One such element is the time delay circuit included with the relays In order to determine the actual time delay involved, the following experimental means were used

An accelerometer element was mounted on the plate of the vibration pickup calibrator, as indicated in figure 6, and the switch was arranged with respect to the recorder circuit so that only one relay would be energized when the switch was closed As the calibrator plate vibrated, the stop attached to the frame of the calibrator closed the switch The fraction of a period during which the switch remained closed was controllable by adjustment of the calibrator amplitude The length of time the switch was closed was adjusted by varying the frequency As long as the frequency is such that the time interval during which the switch is closed is longer than the delay time, the Teledeltos paper will be marked The highest frequency at which marking occurred was noted, and from the frequency and the fraction of one complete vibration for which the switch was closed, it was possible to compute the delay time The fraction of a period involved was determined by turning over the flywheel of the calibrator slowly by hand and noting the fraction of a revolution for which the switch was closed

Delay times determined in this fashion were

Relay circuit No 1	0 092 (1/11) seconds
Relay " No 2	0 092 (1/11) "
Relay " No 3	0 075 (1/15 4) "
Relay " No 6	0 022 (1/45) "

As relay circuits 4 to 11 are nominally identical, insofar as circuit constants are concerned, the measurement on circuit 6 served to identify the approximate magnitude of the others Thus, transient shocks having a magnitude of 1 5 to 2 0 g must have a duration of the order of 0 1 seconds or longer, in order to be recorded by the automatic recording accelerometer This should filter out engine vibrations effectively since any periodic acceleration in the range of 1 5 to 2 0 g having a frequency greater than about 5 c p s could not energize the relays For higher accelerations, shorter time delays are permissible, since engine vibrations would not be expected to have amplitudes in the higher range of acceleration

The frequency response of the intermittent paper-advance mechanism was next determined It was ascertained that it followed pulses faithfully for frequencies up to three per second, the pulses lasting more than 0 1 second as required by the time delay circuit This characteristic of the paper advance effectively limits the response of the entire instrument, because successive shocks occurring at time intervals less than 1/3 second apart will not be resolved correctly Further, unreliable paper-advance operation will occur if the pulse is much shorter than 1/3 second

Laboratory Shock Tests

In order to determine the reliability of operation of the automatic recording accelerometer under shock excitation conditions, it is necessary to subject the accelerometer to known transient accelerations A very simple method of producing shock excitation is to hold the accelerometer box in one's hands and then give it a sharp jerk vertically upward or downward If a calibrated vibration pickup (accelerometer) is mounted on the accelerometer box so that its axis of response is in the vertical direction and if suitable recording means are used to record the resultant transient shock, it is possible to compare the acceleration indicated by the automatic recording accelerometer with that obtained from the vibration pickup

Figure 7 is a schematic diagram showing the experimental set-up which was used to conduct these tests The vibration pickup was a piezoelectric accelerometer utilizing a rochelle salt crystal as the acceleration responsive element With an appropriate external impedance the acceleration response is practically flat from very low frequencies up to 500 c p s Figure 8 shows the computed change in output voltage in decibels as a function of frequency for various external resistances R A 20-megohm resistor was used for R in this case so that the response is flat down to a frequency of approximately 5 c p s

The 0 5-mf condenser and 1-megohm attenuator are standard circuit components of the amplifier used in these experiments and could not be changed readily This necessitated use of the series resistance R and a consequent loss in output Figure 9 shows a front panel view of a special four-channel amplifier built to the Technical Development Division's specifications by Electrical Research Products, Inc The performance of this amplifier will be described in a subsequent report It will suffice here to say that two integrating circuits are provided so that an acceleration input may be integrated once to obtain velocity records, or it may be integrated twice to obtain displacement records

The recording oscillograph is a multi-channel device having 12 D'Arsonval wound-coil galvanometers, the deflections of which are recorded directly on photographic paper by means of light beams reflected from mirrors mounted on the galvanometers.

Figure 10a is a typical acceleration curve recorded by the oscillograph, while figure 10b is a typical velocity curve which is obtained when the output from the accelerometer is integrated once In figure 10a the pickup was jerked downward so that it had an initial downward acceleration At the end of its path the pickup was stopped sharply so that it had a large deceleration or upward acceleration Figure 10b tells a similar story except that the motion or velocity was upward. Accelerations are computed from the velocity records by determining the slope of the velocity curve Timing lines appear at 0 01-second intervals along the edge of the paper.

The indicated accelerations on the figures represent dynamic components only, to which + 1 g must be added to obtain the effective acceleration since the vibration pickup and remainder of the vibration measuring system will not indicate static, or very slowly varying accelerations The crystal pickup was calibrated by means of a vibration pickup calibrator which supplied known frequencies and amplitudes Over a range of test frequencies from 10 to 70 c.p s the response is essentially flat with an average scatter of about ± 10 percent in the test points, although some points scattered more than this. For the velocity calibration it was possible to take measurements down to 3 c.p.s since the effect of the integrating circuit is to cause considerable attenuation in circuit noise and in 60-cycle hum picked up in the high impedance input to the amplifier. The velocity calibration indicates that the overall response of the system is essentially flat down to 5 c p.s A typical overall calibration curve of the vibration measuring system is given in figure 11

Table VI summarizes the results obtained by comparing the responses of the automatic recording accelerometer and the crystal accelerometer to transient accelerations. A study of table VI indicates that, in general, the automatic recording accelerometer responds to transient shocks having a duration as short as the time delay of the relays, i e ,1/15 second for 1.5 g and 2.0 g, and 1/40 second for 2.5 g to 5 0 g Record 146 indicates that the 3.0 g accelerometer element requires a somewhat longer time than 0.025 seconds before it will respond or close the switch This same behavior of the 3 0 g element appears in record 2, in which it will be noted that an acceleration of 3.0 g was exceeded for 0 055 second. Similarly, the error in record 126 may be explained on this basis. This evidently is an error in the dynamic response of the 3.0 g element itself and not in the relay circuit If the relay circuit required an excitation time greater than 0.025 second, no marking would result for durations less than this, even for elements triggering at lower accelerations, unless the rate of change of acceleration was such that intermediate accelerations lasted more than 0 025 second (or 1/15 second for 1 5 g and 2 0 g). In the records considered here the rate of change of acceleration exceeded the latter rate

A certain amount of mechanical malfunctioning was possible in the accelerometer element This would occur when the stop adjustment of the element was turned down too far, so that the switch remained open, but was on the verge of closure. Under the influence of the appropriate acceleration the switch closed However, it remained closed after the shock was over due to the instability characteristic of the switch previously discussed, since the restraint offered by the stop was now sufficient to keep the switch closed It is believed that the erroneous indication in record 118 may have arisen from such a cause, for if the 2.5 g element had been closed and the acceleration had reached 2.0 g, a reading of 2 5 g would have been obtained

FLIGHT TESTS

A basic supposition in the application of the automatic recording accelerometer to the measurement of landing shocks is that the duration of the landing

TABLE VI

COMPARISON OF ACCELERATION MAGNITUDES INDICATED BY AUTOMATIC RECORDING ACCELEROMETER
WITH THE VALUES INDICATED BY VIBRATION MEASURING SYSTEM

Record No.	Amplifier Setting	Auto. Rec. Accelerometer Max. Acceleration Marks at	Vibration Measuring System Acceleration	Time Duration	Remarks
116	No Integration	None (1.5 g)	1.40 g	0 028 sec	Correct operation
114	–	None (1 5 g)	1 55 g	0 10 sec	Within error tolerance of ± 0 1 g allowed for Auto Rec Acc
115	Accelera-tion output	1 5 g (faint)	1.42 g	1/15 sec	Correct operation
118		2.5 g (faint)	1.78 g	0 020 sec	Incorrect Auto. Rec Acc indicated too high
126		2.5 g	3 38 g	0 025 sec	Incorrect Auto Rec Acc indicated too low
147		2.5 g	2.75 g	0 025 sec	Correct Operation
2		3.0 g (faint)	3.45 g	0 025 sec	Auto Rec Acc indicated low with a possible significant error of about 0 2 g
140	One	None (1.5 g)	1 52 g	0.058 sec	Correct Duration too short
141	Integration	None (1.5 g)	2 21 g	0.032 sec	Correct Duration too short
144	–	2.5 g (faint)	2 83 g	0.025 sec	Correct Operation
146	Velocity	2.5 g	2 78 g	0 034 sec	Correct Operation
	Output		3.20 g peak	0.026 sec	Duration on the verge of being too short
120		2.5 g	2.64 g	0 035 sec	Correct operation
119		2 5 g	2 93 g	0 028 sec	Correct operation
122		2 5 g	2 30 g	0 026 sec	No significant error
142		4 0 g	4 23 g	0 028 sec	Correct Operation
145		5.0 g (faint)	5.20 g	0 020 sec	Correct Operation

accelerations should be considerably longer than the 1/40 second time delay used in the relay circuits. If this condition is not met, the accelerometer will not indicate the peak accelerations faithfully. To check the validity of this assumption and to determine the performance of the device under actual flight conditions, a number of landing shock measurements were made on the Division's Boeing 247-D airplane (NC-11).

The experimental set-up in the Boeing was exactly like that used in making the laboratory shock tests, with the exception that it was considered of interest to measure not only the vertical component of acceleration but also the lateral and longitudinal horizontal components. Accordingly, three crystal vibration pickups, together with the accelerometer unit, were mounted on the front spar of NC-11, which is located near the center of gravity of the airplane. Figure 12 shows this installation. Figure 13 shows the complete installation in the Boeing of the vibration measuring system indicated in figure 7 and previously discussed in the text.

In taking measurements of the landing shocks experienced by NC-11, it was discovered soon that it is not feasible to record accelerations directly because engine vibrations obscured the record. Hence, most of the measurements were taken with the amplifier in the single-integration position, since the integrating circuit discriminated against the high frequencies caused by engine vibration.

The first velocity record taken is reproduced in figure 14a. The velocities given in this figure are the dynamic components only and therefore the actual sinking speed before contact with the ground is not indicated in the record. The directions of the velocity components are indicated by the signs and are in accord with the standard NACA notation. Figure 14b indicates the equivalent acceleration record obtained from 14a by measuring the slope of the velocity curve. The positive directions for the lateral and longitudinal accelerations are taken in the same directions as for the velocities. However, the normal acceleration is taken opposite in sign from that of the normal velocity, or the assumption that the normal component of the acceleration does not differ to any considerable extent from the vertical component during the landing, hence, according to custom, it must be assumed that the positive direction is vertically upward. It is assumed further that the weight of the aircraft is entirely airborne[6] just prior to contact with the ground, necessitating the addition of 1.0 g to the measured dynamic vertical component.

Figures 14a and 14b show that the maximum positive acceleration during the first impact was 1.41 g and lasted 0.1 second, while during the second impact it was 1.97 g for 0.04 second. The automatic recording accelerometer did not indicate for either impact, since in the first case the magnitude was too low and in the second case the time duration was too short. Accordingly, it was decided to eliminate the time delay and relay circuits from the recorder, because the actual landing shocks were of shorter duration than the time delay. It was felt that engine vibrations would not affect the recorder performance, since the engine vibration amplitude was approximately 0.2 g at the place where the accelerometer was mounted, and since the paper-advance mechanism would not operate at frequencies as high as engine frequencies. Operation of the recorder in airplane NC-11 during the flight tests with the relay circuits deleted, and also under conditions when the engine was run up to its maximum speed of 1850 r.p.m., bore out this contention, as no marking occurred as a result of engine excitation alone.

In table VII there are summarized the results of the flight tests on the automatic recording accelerometer with the time-delay and relay circuits missing from the recorder. Figures 15a to 17a are some actual velocity records obtained

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[6] Hootman and Jones in NACA TN 863, "Results of Landing Tests of Various Airplanes," have indicated that the aerodynamic support at the instant of ground contact may vary from 0.6 to 1.0 times the airplane weight, so that the indicated accelerations may be too large by about 0.4 g with a possible average error of about 0.2 g.

during landings, and figures 15b to 17b are the corresponding acceleration records All of the records are partially vibratory in character because of the bouncing of the airplane, caused by the elastic nature of the shock absorber All accelerations measured at the rear spar were considerably higher than those at the front spar This no doubt resulted from the additional rotational velocity which the airplane experienced about its center of gravity as a result of its impact with the ground Record 1163 (figures 17a and 17b) is an extreme case of such an impact and shows that the acceleration was quite vibratory in character In this landing one wheel landed off the runway and considerable shock was experienced in all three directions, viz , vertical, lateral, and longitudinal The acceleration record obtained in figure 17b is similar to those obtained by other observers[7] when using accelerometers having a relatively high natural frequency However some landing accelerations made by Hootman and Jones[8] using accelerometers[9] having a natural frequency of 20 c p s or less did not show these high frequency variations

A study of table VII indicates that, in general, the automatic recording accelerometer performed satisfactorily under impact conditions existing during actual landings Accelerations having a time duration of 0 02 second or greater were measured accurately, although high frequency vibratory components such as appeared in record 1163 could not be resolved because of the slow response of the paper-advance mechanism The latter mechanism did not operate always because the duration of the accelerations was considerably less than that required for reliable operation of the device

It may be concluded that if it is necessary to determine the maximum positive acceleration experienced during any one impact or contact with the ground, the paper advance must be designed so as to respond to shocks of 0 02 second or greater If, in addition, it is necessary that successive positive accelerations occurring during the same impact be measured, the paper advance should be capable of responding to accelerations spaced at time intervals as short as 0 1 second This would record all accelerations other than high-frequency vibratory components, which one could not expect to measure with this type of device

A number of landing shock measurements also were made on the Technical Development Division's Waco, Model AVN-8, airplane NC-17 to determine the performance of the automatic recording accelerometer in a light plane Since it was not possible to install the vibration measuring system in the Waco, because of space and weight limitations, only the automatic recording accelerometer was installed (figure 18) As before, the time-delay and relay circuits were not included in the recorder

While "revving up" the Waco prior to take-off, intermittent or chattering operation of the paper-advance and intermittent marking at 1 5 g occurred, indicating that an acceleration of 1 5 g was possible at this location on the airplane because of engine excitation The maximum acceleration experienced during the landings was 2 5 g, though a considerable number of the landings indicated at the 2 0 g level No intermittent marking occurred at accelerations greater than 1 5 g, indicating that engine vibrations did not interfere in the recording process for accelerations greater than 1 5 g Figure 19 is a photograph of a portion of the record obtained in the Waco tests

While engine excitation did not interfere with the recording process for accelerations greater than 1 5 g, the actual indicated accelerations may have resulted from a superposition, or addition of the acceleration, caused by both the landing shock and the engine excitation This is not considered undesirable because the instantaneous load factor acting on the structural component in question actually results from these

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[7] NACA TR No 99, "Accelerations in Flight," by F. H Norton and E T Allen
[8] See reference 6 on page 11
[9] NACA Miscellaneous paper No 47, "A Method for the Dynamic Calibration of Accelerometers," by James A Hootman

TABLE VII

COMPARISON OF LANDING ACCELERATIONS OF AIRPLANE NC-11 (BOEING 247-D) AS INDICATED BY AUTOMATIC RECORDING ACCELEROMETER AND THE CRYSTAL VIBRATION PICKUP

Record No	Amplifier Setting	Auto. Rec. Acc. Marks at	Crystal Vibration Pick-up		Pick-up Location	Remarks
			Acceleration	Time Duration		
1154	Velocity Output	None	1.4 g		Front Spar	
1155 (figs) (15a,15b)	Velocity Output	1.5 g	1.59 g 1.52 g	0.053 sec 0.030 sec	Front Spar	One impact-0.25 sec interval between 1.52 g and 1.59 g. Only one 1.5 g mark on Auto Rec Acc
1156	*Acceleration Output	None	1.4 g 1.4 g	0.012 sec	Front Spar	First impact } Time be- Second impact } tween impacts = 1.0 sec.
1157	*Acceleration Output	None	1.45 g		Front Spar	
1161	*Acceleration Output	1.5 g	1.5 g	0.02 sec	Rear Spar	
1162 (figs) (16a, 16b)	Velocity Output	2.0 g 1.5 g	2.03 g 1.43 g	0.04 sec 0.06 sec	Rear Spar	One Impact-0.6 sec interval between 2.03 g and 1.43 g. Paper advance mechanism did not operate
1163 (figs (17a,17b)	Velocity Output	1.5 g 2.0 g	2.00 g 1.53 g 3.0 g etc	0.013 sec 0.10 sec 0.01 sec	Rear Spar	Hard Landing-one wheel landed off runway. Paper advance mechanism operated once only and 1.5 g and 2.0 g marks were not displaced on the record
1164	*Acceleration Output	1.5 g	1.6 g	0.02 sec	Rear Spar	Paper advance mechanism Operated

* Results from acceleration records are approximate only since engine hash present in record makes accurate measurements difficult.

two causes The important consideration is that engine vibration should not paralyze operation of the recorder or render difficult the interpretation of the record

CONCLUSIONS

The following conclusions relative to the performance of the automatic recording accelerometer may be deduced from the results of the laboratory and flight tests

1 The automatic recording accelerometer may be adjusted to indicate accurately the acceleration interval in which the maximum acceleration happens to fall, for shocks having a duration longer than 0 02 second

2 The lower and upper acceleration limit defining the acceleration interval between any two consecutive accelerometer elements may be adjusted to an accuracy of approximately $\pm$ 0 15 g

3 Use of the time delay circuits is not desirable because landing shocks may have a duration comparable to or less than time delays used in the present instrument

4 Operation of the paper-advance mechanism is not reliable because of the short time interval involved.

FIGURE INDEX

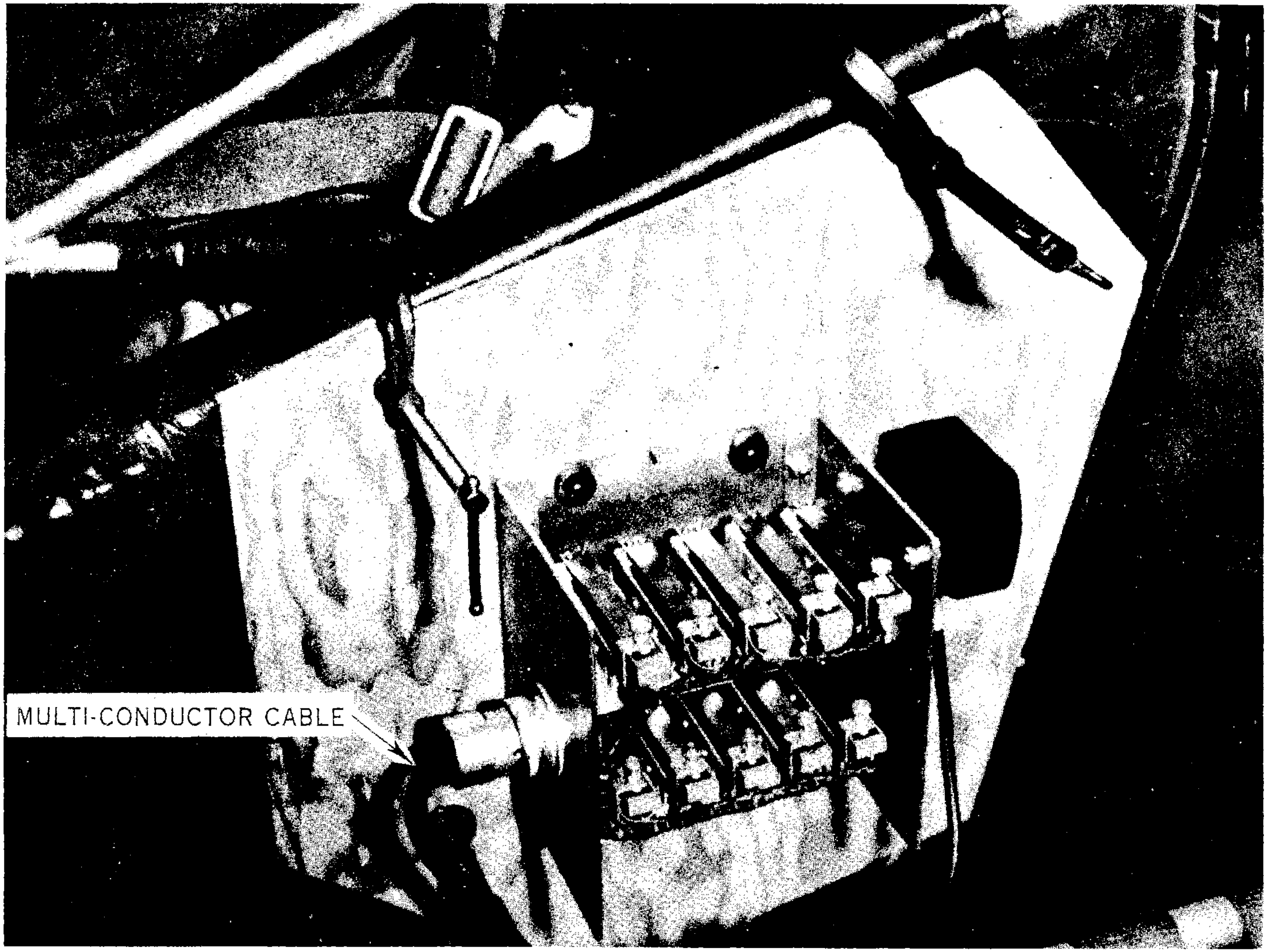


Figure 1. Accelerometer Unit Containing Ten Classifying Elements.

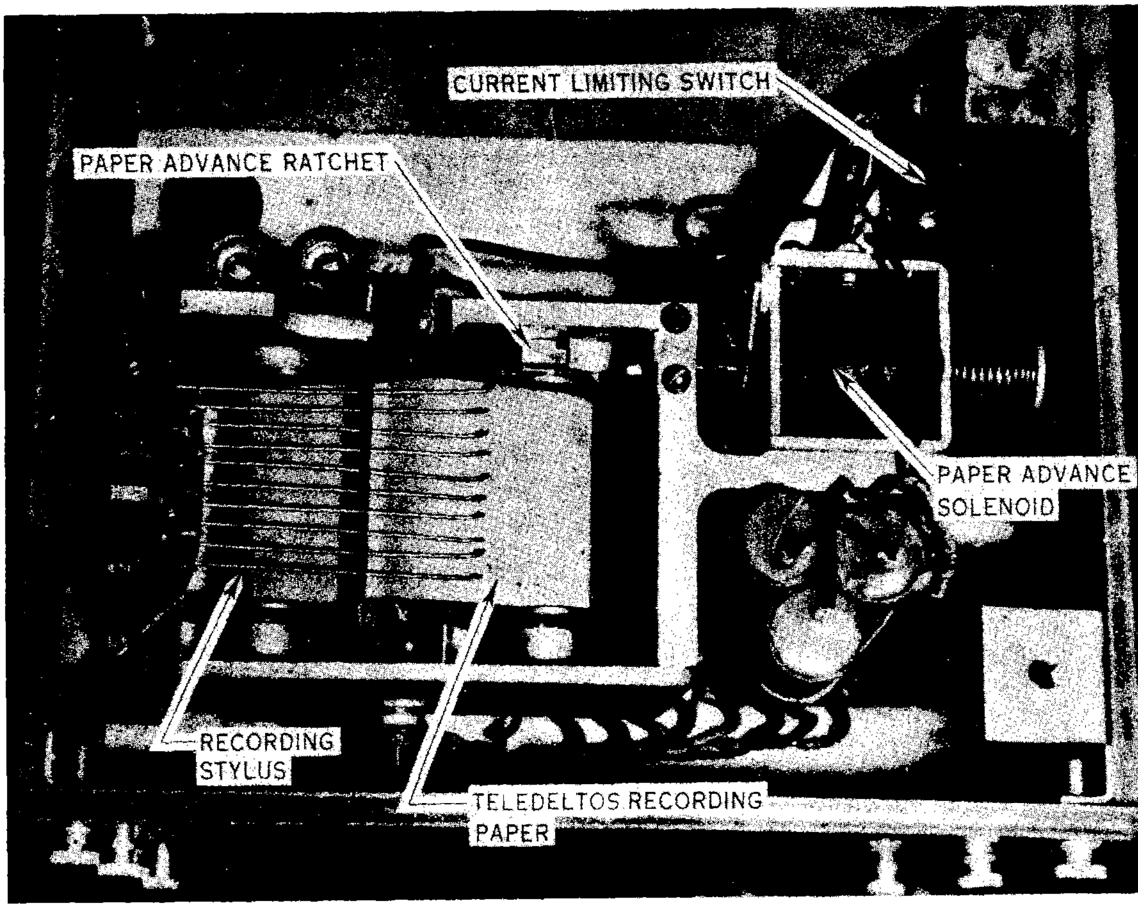


Figure 2. Recorder Unit

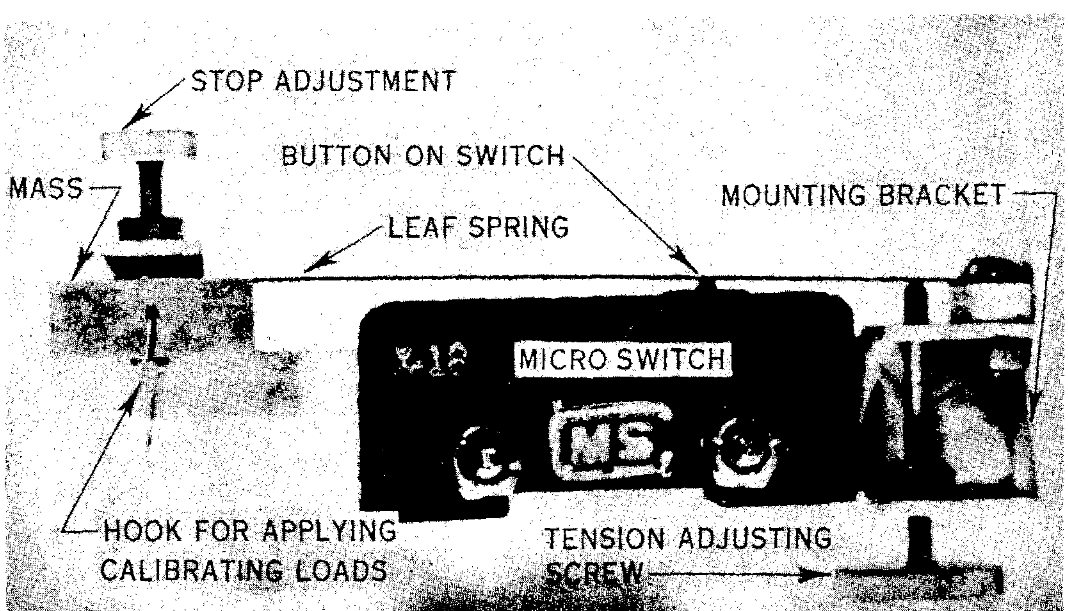
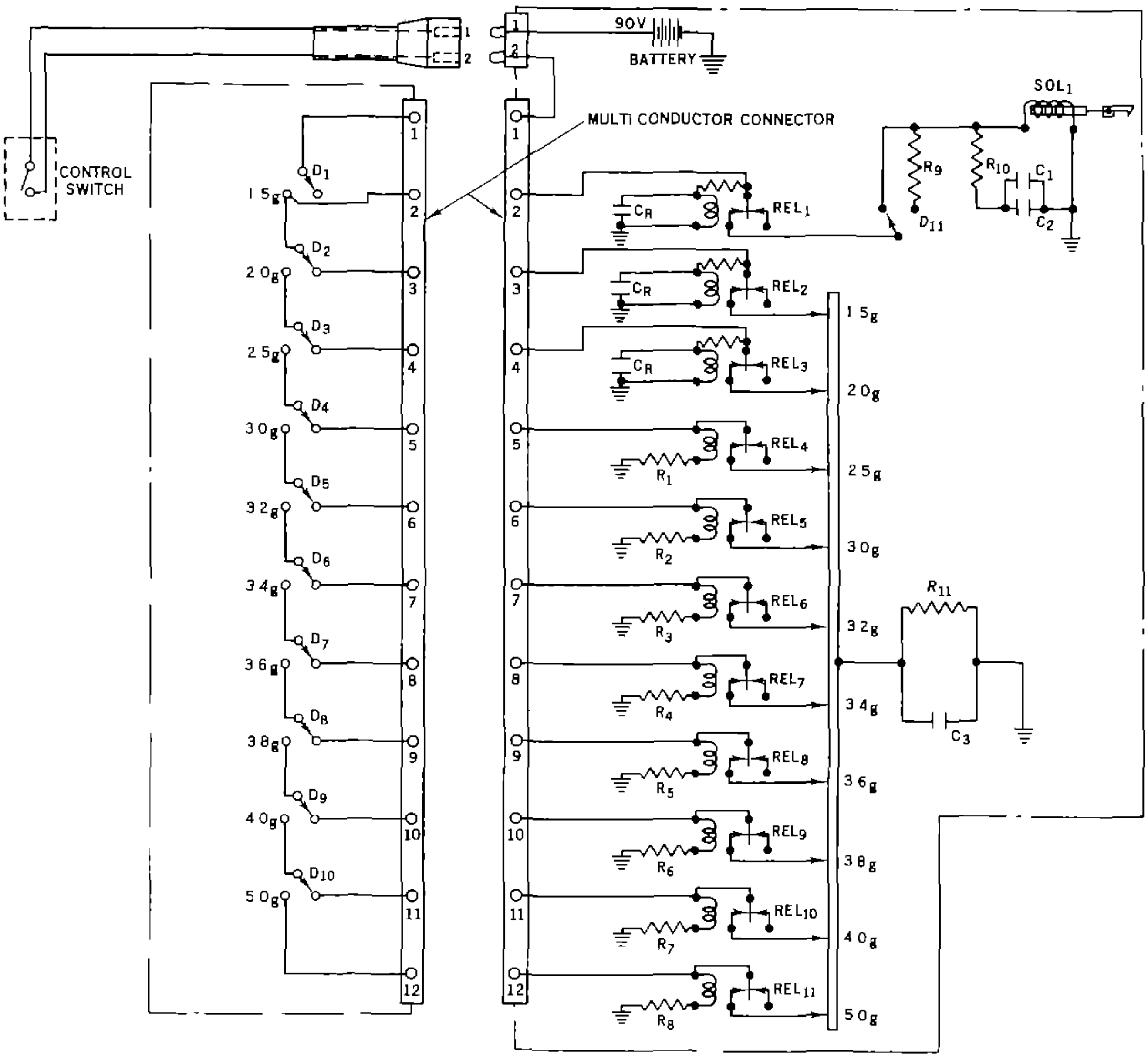


Figure 3. Accelerometer Element



DESIGNATION	APPARATUS	VALUE
BATTERY	2 BURGESS M 30 BATTERIES	45V
CR	CONDENSERS FURNISHED WITH RELAYS	40MF−350V.
C1 & C2	CORNELL-DUBILIER BR 2015 (BLUE BEAVER) CONDENSER	20MF−150V.
C3	CORNELL DUBILIER BR 815 (BLUE BEAVER) CONDENSER	8MF −150V.
D1 TO D11	MICRO-SWITCH BZ R8 SPECIAL WITH BRASS BUSHING	
J1 & J2	AMPHENOL P012F CHASSIS CONNECTOR	
J3	AMPHENOL SP MCZM CHASSIS UNIT	
PG1	AMPHENOL MC 2F CABLE CONNECTOR	
PG2 & PG3	AMPHENOL 012M CABLE CONNECTOR (NOT SHOWN ON SCHEMATIC)	
RR	RESISTOR FURNISHED WITH RELAYS 1 WATT	3800 Ω
R1 TO R8	IRC TYPE BT 1 RESISTOR	5000 Ω
R9	IRC TYPE BT 1 RESISTOR	3500 Ω
R10	IRC TYPE BT 1 RESISTOR	500 Ω
R11	IRC TYPE BT 1 RESISTOR	1000 Ω
REL1 REL11	POTTER AND BRUMFIELD MFG CO SPDT 25V 2500 Ω COIL RELAY MODIFIED BY PHOTOBELL CORP	
SOL1	GUARDIAN ELECTRIC TYPE 2 90V 290 Ω COIL PLUNGER TYPE SOLENOID	
PAPER	WESTERN UNION TELEDELTOS GRADE L 1 7/8" WIDE X 12−0" LONG	

Figure 4 Circuit Diagram for Automatic Recording Accelerometer

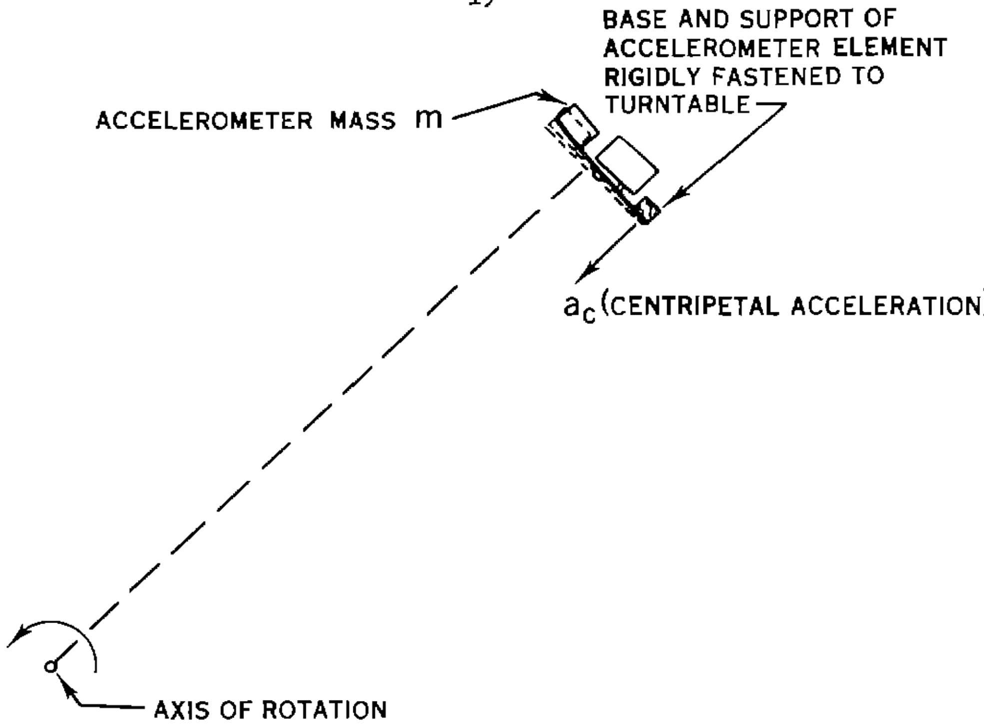


Figure 5 Action of Rotating Turntable on Accelerometer Element (Schematic)

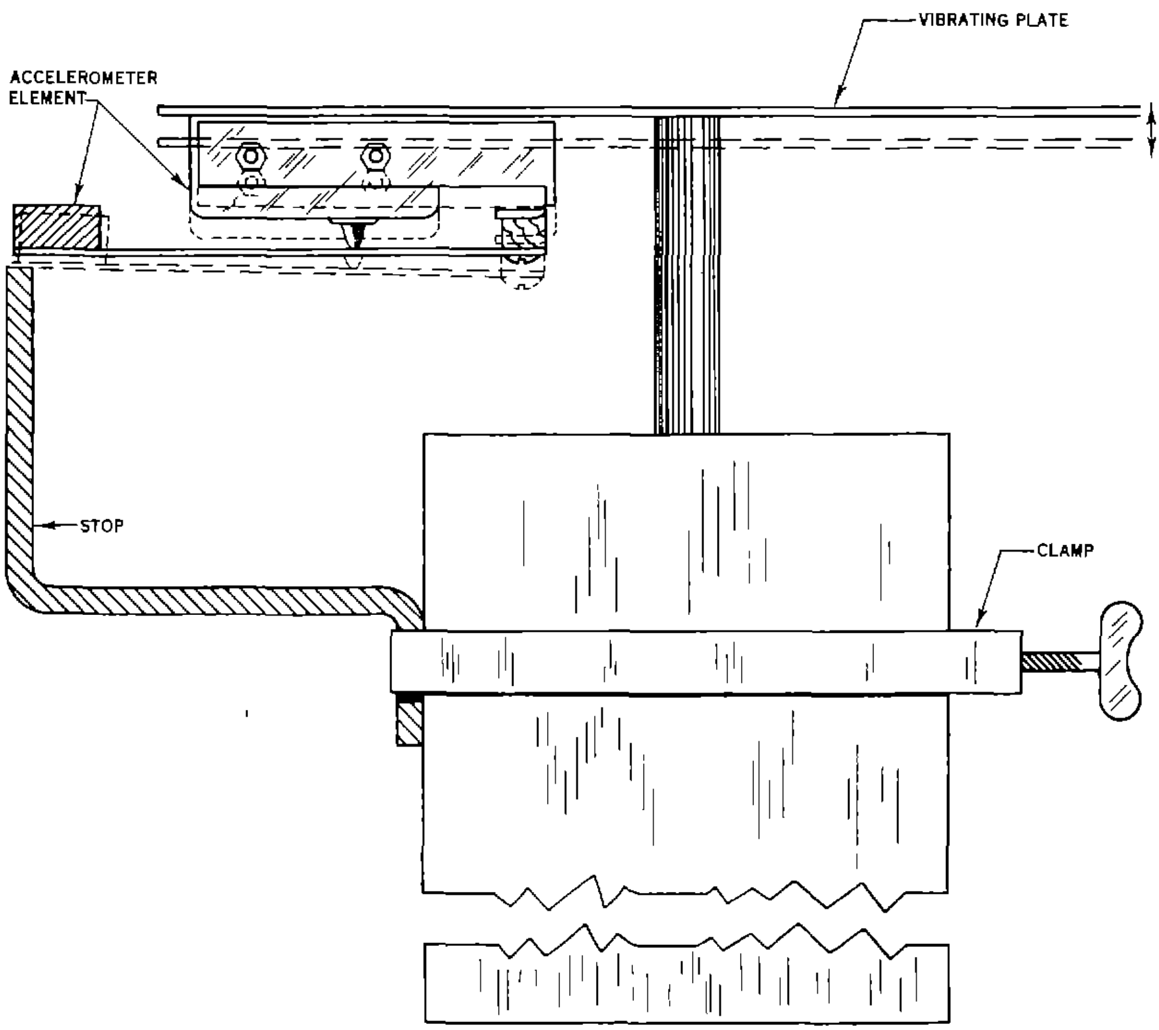


Figure 6 Arrangement Used in Determining Time Delay of Relay Circuits

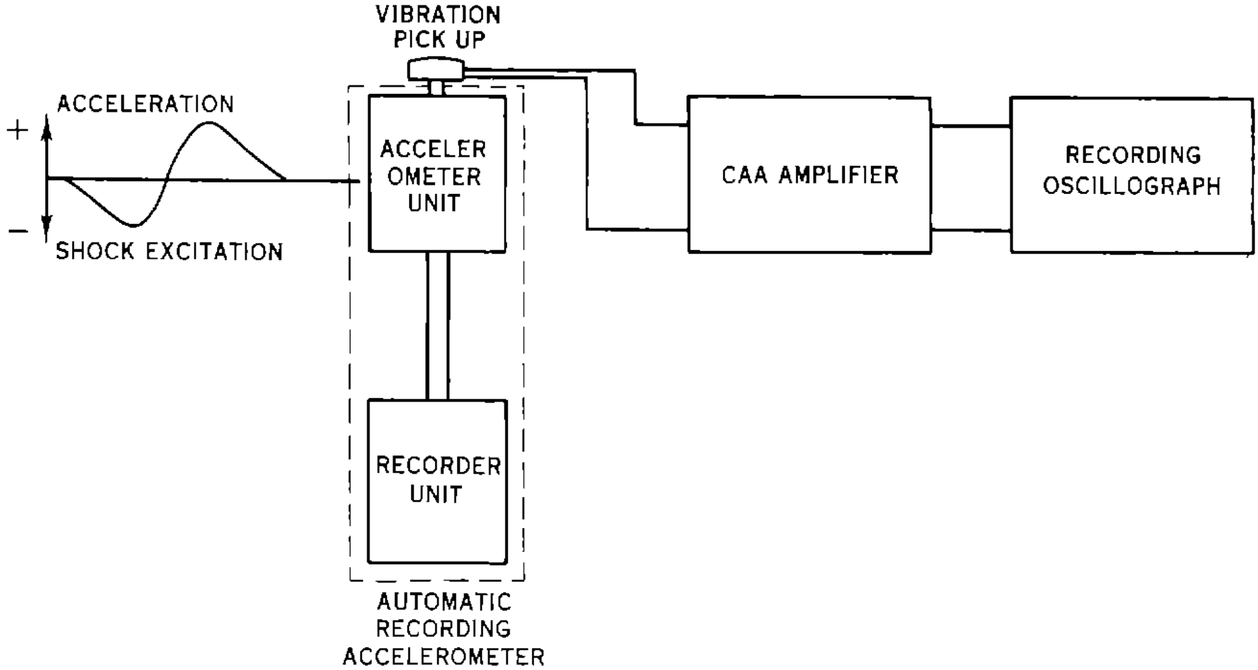


Figure 7 Schematic Diagram Showing Arrangement for Determining Response of Automatic Recording Accelerometer to Transient Accelerations

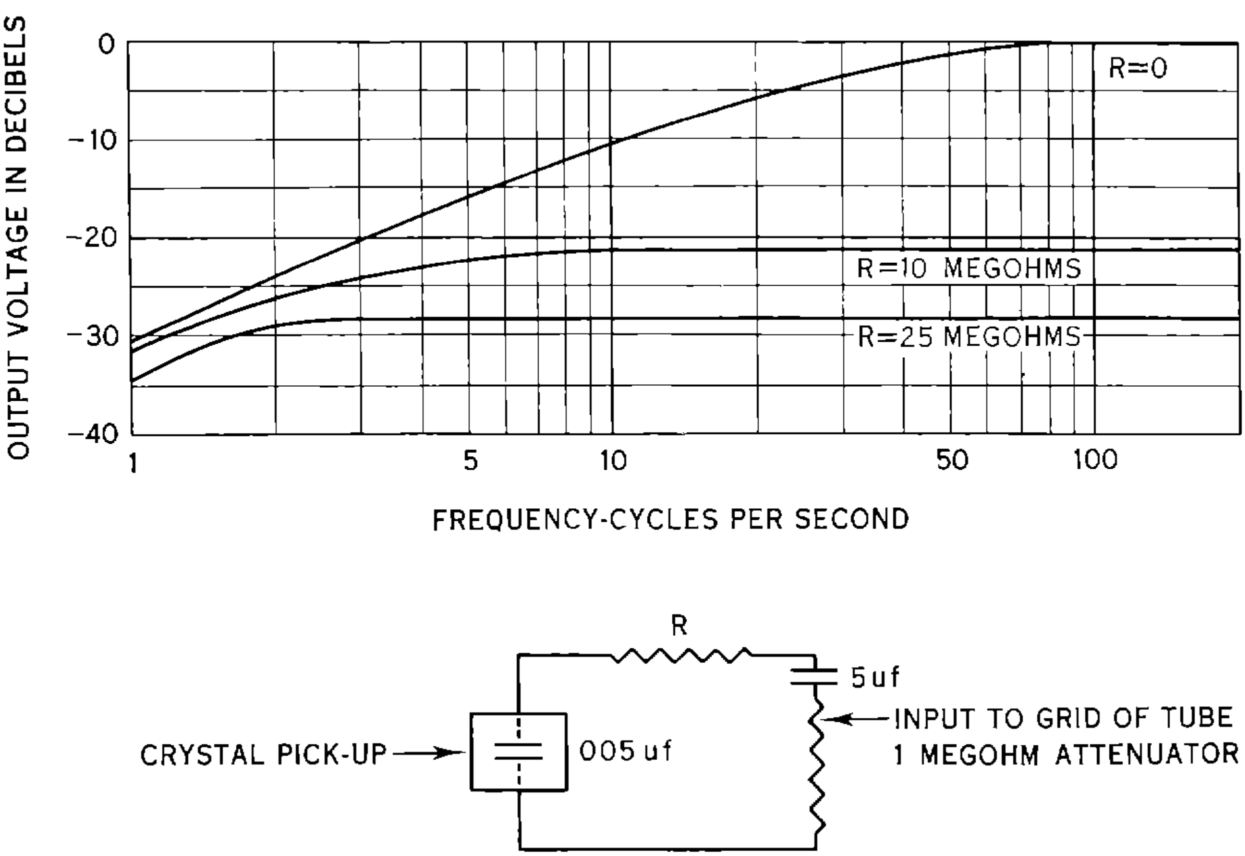


Figure 8 Effect of External Resistance R on Output Voltage of Crystal Pick Up with Constant Acceleration Amplitude Applied

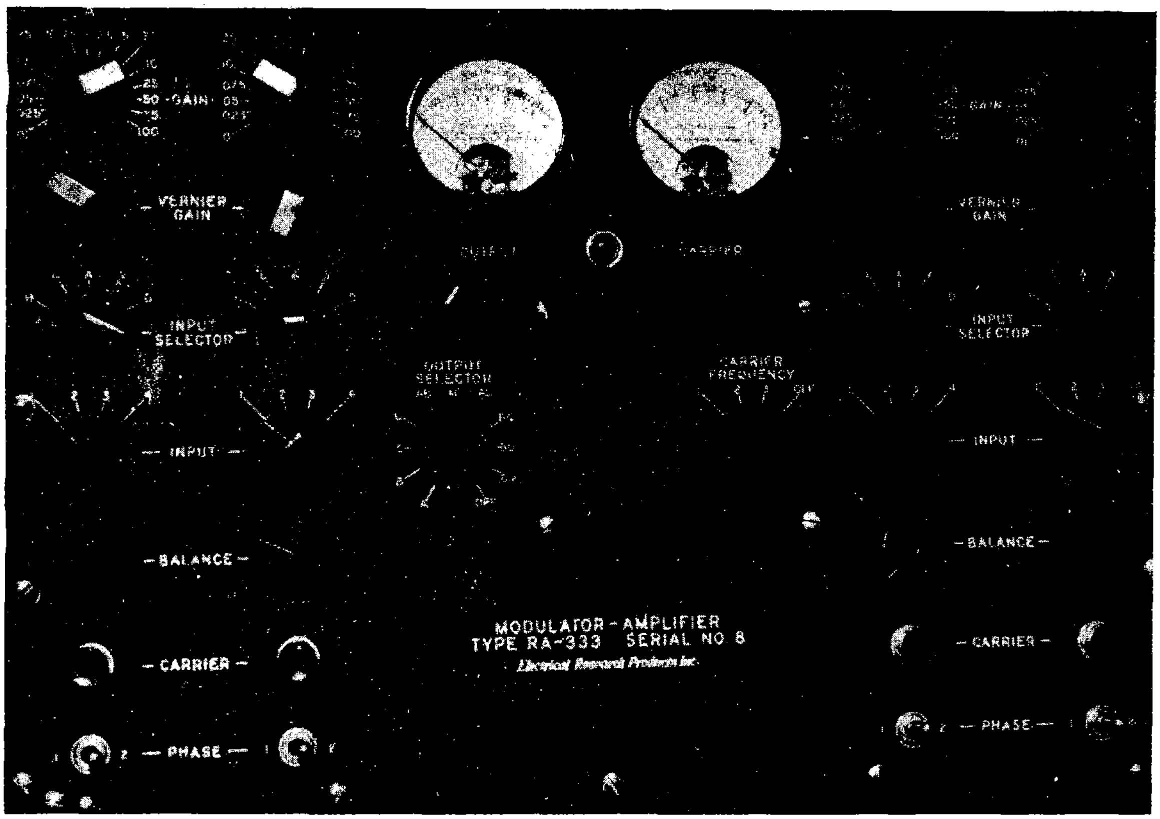


Figure 9. Front Panel of C. A. A. Amplifier

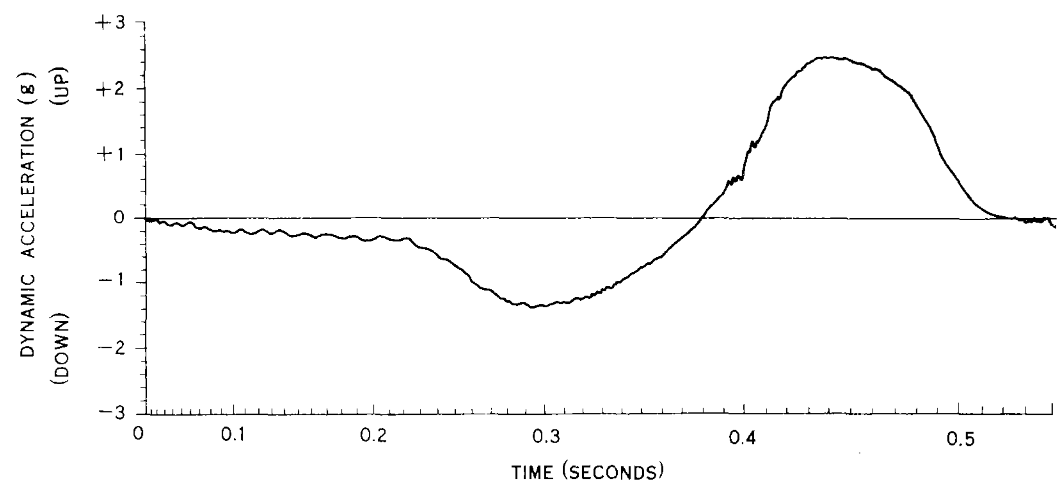


Figure 10a. Acceleration Record for Shock Excitation.

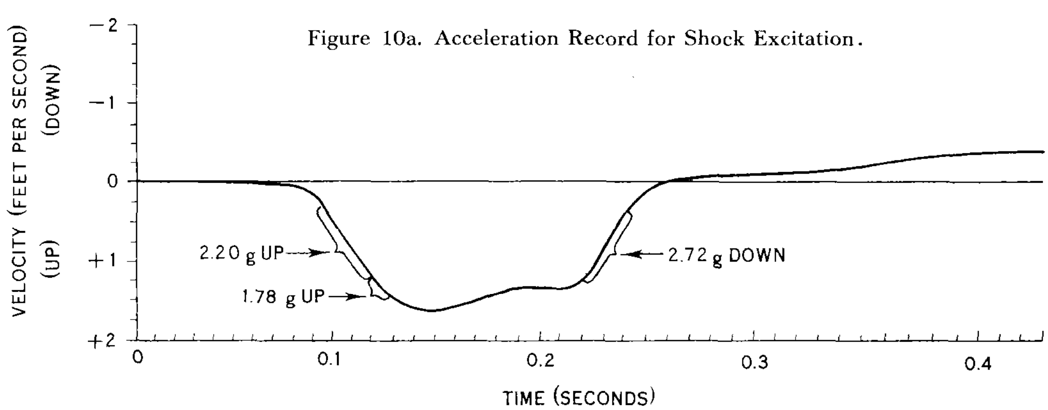


Figure 10b. Velocity Record for Shock Excitation.

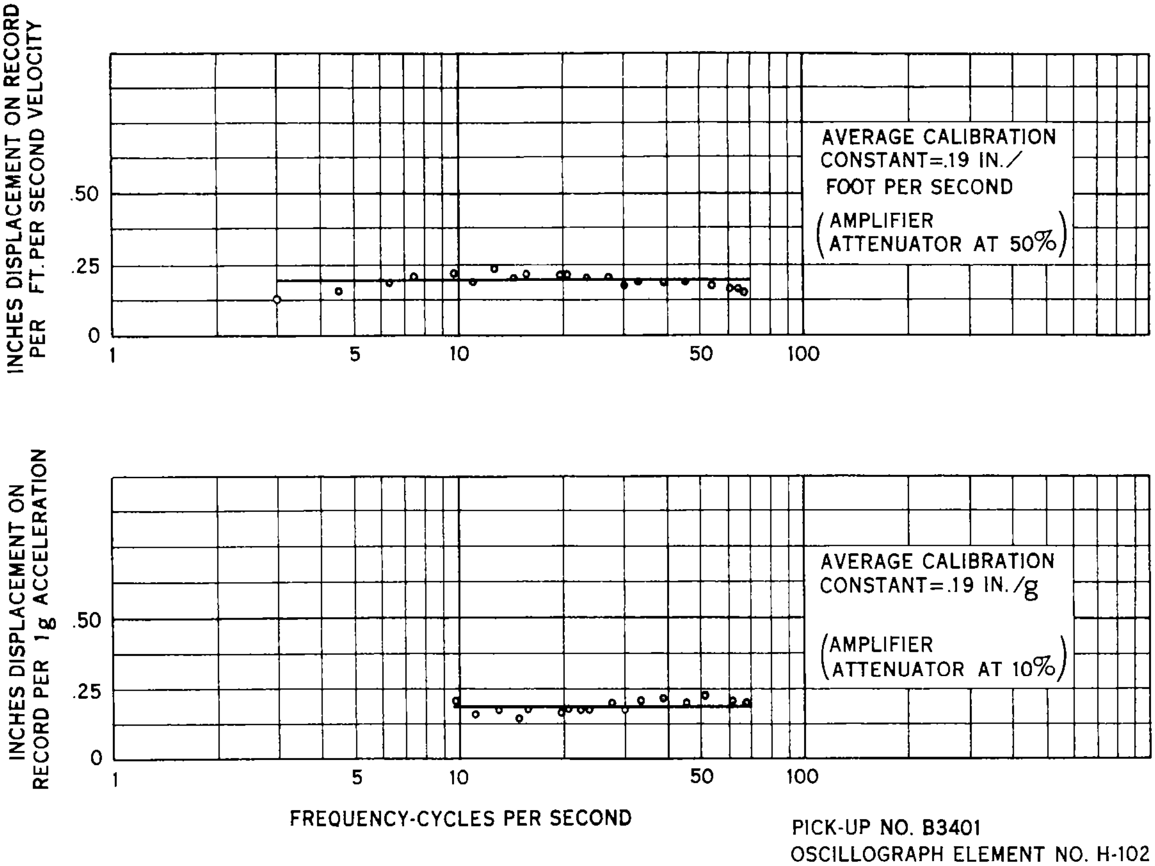


Figure 11. Calibration of Vibration Measuring System.

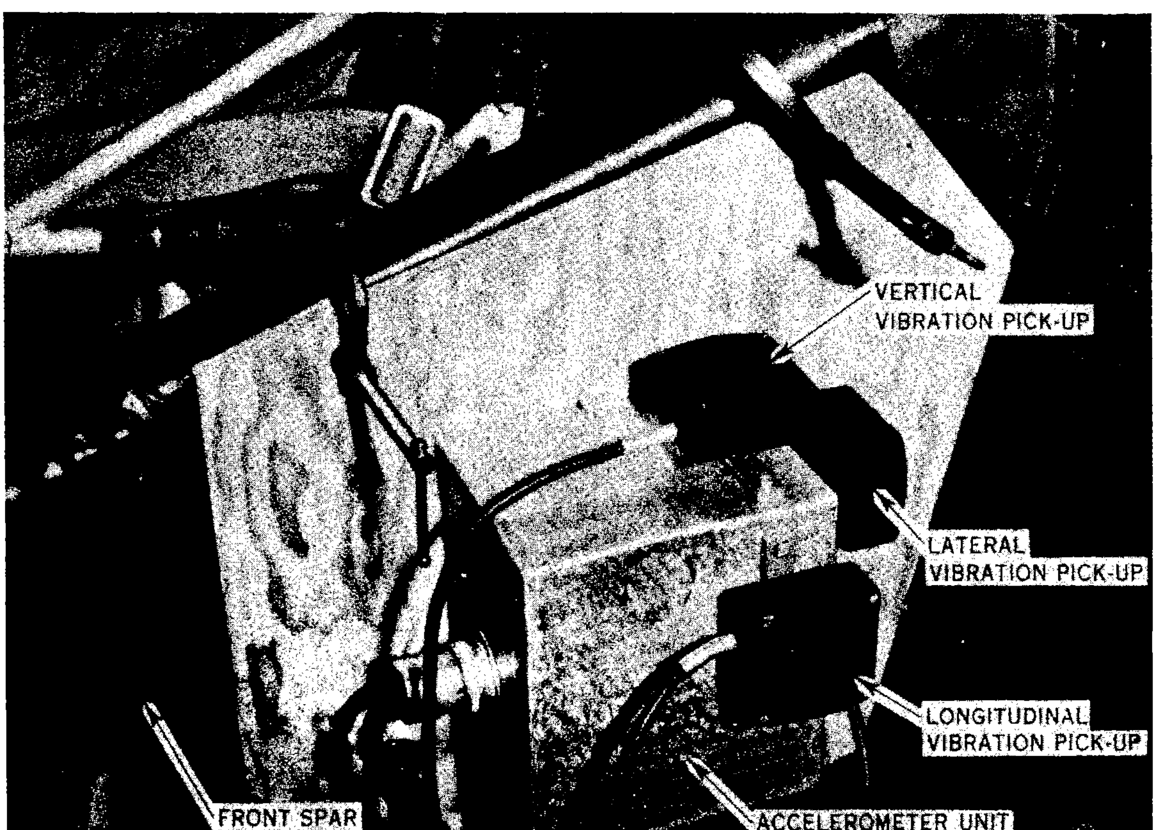


Figure 12. Location of Vibration Pick-Ups and Accelerometer Unit in Boeing 247-D

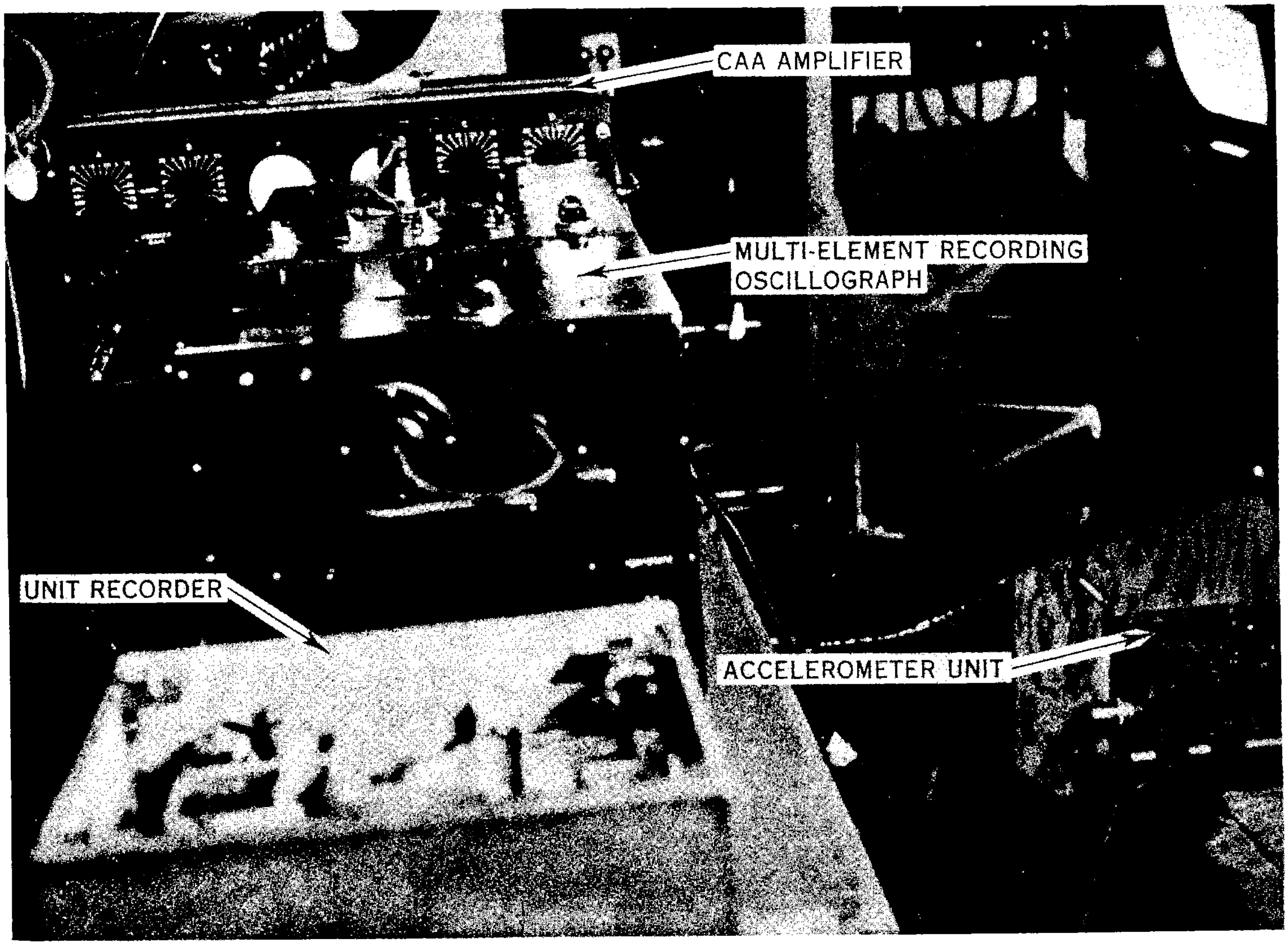


Figure 13. Installation of Vibration Measuring System Inside of Boeing 247-D

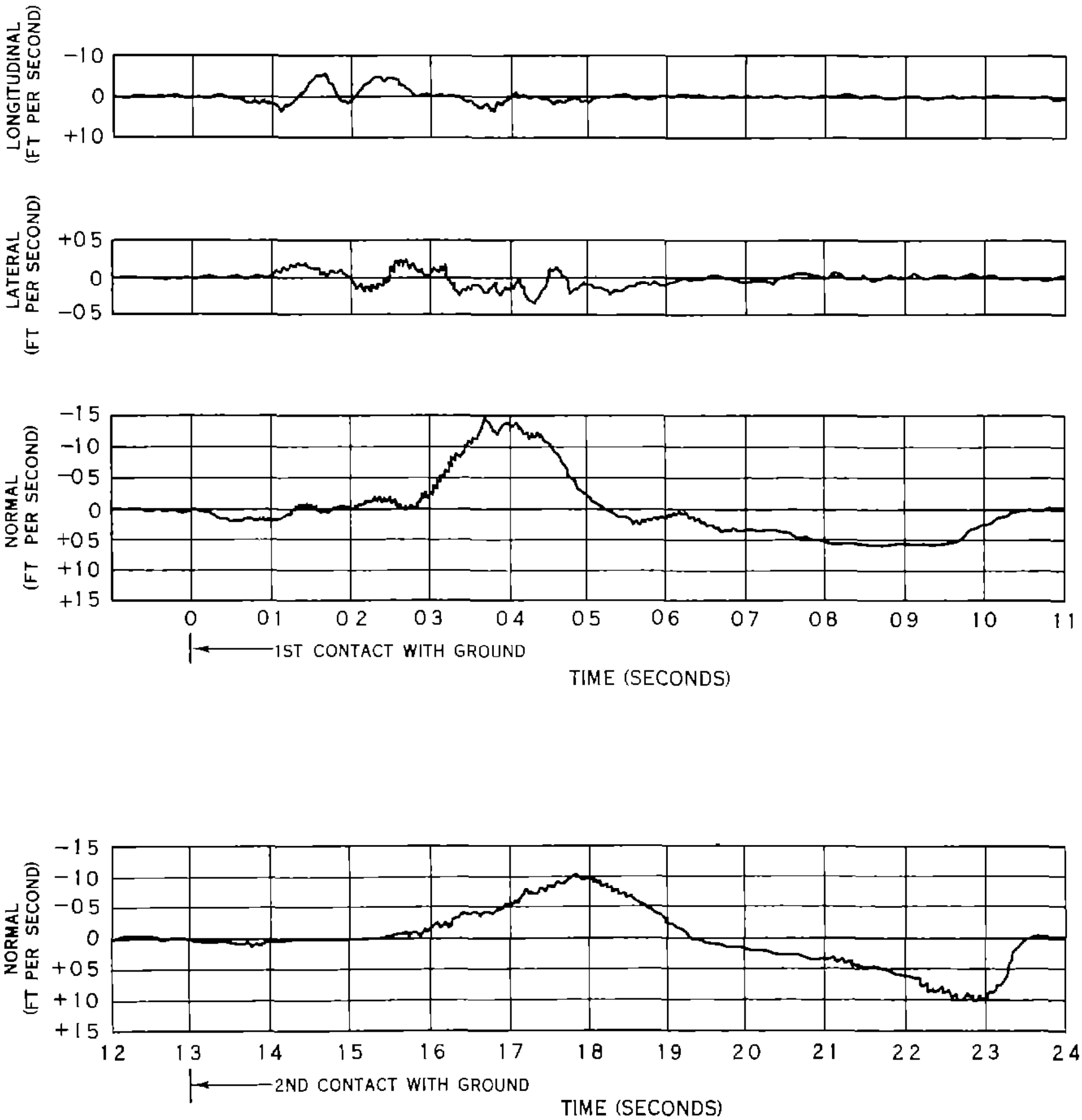


Figure 14a. Dynamic Velocity Record of Boeing (NC 11) Landing (Record No 1151)

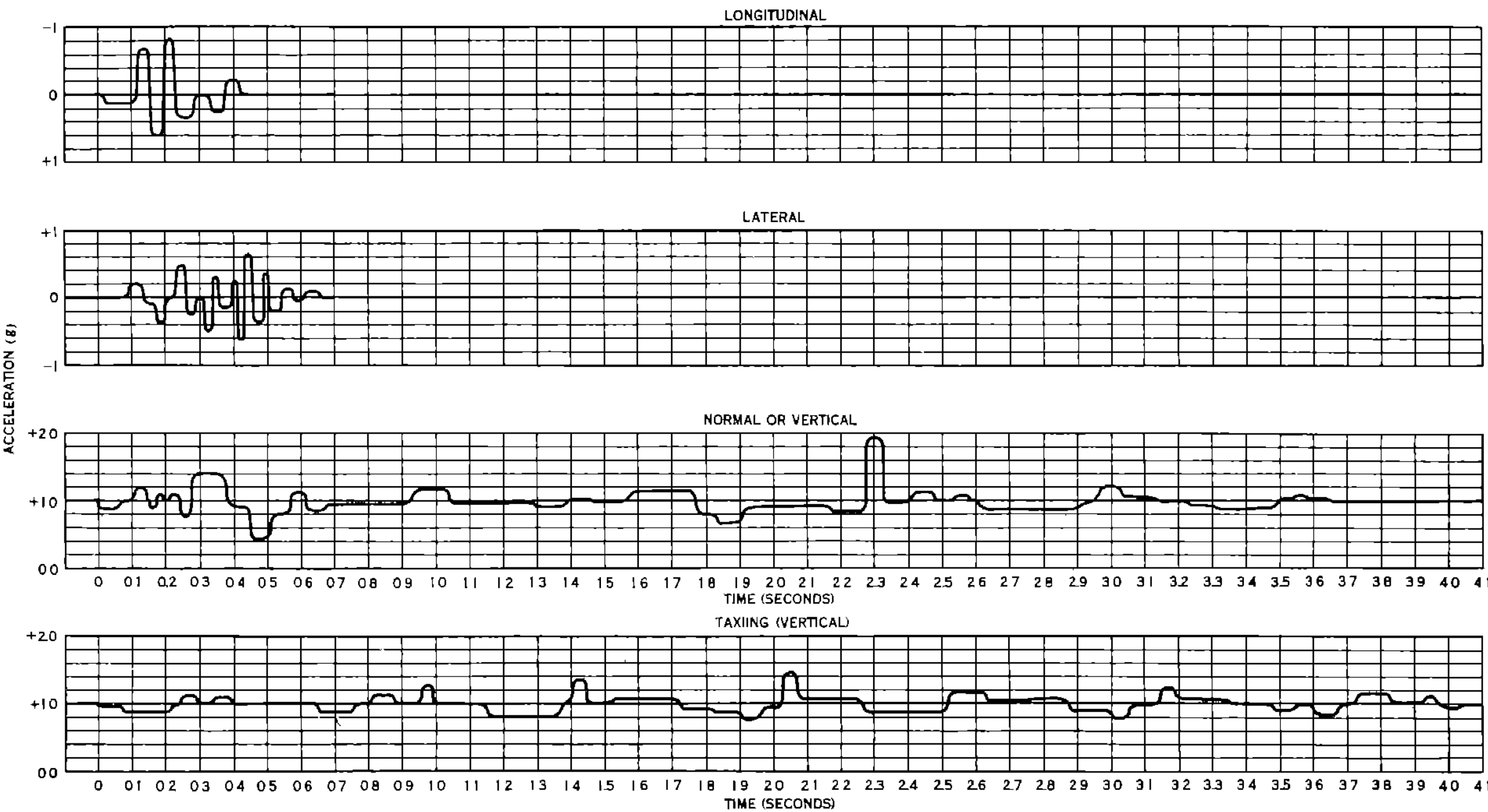


Figure 14b Acceleration Record (Computed from Figure 14a)

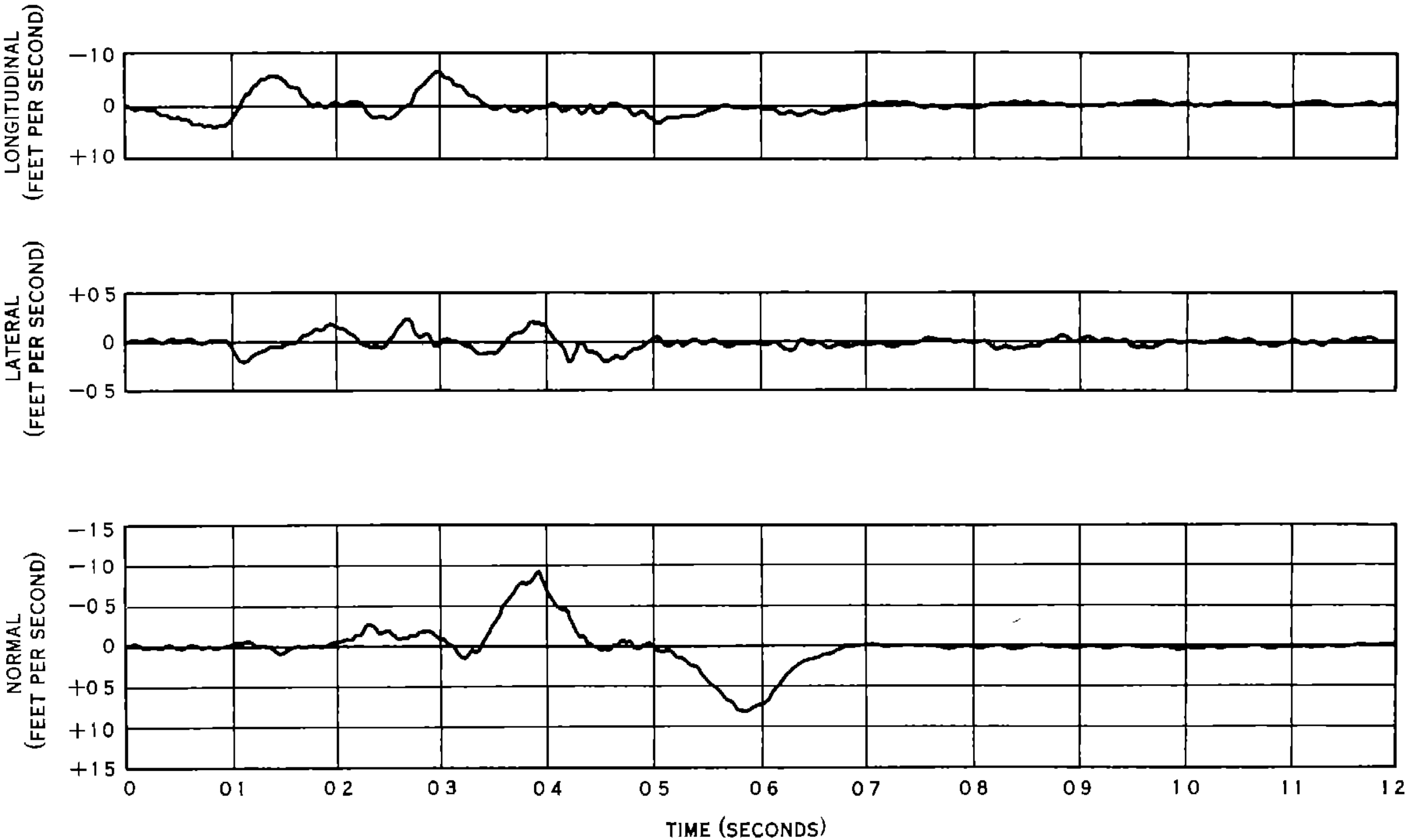


Figure 15a. Dynamic Velocity Record of Boeing (NC-11) Landing (Record No 1155)

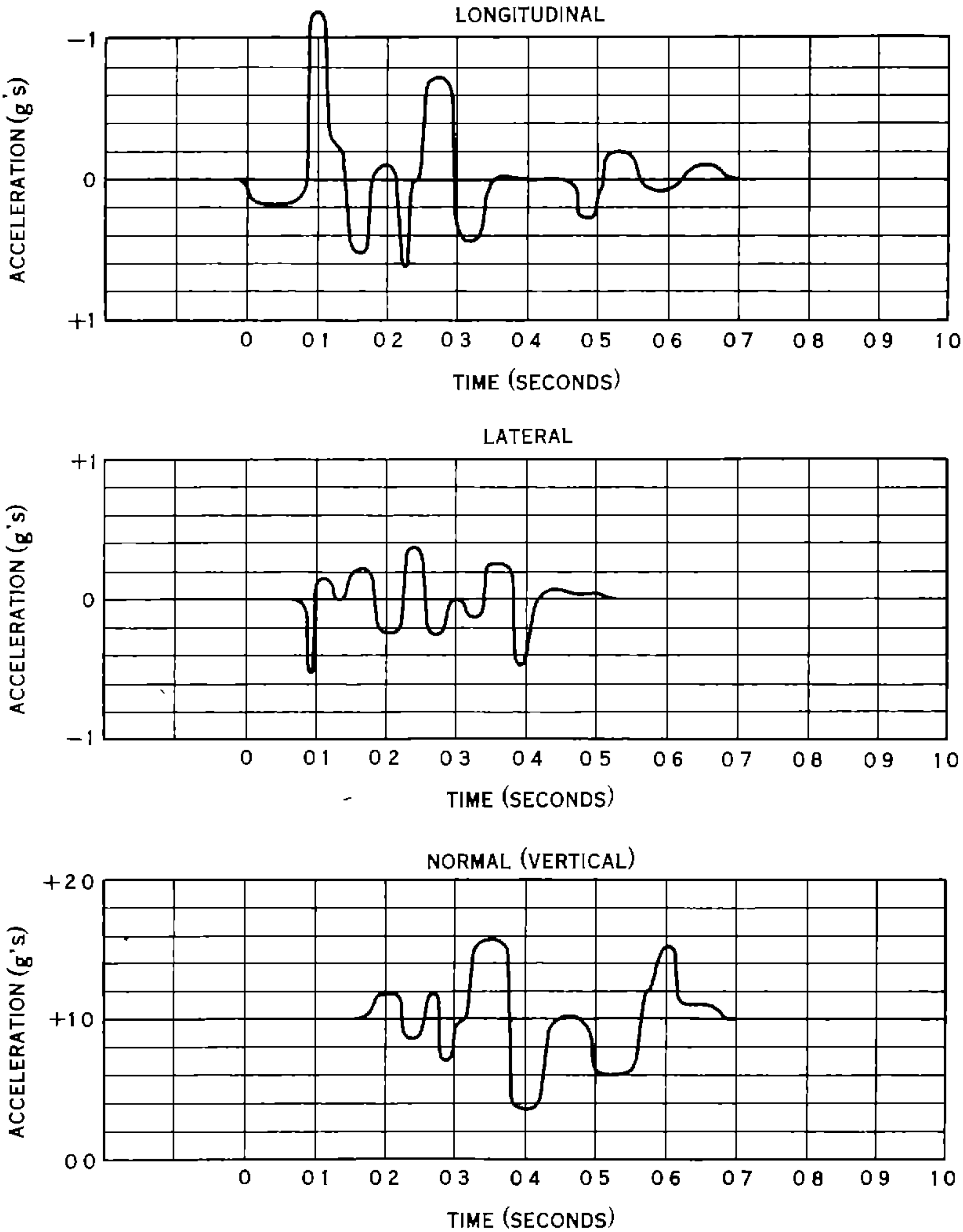


Figure 15b Acceleration Record (Computed from Figure 15a)

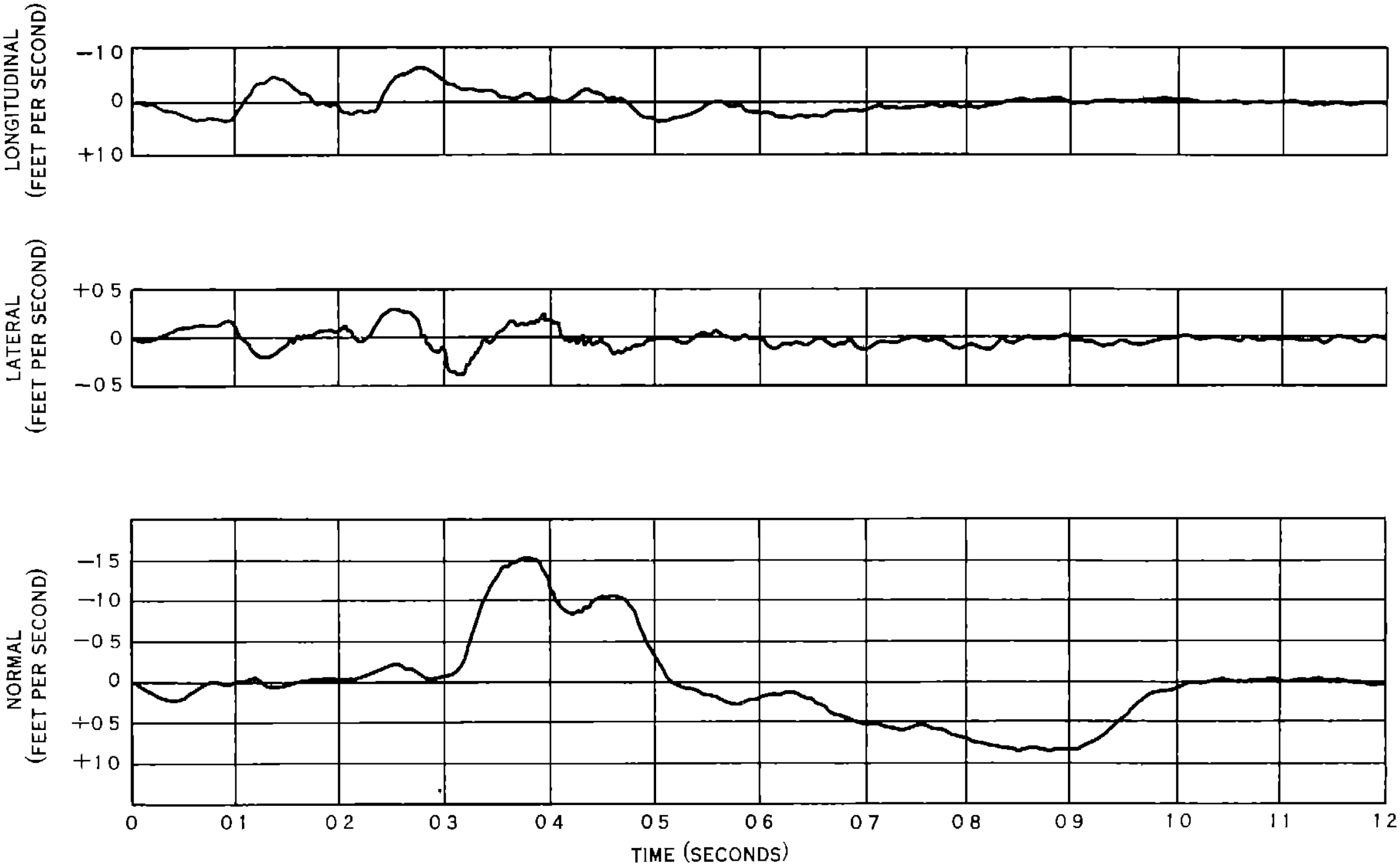


Figure 16a Dynamic Velocity Record of Boeing (NC-11) Landing (Record No 1162)

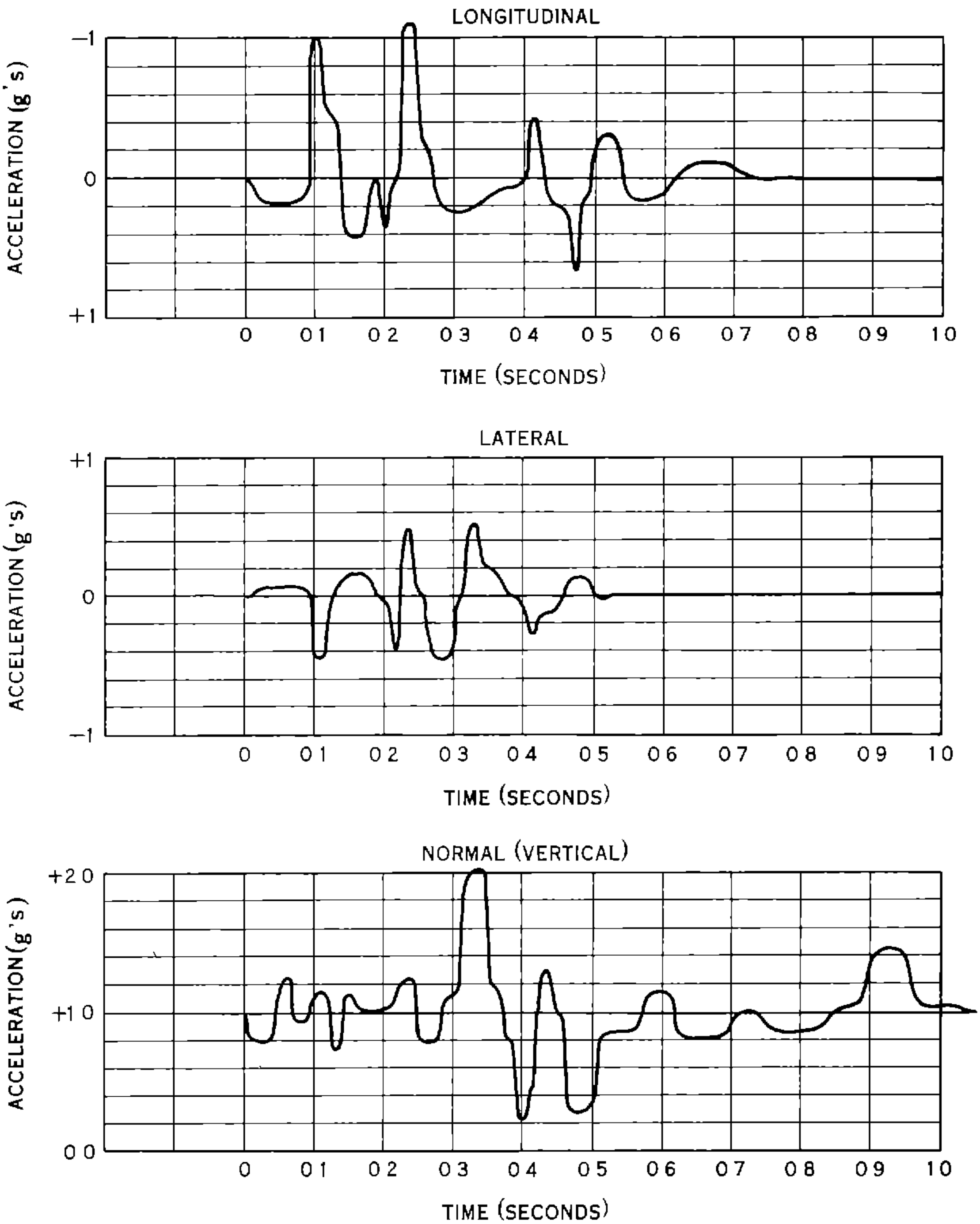


Figure 16b Acceleration Record (Computed from Figure 16a)

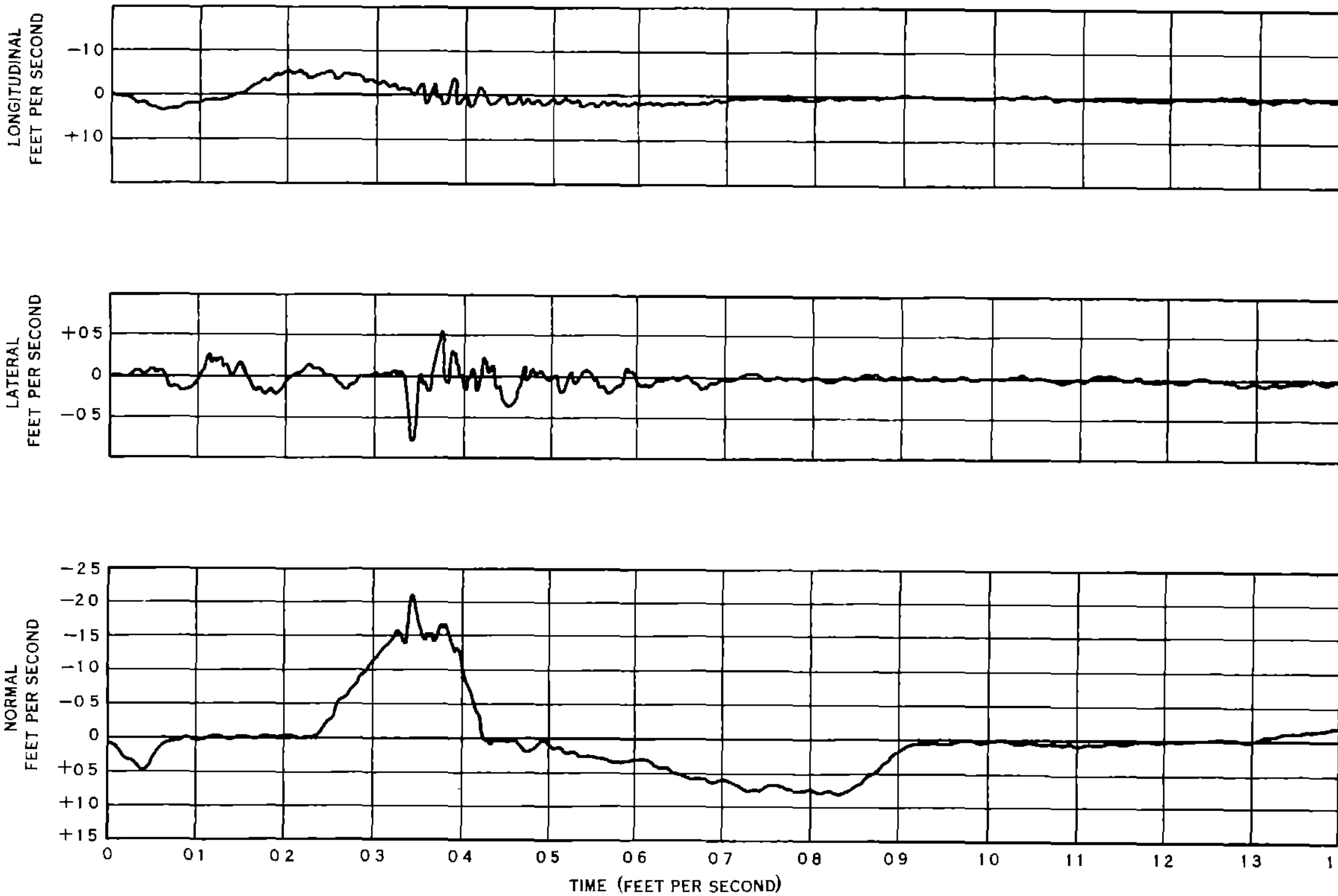


Figure 17a Dynamic Velocity Record of Boeing (NC-11) Landing (Record No 1163)

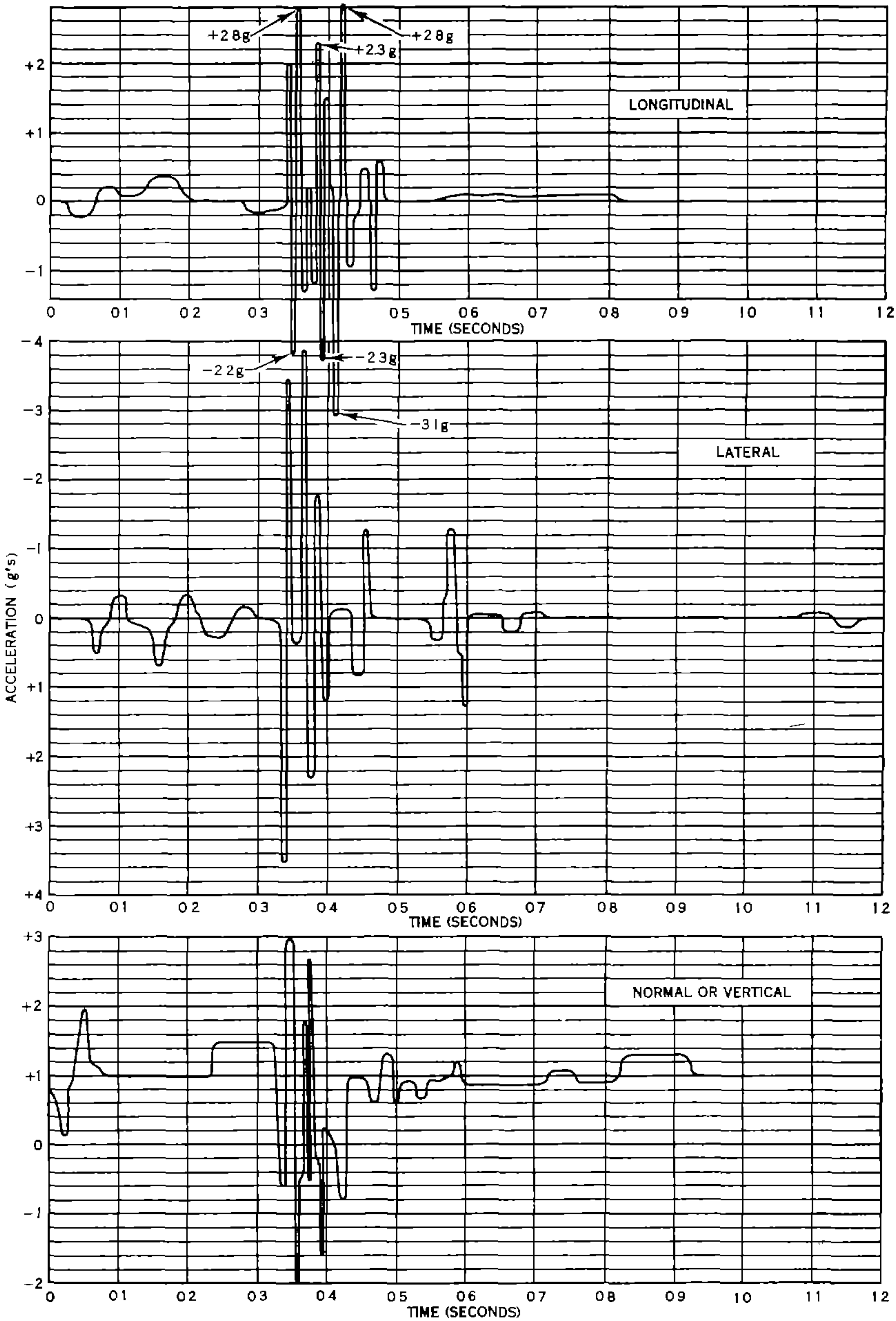


Figure 17b Acceleration Record (Computed from Figure 17a)

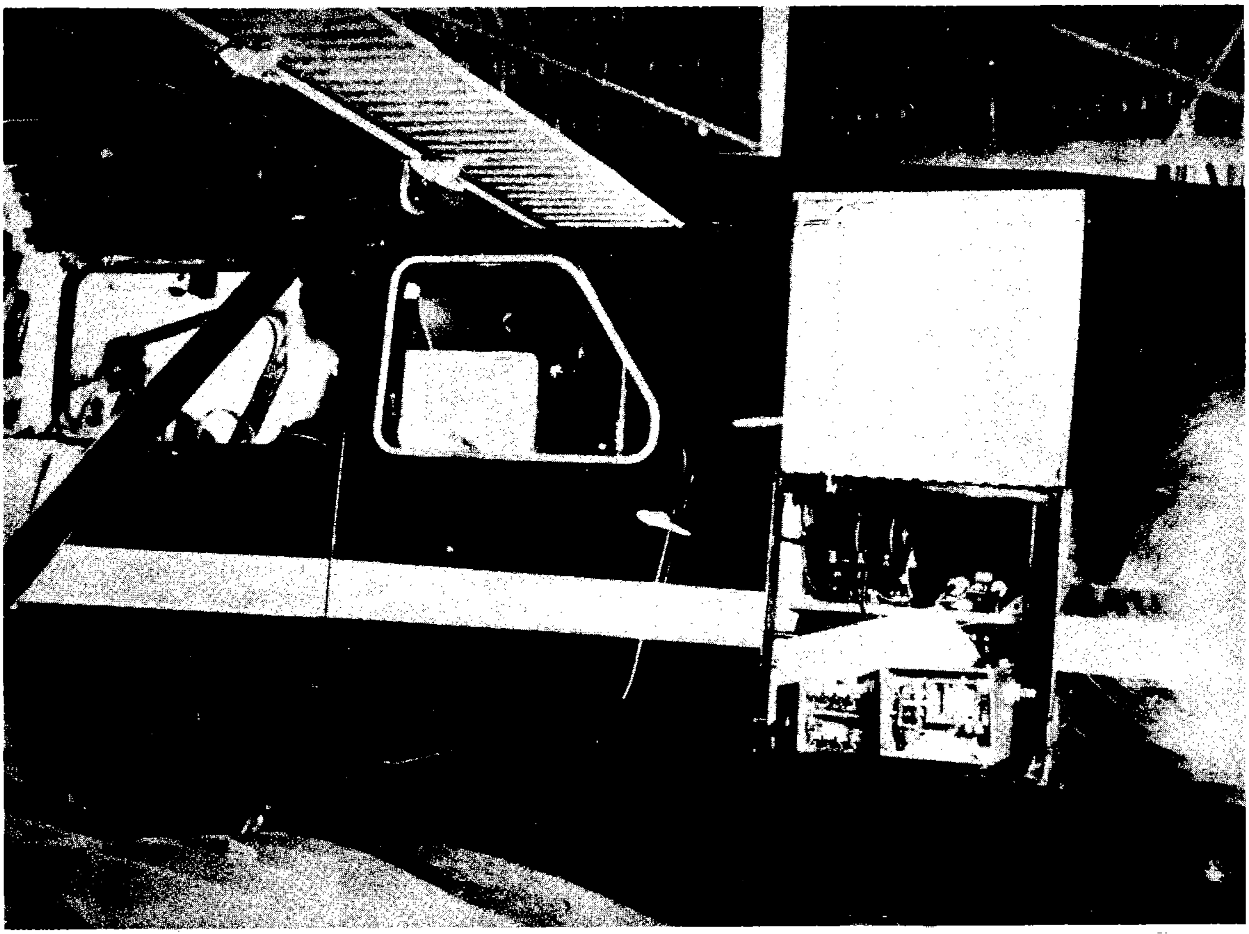


Figure 18. Installation of Automatic Recording Accelerometer in Waco (NC-17) Airplane.

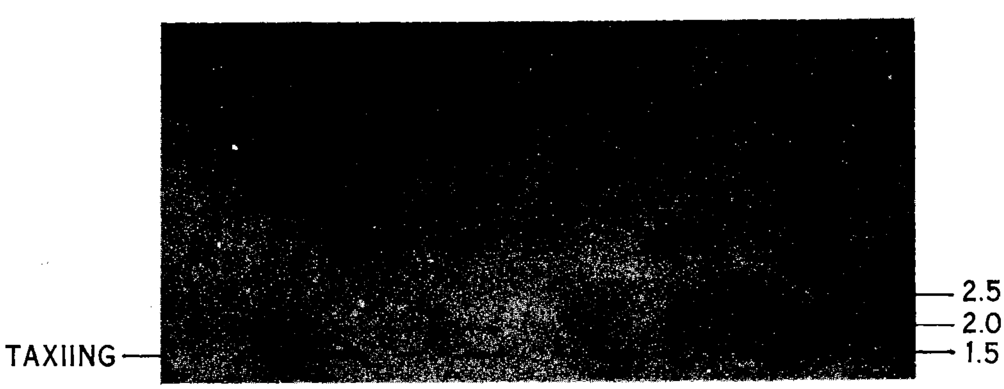


Figure 19. Record of Accelerations Experienced During Landings of Waco Airplane.