AN INSTRUMENT SYSTEM

FOR

MEASURING PAVEMENT DEFLECTIONS

PRODUCED BY

MOVING TRAFFIC LOADS

by

Gilbert Swift

Research Report 162-1F
Research Study No. 2-8-72-162
"Development of Instrument System for Measuring
Pavement Response to Moving Traffic Loads".

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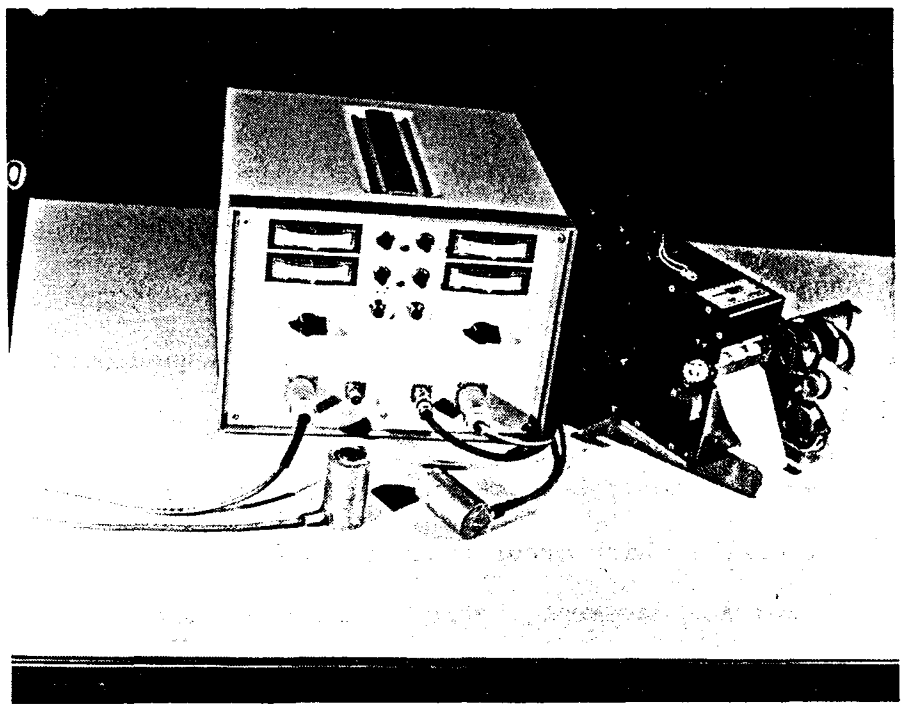
PREFACE

This is the first and the final report on Research Study No. 2-8-72-162. This one-year feasibility study, entitled "Development of Instrument System for Measuring Pavement Response to Moving Traffic Loads", was conducted by the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department and the Department of Transportation, Federal Highway Administration.

The author wishes to thank all members of the Institute who assisted in the work leading to the present report.

The author is grateful to the Texas Highway Department for their interest and cooperation, especially to Mr. James L. Brown and Mr. L. J. Buttler of the Highway Design Division for their support of this research.

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification or regulation.



Frontispiece

Pavement Displacement Measuring System.

ABSTRACT

This report describes a feasibility study which has led to the development of a "first generation" instrument system for measuring transient pavement deflections. Accelerometers embedded in the pavement structure are employed to sense the basic motion. Dual analog integration is utilized to obtain and record output indications proportional to displacement. The circuit characteristics are such that transient vertical movements as small as 0.002 inch, or horizontal movements as small as 0.0005 inch, occurring within less than two seconds can be recorded. These characteristics enable the system to be used, with vehicles travelling at speeds above 20 mph, in any normal pavement structure. These performance characteristics could be altered, if desired, to accommodate the larger, longer movements which occur on bridge decks.

Key Words: Pavement, Deflections, Measurement, Traffic-Loading.

SUMMARY

An instrument system has been developed for measuring the deflections which occur within a pavement structure under the action of vehicular traffic loading. The system utilizes one or more accelerometers buried in a small cavity drilled into the structure. The system integrates the accelerometer signals twice and thus produces recordings of the pavement deflections. The measuring system is operated from batteries and may be used in a vehicle parked beside the location at which the accelerometers are installed. Either vertical or horizontal deflections, induced by vehicles traveling at speeds above 20 mph, can be recorded.

IMPLEMENTATION STATEMENT

This study has demonstrated the feasibility of the concept of measuring the deflections of a pavement structure produced by traffic loading, by means of accelerometers installed in the pavement. The instrument system developed in this study has been found suitable for field use and can be applied to measure the dynamic vertical and horizontal displacements which occur at any selected depth within a pavement structure subjected to normal traffic loading. By minor modification, the system can be adapted to record the larger, longer-duration movements which occur on bridge decks.

It can be used to determine the effects of vehicle loading and speed on the deflection behavior of typical pavement structures. The system can also be utilized to compare pavement structure response to traffic loading with that observed under Dynaflect or Benkelman beam test conditions.

A simple installation procedure was developed for placing the sensors where desired. The recording portion of the system can be carried in a passenger vehicle and may be operated while parked in the vicinity of the installation. Thus, the deflection behavior of pavements, or of bridge decks, can be measured quickly and conveniently to provide a better understanding of their responses to traffic loadings.

The principal limitation of the present system was found to be the tendency of the accelerometers to "drift". This instability frequently spoils the recording of the passage of a particular vehicle. Accordingly, any future development efforts should be concentrated on reduction of this tendency.

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1. INTRODUCTION

This final report covers an investigation of the feasibility of developing an instrument system for measuring the dynamic transient deflections which occur in pavement structures under normal traffic loading conditions.

Measurements of pavement deflections have heretofore been limited to observation of rebound, upon removal of a previously stationary heavy vehicle (Benkelman Beam Testing), or to cyclic measurements, such as those obtained with the Dynaflect, which applies a repetitive 1000 lb. load eight times per second, or to static load tests such as the Plate Bearing Test.

Direct observation of the deflections induced by moving traffic loads, has, so far is known, not been possible, for lack of suitable instrumentation. (See note under reference (5).) The principal limitation which has hindered the development of instrumentation for this purpose is that a reference location, sufficiently fixed in position and sufficiently near the point whose deflections are to be measured, is not available. Accordingly, the present study undertook to determine the feasibility of a measuring system which employs inertial sensors and therefore requires no external fixed reference point.

2. BACKGROUND

This research had its inception in a Technical Proposal dated May 23, 1969, which was submitted to the U. S. Department of Transportation, Federal Highway Administration, in response to their prospectus RFP-154. Specific Objective 1 of the prospectus read as follows:

> "Development of transducers and devices for measuring the essentially recoverable (under dynamic, momentary loading) vertical deflections of the pavement surface and of points beneath the pavement surface in any component of the pavement including subgrade, subbase, and base due to stationary and moving loads. The devices shall have a range of vertical displacement of 0.0 - 0.05 inches with precision of measurement to 0.0001 inch. The devices shall have a flat frequency response from 0 to 100 cycles per second within 2 percent, and shall be designed to produce noise-free, usuable data under normal traffic loads."

The plan of approach for meeting this objective, was described in the proposal, as follows:

> "The tentative plan for this item is to develop a small, rugged, hermetically sealed unit containing a force-balance servo-accelerometer as its basic motion sensor. The accelerometer signal, after being brought out away from the pavement structure through a suitable cable, will be integrated twice by solid-state electronic integrators to provide displacement indications. All specified requirements, except the frequency response range, will be met."

Consideration of the requirements of Objective 1 in the light of present technology of motion-sensitive transducers, and of existing techniques for applying them, led to the conclusions that an inertial reference should be used and that accelerometers were available having the characteristics required to fulfill the objective of measuring displacements of 0.0001 to 0.05 inches at all frequencies between 1.0 and 100 Hz. (See Figure 1.) It was also mentioned that the low frequency limit might be extended to the vicinity of 0.1 Hz if the maximum displacements of 0.05 inches were limited to frequencies below 30 Hz.

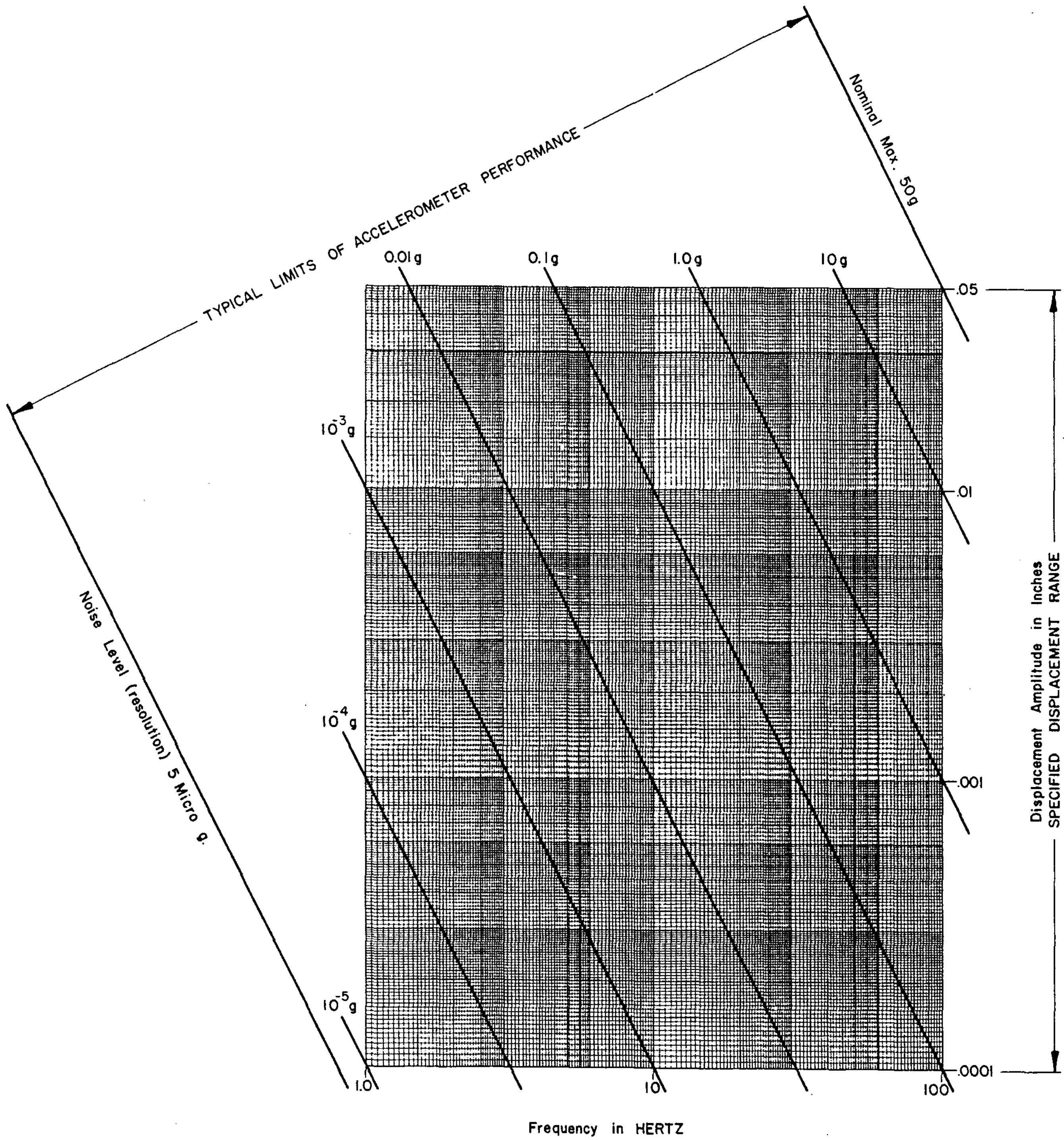

Figure 1: Relationship Between Displacements and Accelerometer Performance Limits.

A paramount consideration underlying this proposed plan was the fact that one aspect of the stated objective is believed unattainable. Specifically, it is not deemed feasible to measure this wide span of small displacements to the accuracy required, over the entire frequency range down to and including zero frequency. Any displacement measurement requires a reference point. If a physical, tangible, reference point is to be utilized, it must be sufficiently remote to remain undisturbed during the measurement, to the extent set by the specified accuracy of the measurement. In a pavement system subject to normal traffic, suitable physical reference points are quite remote; at least as far as 50 feet, and perhaps as far as 400 feet distant on the surface, or as deep as 20 feet or more below the point of application of load. Use of such reference points is considered incompatible with the specified performance, especially over a wide range of frequencies up to 100 Hz or greater. Accordingly, an inertial reference is believed to be the most practical alternative. Such a reference point may be regarded as the average location of the measuring point during the recent past. Displacements relative to an inertial reference point may be measured with great accuracy over wide ranges of amplitude and frequency by integrating the response of suitable inertial (velocity or acceleration) transducers, such as geophones or accelerometers[1]. The principal limitation introduced by the inertial reference is that displacement response down to zero frequency (static response) is not attainable. However, it appears fully feasible to obtain flat (constant within 2%) displacement response from below 1.0 Hz, to above 100 Hz together with the desired displacement ranges by using this approach.

Modern force-balance servo-accelerometers are obtainable under specifications which permit, after two integrations of their output signals, measuring the displacements expected within pavement systems under moving traffic loading. Furthermore, it appeared that suitable electronic apparatus for performing the necessary integrations with adequate accuracy and stability could be developed within the existing state of the art.

Accordingly, the basic measuring system was originally proposed in 1969. However, that proposal was abandoned when RFP-154 was cancelled in 1970. In the belief that there exists a need for instrumentation which can record the deflections, both vertical and horizontal, within a pavement structure under the transient loading provided by passing vehicles, a new but similar proposal was made to the Texas Highway Department in March 1971 to initiate the present one year feasibility study directed toward the following objective:

> "The design and construction of a prototype displacement measuring system and demonstration, in a pavement structure, of its feasibility and its performance characteristics."

3. CHRONOLOGICAL ACCOUNT

This study began in September 1971 with preparation of purchase specifications for the critical components. Accelerometers were purchased in accordance with the specifications detailed in Appendix A.

Upon completion of verification tests to insure that the specified performance of these sensors had been attained, the circuit development was conducted. During this phase it became apparent that, in a system of two integrators in cascade, it is extremely difficult to obtain long-term stability. If two integrators are directly coupled, an offset in the first necessarily produces the integral of this offset, which is a steady drift, at the input of the second. The output of the second integrator thereupon drifts at an ever accelerating rate. The stability was substantially improved by coupling one integrator to the other through a suitable capacitor which provides infinite attenuation at zero frequency while passing all frequencies of interest (those above approximately 0.03 Hz in the present apparatus).

At the completion of the electronic circuit design phase, overall system response tests and displacement calibrations were performed. Initially it had been planned to operate the system with an available galvanometer type of recorder. However it was found that the large power requirements of this device, together with interference between its 115 volt AC chart-drive motor and the displacement measuring system, made this recorder unsuitable for field use. A recorder (shown in Figure 2), of the heat-writing type, was then obtained and converted to operate from batteries. This recorder has been completely satisfactory.

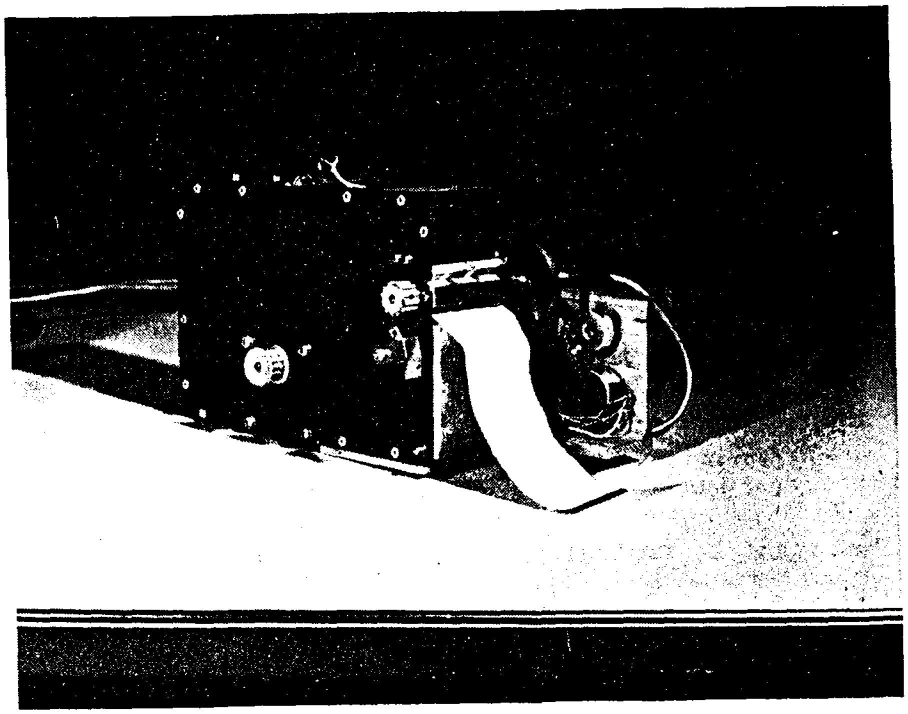

Figure 2: Single Channel Recorder.
(Modified for operation from batteries.)

The first field installation of the system was made at the Texas A&M Research Annex. One accelerometer was buried in a typical flexible pavement roadway and the vertical deflections produced by one passenger car and one truck were recorded. Dynaflect* measurements (2) were also made on this site. However, before any horizontal displacements could be recorded, the opportunity arose to install the equipment in the vicinity of Fairfield, Texas where vertical deflections were recorded on a private haul-road under specialized vehicles carrying loads up to 240,000 pounds. At this location approximately 100 recordings were made of the passage of these 3 axle vehicles, some fully loaded, others empty, at approximately 25 differently constructed test sites. The measured deflections were utilized in another research study to evaluate the elastic properties of the several sites. While most of these recordings were satisfactory, it was learned during this series of measurements that it is very important to implant the accelerometers firmly and relatively deep in the pavement system in order to avoid initial shifts of position upon application of the first few loadings after installation (see Appendix B).

After re-implanting the sensors in a second flexible pavement at the A&M Research Annex, a series of recordings was made using a variety of vehicle speeds and loadings. That activity, data analysis and the preparation of this report represent the final phases of this one-year feasibility study.

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*Registered trademark, Radiation Engineering & Manufacturing Company (REMCO) 7450 Winscott Rd, Fort Worth, Texas.

4. APPARATUS

4.1 Accelerometers

The Kistler Model 305T Servo-Accelerometer utilized in this study meets the most exacting specifications of any commercially available accelerometer known to the author. (See Appendix A.) Almost unique among instruments of any kind is its ability to respond throughout a range of ten million to one; that is from 5 micro-g to 50 g. However, for this application it would be preferable if its response ranged, instead, from 0.5 micro-g to 5 g.

The operating principle of a force-balance servo-accelerometer is illustrated by Figure 3 which has been taken from the Kistler Company's literature. As shown in this figure, the seismic mass of a few grams, is non-pendulously suspended by 3 pairs of flexible arms which constrain it to move only axially. Movement of this mass is sensed by a capacitive displacement sensor, which, through its associated amplifier, produces a current in the forcer coil such as to restore the mass to its original position. The servo constraint is sufficiently "tight" that almost no appreciable movement ever occurs. Thus the current in the forcer coil, to which the output signal is proportional, continuously corresponds to the force acting on the seismic mass. Since force is equal to mass times acceleration, this current constitutes an accurate measure of the instantaneous acceleration acting along the sensitive axis.

The overall dimensions of the basic accelerometer are 1.125 inches diameter by 2 inches long. However, for use in this study the accelerometers were placed in slightly larger waterproof housings as shown in Figure 4. Each accelerometer was equipped with a 40-foot shielded multi-conductor cable terminated in a plug which fits a receptacle on the panel of the

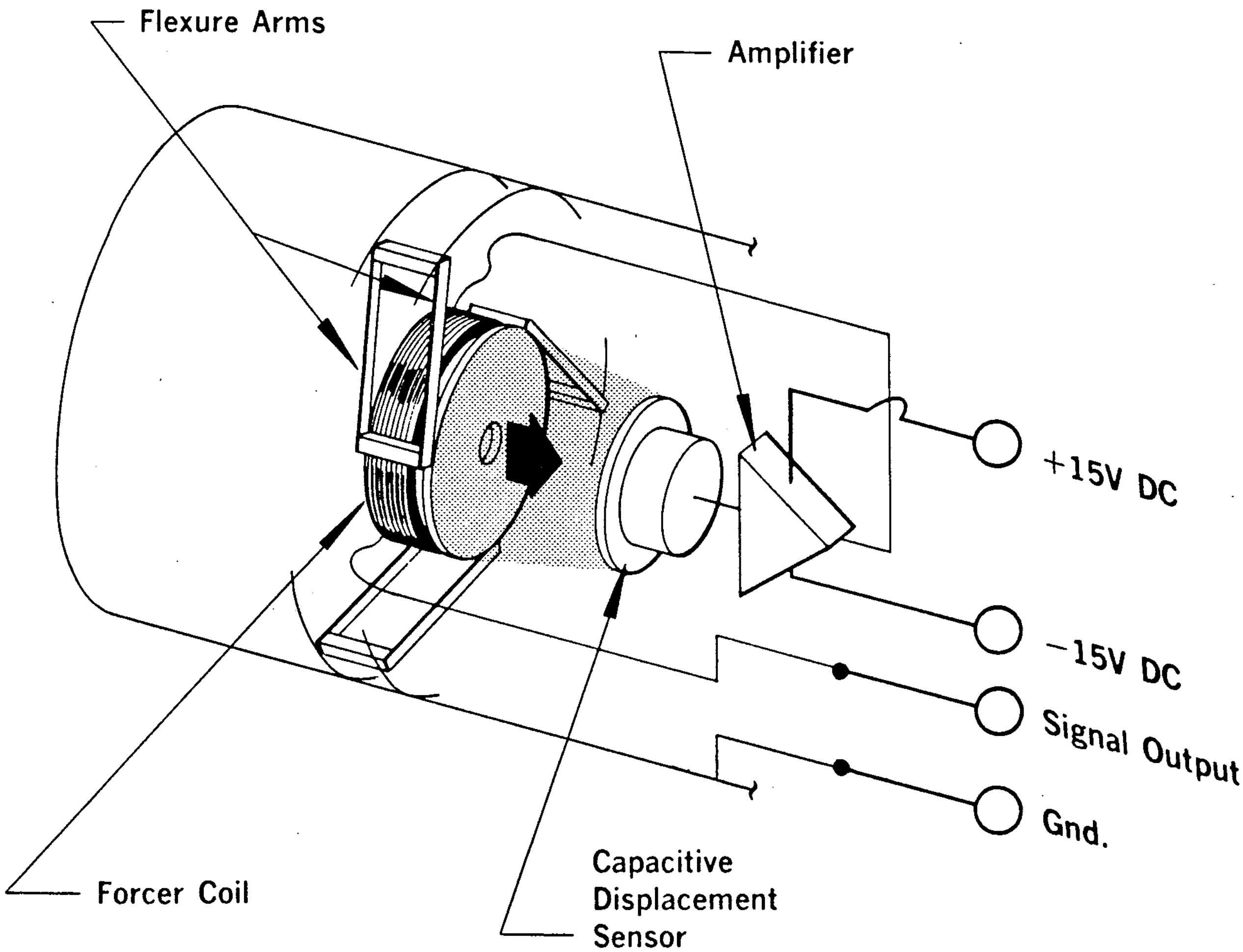


Figure 3: Diagram showing the working elements of a Force-Balance Servo-Accelerometer.

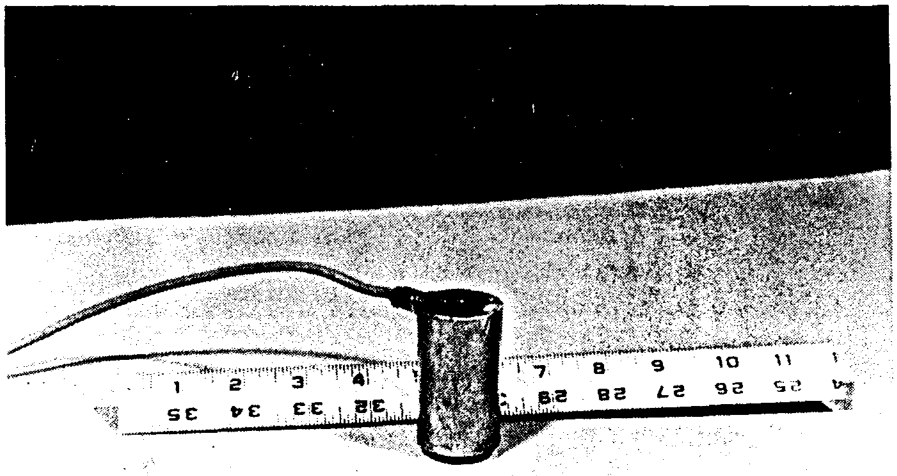


Figure 4: Accelerometer in Waterproof Housing.

dual integrator unit.

4.2 Dual Integrator Unit

This unit, shown in Figure 5, provides two channels which may be used separately or simultaneously. Each channel accepts the output signal from an accelerometer, provides an adjustable nulling current to oppose the effect of gravity, and performs a dual analog integration on the accelerometer signals. Thus it provides output signals proportional to displacement.

The instrument is equipped with meters which monitor the output of each integrator. The gravity-null control serves to center the pointer of the lower meter while the bias control of the second integrator serves to center the upper meter. A push-button below these controls restores the second integrator to zero.

4.3 Integrator Characteristics

An analog integrator comprises, basically, an operational amplifier with a capacitor as its feedback element, as shown in Figure 6. Its equations of operation[3] are:

$$e_o = -\frac{1}{RC}\int_0^t e_1 dt; \text{ for an ideal amplifier of infinite gain.}$$

Equation (1)

or, taking into account the dc offset voltage, V_{os}, and the input bias current, I_B, (Figure 6),

$$e_o = -\frac{1}{RC}\int_0^t e_1 dt + \frac{1}{RC}\int_0^t V_{os} dt + \frac{1}{C}\int_0^t I_B dt + V_{os}.$$

Equation (2)

While the effects of V_{os} and I_B can be effectively nulled by introduction of an adjustable compensating bias, any change of V_{os} or I_B will necessitate readjustment of the compensation. Such changes occur with time and with temperature changes, even in the most stable obtainable

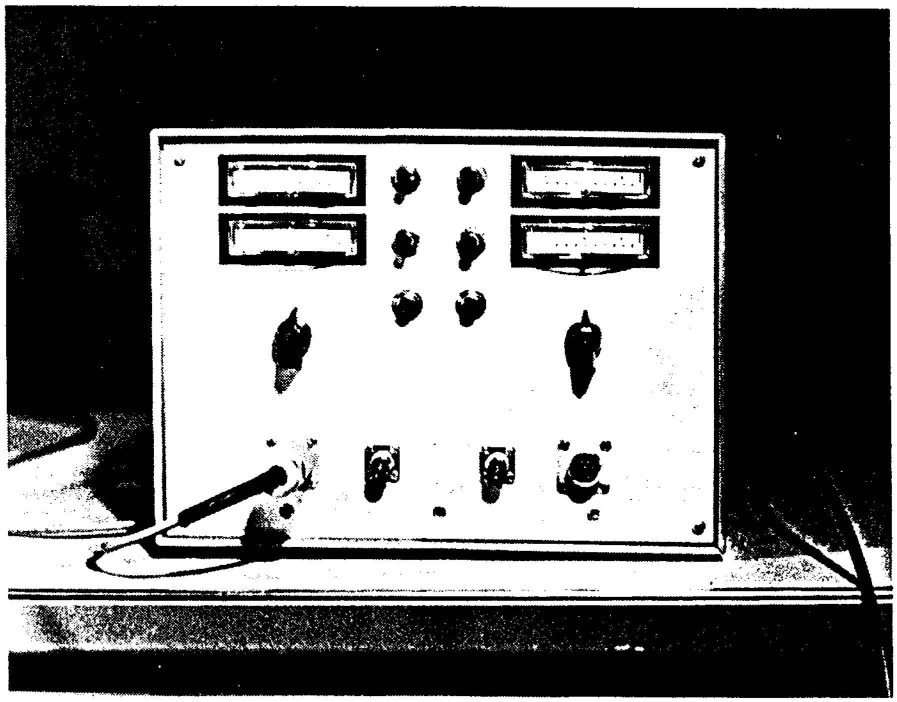


Figure 5: Two Channel Dual Integrator Unit.

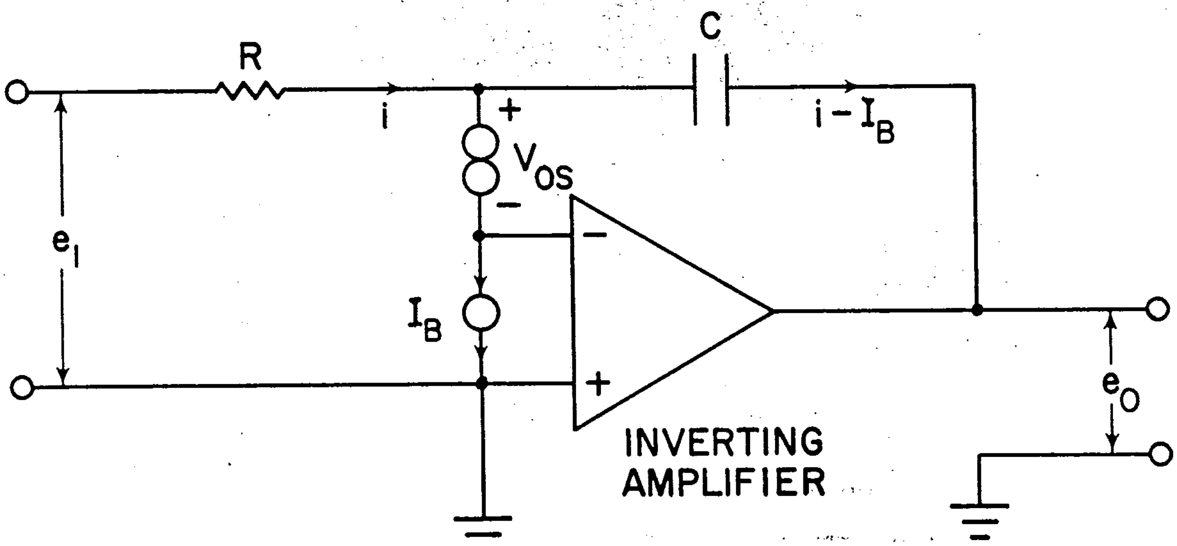


Figure 6: Basic Analog Integrator.

amplifiers. Whenever such a change occurs, the output of the integrator begins to drift. That is, it steadily increases or decreases with time in accordance with the second and third terms of equation (2).

This effect is compounded in a double integrator. An offset at the input of the first integrator produces a steady drift at its output. However, this output constitutes the input to the second integrator, which therefore produces an output signal which drifts at an ever increasing rate. Accordingly, a successful double integrator must be designed to minimize these effects to the greatest extent possible.

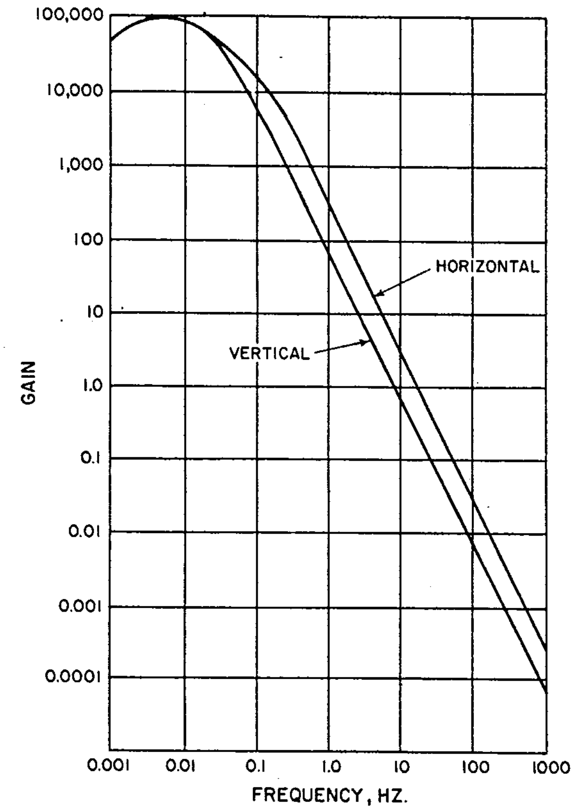
In addition to selecting amplifiers having the utmost stability, the seriousness of the drift problem can be diminished by suitably limiting the frequency band or time-period throughout which the integration is maintained. In no case can this period be unlimited since amplifiers having infinite gain are not attainable. However, the nature of the data to be integrated determines the maximum integration time, or the low frequency limit, for the integrating circuitry.

In the case of pavement deflections caused by moving traffic loads it can be presumed that for normal vehicle velocities above, say, 20 mph, the duration of the appreciable vertical deflections will not exceed about 2.0 seconds and that the duration of the appreciable horizontal displacements will be somewhat shorter. In order to reproduce such displacements faithfully by twice-integrating the corresponding accelerations, it is necessary to extend the integration time substantially beyond the actual duration of the signals. This requirement occurs because of unavoidable phase shift associated with the truncation of the integrator response at a finite frequency (or time) limit.

The present apparatus has been constructed with an integration time of 5.0 seconds for the vertical signal channel and 1.2 seconds for the horizontal channel. Phase shift effects are less serious in the horizontal channel, despite its shorter integration time, because the horizontal motions are inherently bi-directional, while the vertical displacements are always downward.

The response characteristics of the two dual-integration channels are shown in the accompanying figures 7 and 8. Figure 7 depicts the overall response in the frequency domain, and may be regarded as indicating the system response to sinusoidal input signals of equal magnitude, with respect to their frequency. It will be seen in the upper portion of this figure that the frequency range over which the gain diminishes at the rate of 100:1 per decade of frequency, (the slope which corresponds to dual integration), extends from 0.05 Hz to beyond 1000 Hz for the vertical channel, and that the maximum gain (two integrators in cascade) is 100,000 for each channel. This gain is in addition to the gain of the internal amplifiers within the accelerometers. The response with respect to displacements is indicated in the lower diagram of Figure 7.

In a channel having these characteristics, a change of V_{os} within the first integrating amplifier equal to 1 microvolt, or an equal change at the output of the accelerometer, necessarily results in an output signal which rises at the rate of one volt per second. Should a change of this magnitude occur, while the system is being used to record pavement displacements, it would falsely appear that the pavement had suddenly begun to move at the rate of several mils per second. Accordingly, for satisfactory operation of the system, the stability of the first amplifier and of the accelerometer is required to be substantially better than 1 microvolt.



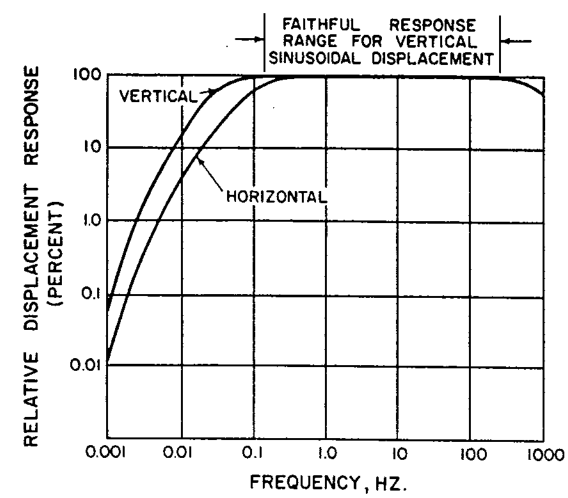


Figure 7: Integrator Response in the Frequency Domain.

Above: Overall gain versus frequency; this also represents the relative response to equal sinsusoidal accelerations.

Below: Displacement response versus frequency; this represents the relative response to equal sinsusoidal displacements.

In practice outdoors in the field it has been found feasible to set the compensating controls of the integrators such that the output does not drift appreciably during a period as long as two hours, provided the accelerometers are disconnected. However, random changes which occur in the accelerometer output signals make it impossible to maintain freedom from drift, except for brief periods ranging up to perhaps 30 seconds. This effect, which would appear to require a major accelerometer development effort to overcome, sets the attainable limits with respect to measuring small transient displacements which occupy a finite period of time.

The limits, with the present accelerometers, have been found to be in the vicinity of:

2.0 mils minimum, for vertical displacements occupying 2.0 seconds, and,

0.5 mil minimum, for horizontal displacements occupying 0.5 second.

However, repetitive sinusoidal displacements, within the frequency range 0.5 to 400 Hz, can be measured down to the order of millionths of an inch. By simple alterations of the circuitry, slower transient displacements could be accommodated, provided their magnitudes were correspondingly greater, and vice-versa.

The impulse response of the vertical channel is shown in Figure 8 to indicate the type of distortion which is introduced by truncating the frequency response. Distortion of the signal is substantially negligible for impulses which are short compared with 1.0 second but becomes appreciable as the impulse duration approaches or exceeds 5.0 seconds. Phase correction networks which diminish this effect during the initial one or two second interval were installed, but were removed from the circuit because of their deleterious effects on the longer period behavior. This effect is more severe for the rectangular impulses shown

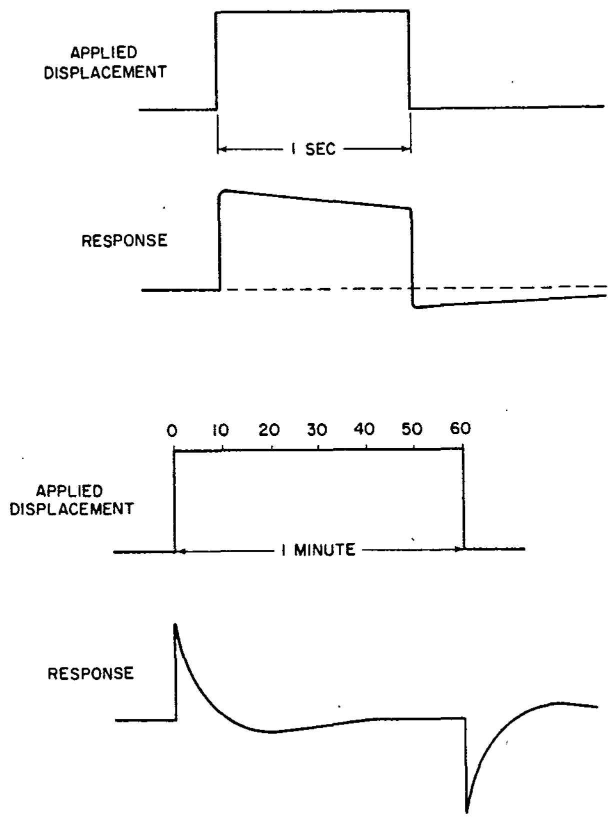


Figure 8: Integrator Response in the Time Domain. The response shown is that of the vertical channel of the dual integrator unit. The response of the horizontal channel would appear the same if drawn to a time-scale approximately one-fourth as long.

in the figure than for the rounded shapes represented by pavement deflections. Figures 9 and 10 show examples of typical pavement behavior. In each of these figures the upper curve depicts the variation of acceleration versus time, the central curve indicates the first integral of the acceleration, which is the velocity and the lower curve shows the second integral, which is the displacement. Figure 9 represents the passage of a single wheel while Figure 10 is representative of a two-axle vehicle.

4.4 Recorder

A recorder found to be suitable for use in the field with the displacement measuring system is that shown in Figure 2. It is basically an Astro-Med model 102C modified to operate from batteries. If a two-channel recorder had been purchased instead, it would be possible to record from both channels of the integrator unit simultaneously.

4.5 System Configuration:

Power for operating the accelerometers and the integrator unit is obtained in the field from a pair of 12 volt lantern batteries. The recorder requires, in addition, the use of a 12 volt storage battery.

The entire system is readily transported and operated in the rear seat of a passenger car and may be connected to the car battery. A convenient procedure consists of implanting the horizontal and vertical accelerometers at equal depths in separate holes drilled into the pavement structure, with known spacing of a few feet along the wheelpath.

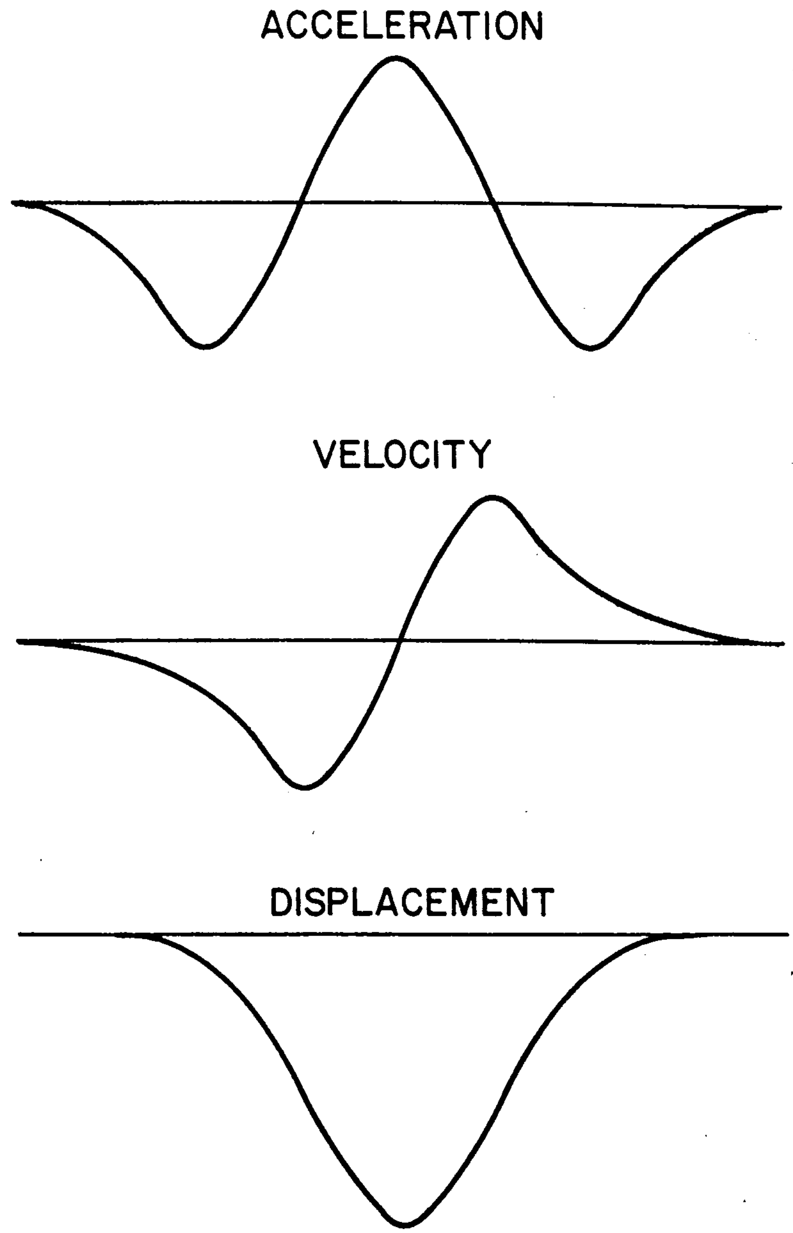


Figure 9: Shapes of the dynamic vertical acceleration, velocity and displacement versus time, in a typical pavement, due to the passage of a single wheel load.

5. SYSTEM CALIBRATION

Calibration of the overall displacement measuring system, comprising an accelerometer and dual-integrator, cannot be done statically, since the system response does not extend down to zero frequency. Accordingly, calibration is best accomplished by application of a periodically repetitive displacement having a known amplitude. A very convenient device for this purpose is the Dynaflect calibrator unit which can provide cam-actuated movements having double amplitudes from 0.005 to 0.020 inch at frequencies within the range 1 to 10 Hz. The actual movements of the Dynaflect calibrator were verified and compared with "static" displacements utilizing the optical displacement tracker[4], as shown in Figure 11, to measure the dynamic as well as the static displacements of the calibration platform. The calibration factors for the system were thus determined to be as follows:

TABLE 1: CALIBRATION FACTORS

Gain Step	Vertical Channel	Horizontal Channel
1	0.1 volts per mil	0.460 volts per mil
1/2	0.0495	0.235
1/4	0.0255	0.119
1/8	0.0130	0.0595

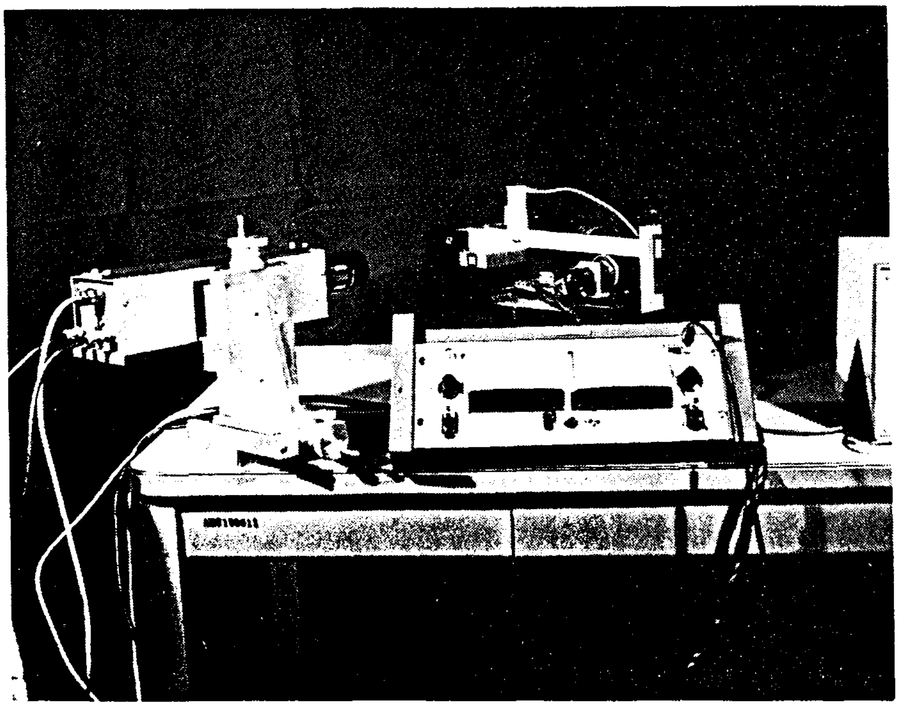


Figure 11: Movement of the Dynaflect Calibrator Unit on which the accelerometer has been mounted for calibration is being verified by means of an Optical Displacement Tracker.

The strip-chart recorder, as used with the system, has a sensitivity of up to 1000 chart divisions (millimeters) per volt. Thus the overall system recording capability extends to:

1 mm chart deflection = 0.1 mil (0.0001 inch) pavement deflections for the vertical channel and

1 mm chart deflection = 0.02 mil (0.00002 inch) for the horizontal channel.

The chart-paper drive speed is 10 centimeters per second; each one millimeter division along the record thus represents 0.01 second.

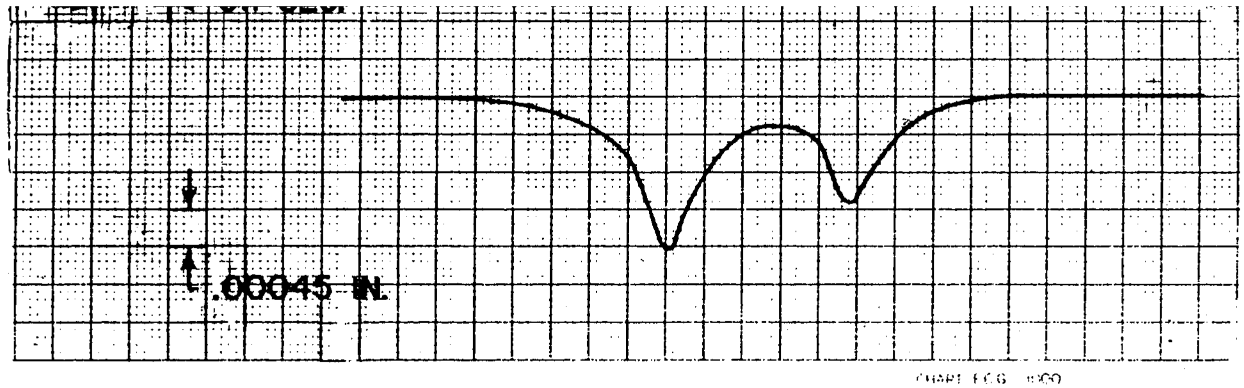
6. MEASUREMENTS

A typical record of the vertical deflection produced by a passenger car is shown in Figure 12a. The deflection basin, as measured by Dynaflect at the same location, is shown plotted to the same scale in Figure 12b.

Figure 13 shows recordings obtained at three differently constructed pavement sections on a private haul road, during the passage of an exceptionally large heavy vehicle. When 2/3 loaded this vehicle applies wheel loads of 26,500 lbs., 72,000 lbs. and 78,000 lbs. respectively at its front, drive and rear wheels. Its overall wheelbase, 52 feet long, requires nearly 1.8 seconds to pass the measuring location when travelling at 20 mph. The recorded deflections necessarily occupy a slightly longer period. Two of the recordings are seen to be satisfactory, and the magnitude and shape of the deflection basins can be readily determined from these records. The upper record, however, illustrates the effect of a drift which began shortly after the passage of the second wheel over the sensor. Except for that portion of the record which portrays the deflections caused by the first two wheels, this record is not useable. A repetition will usually have better than a 50/50 chance of producing a satisfactory record. This chance is further improved if the deflections are of shorter duration, such as from a faster vehicle and/or a shorter wheelbase.

Two recordings of the vertical deflections produced by a lightly loaded conventional truck are shown in Figure 14. In the lower record the effects can be seen of rough surface conditions located approximately 50 ft. away from the measuring point. The vehicle is still bouncing as it passes the sensor. The upper record is from a location of the same road, more remote from the rough area.

In the course of making these sets of deflection measurements a tendency was noted for the accelerometers to sometimes undergo a tilt during the initial load applications at a given site (see appendix B). This effect was considerably diminished when the accelerometers were embedded deeper and more firmly into the pavement structure. In order to minimize or eliminate this effect it is suggested that the accelerometers be installed at a depth of at least 6 to 8 inches beneath the surface and be surrounded with a rather rigid material, such as plaster of paris. The installation can be made very rapidly and conveniently using a 3 inch augar or core-drill to prepare the hole for the accelerometor and an abrasive slotting saw to cut a 1/4 inch wide slot from the hole to the edge of the pavement, for bringing out the connecting cable to the recording apparatus.



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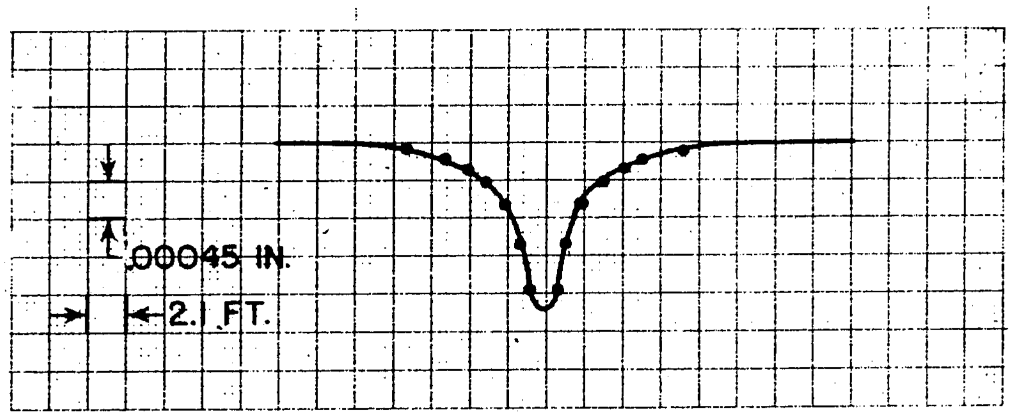


b

Figure 12: a. Upper: Deflection basin due to passenger car at 30 mph. The wheel loads are: front, 1290 lbs; rear, 1010 lbs.

b. Lower: Deflection basin due to Dynaflect, 1000 lb. loading at 8Hz.

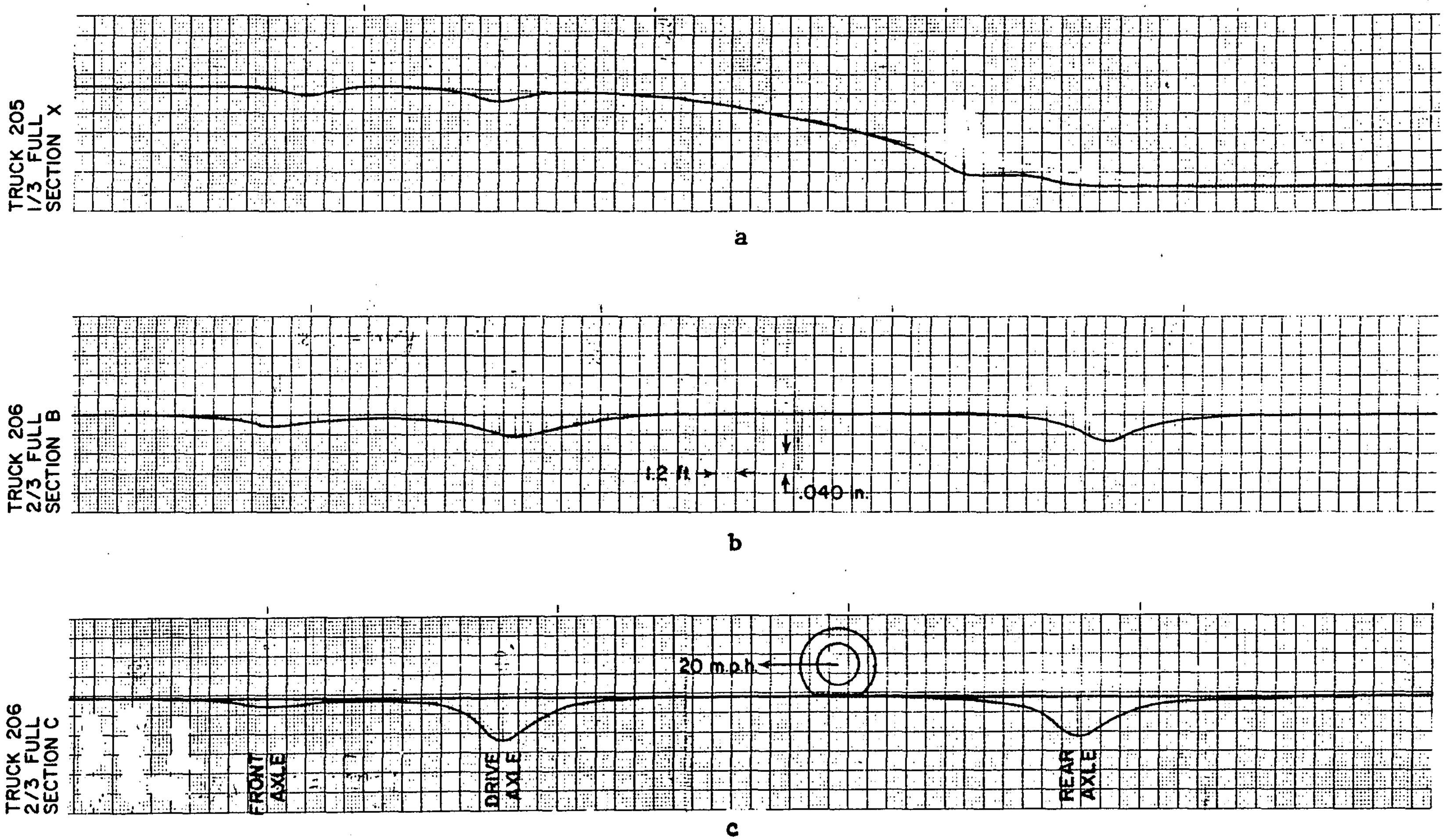
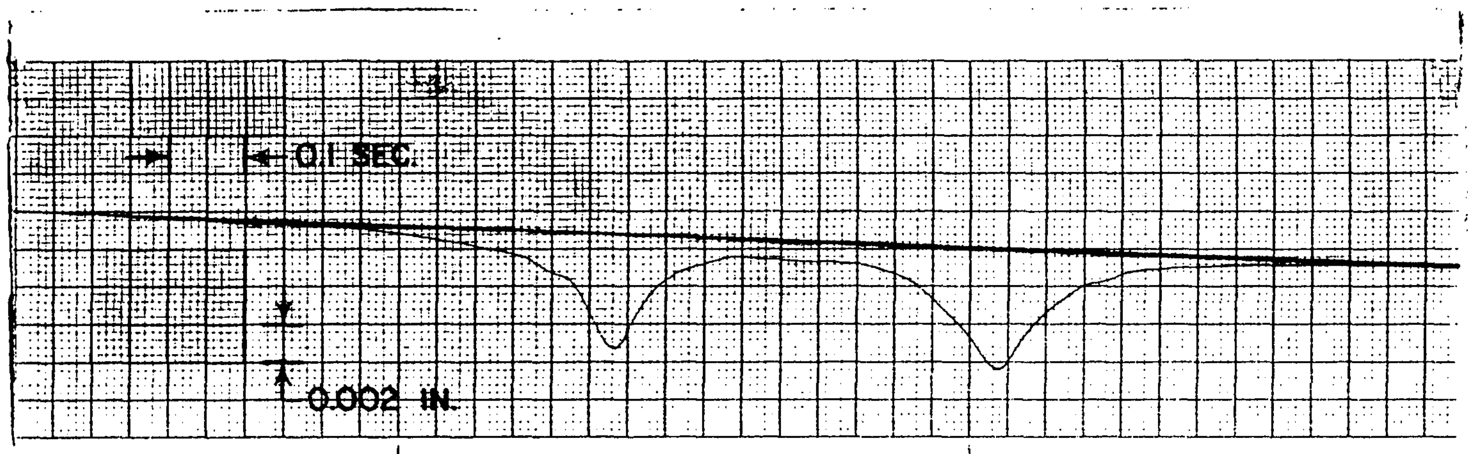


Figure 13:

a. Upper: Record impaired by drift.

b. Center: Deflections produced by an exceptionally large vehicle.
The wheel loads are: front, 26,500 lbs; drive, 72,000 lbs; rear, 78,000 lbs.

c. Lower: Somewhat larger deflections recorded at a different location.



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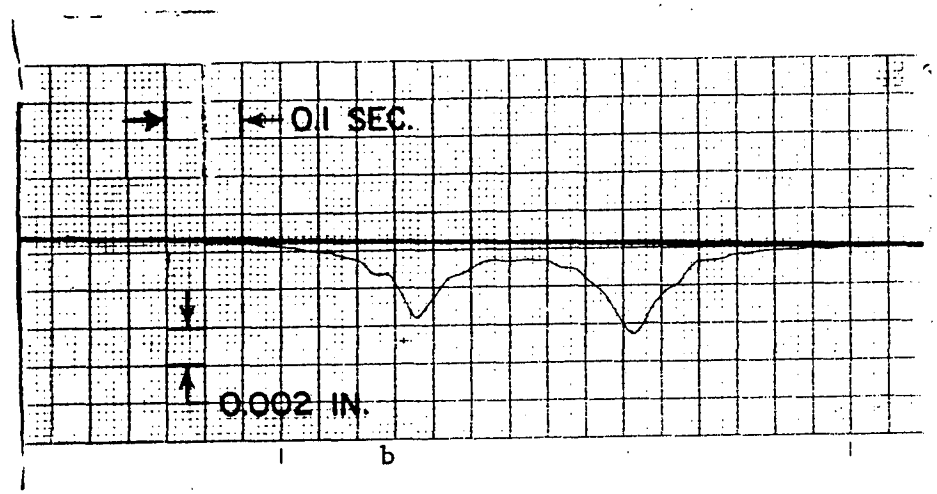

b

Figure 14

a. Upper: Deflection basin due to truck at 25 mph, on relatively smooth pavement.

b. Lower: Deflections with truck bouncing after passing over rough area 50 feet away.

The wheel loads are: front, 3010 lbs; rear, 2530 lbs.

7. CONCLUSIONS

1. An instrument system has been developed which demonstrates the feasibility of the original approach and which is capable of recording pavement deflections under moving traffic loads.
2. It appears evident that, in its present form, this measuring system could be utilized in a field-test program to obtain useful information concerning the deflection behavior of various pavement structures under controlled vehicular and random traffic loadings. It also appears that measurements of this behavior have not heretofore been obtainable. (See note under reference (5)).
3. With minor modification, the present apparatus could be adapted to record the larger but longer-duration movements of bridge decks subjected to traffic loading.
4. Limitations of the system have been noted as follows:
   a. Only one channel, either the vertical or the horizontal, may be recorded at a time. Purchase of a dual-channel recorder would remove this limitation.
   b. The present circuit configuration, chosen to accommodate deflections of the order of 0.001 inch, requires that the transient deflections, in order to be faithfully recorded, not exceed one or two seconds duration. With vehicles of conventional wheelbase this necessitates travel at speeds in the vicinity of 20 mph or greater. Response to smaller and slower transient displacements would require accelerometers having characteristics beyond those known to be commerically obtainable.

c. Requirement for rigid implacement of the accelerometers has been found to be critical, but it is believed that the embedment technique developed during this study will be found adequate. Implantation of accelerometers at depths less than six inches in flexible pavement sections, or less than three inches in rigid pavements, is not recommended. Since the deflections at such depths are ordinarily not very different from the deflections closer to the surface, this limitation is not believed to impair the usefulness of the system.

d. Imperfections (drifts) of the accelerometer output signals represent the principal limitation to the measurement of small slow displacements. Occasionally, (less than 50% of the time) a drift spoils the record of a given vehicular traverse. Accordingly, when seeking to record the deflections produced by a specific vehicle it is sometimes necessary to have the vehicle repeat its traverse.

8. REFERENCES

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(3) Graeme, J. G.; Tobey, G. E.; and Huelsman, L. P., Operational Amplifiers, McGraw Hill Book Co. N.Y. 1971 particularly pp. 213-218.

(4) Moore, W. M.; Swift, Gilbert; and Milberger, L. J., "Deformation Measuring System for Repetitively Loaded, Large Diameter, Specimens of Granular Material", Highway Research Record Number 301, Washington, D.C., pp. 28-39, 1970.

(5) Bohn, A.; Ullidtz, P.; Stubstad, R. and Sorensen, A.; "Danish Experiments with the French Falling Weight Deflectometer" Proc. 3rd International Conference on the Structural Design of Asphalt Pavements, London, England, September 11-15, 1972, Volume I, pp. 1119-1128, University of Michigan, Ann Arbor, Michigan.

Note: Since completion of this work a brief description of a similar instrument developed in Denmark has appeared in the appendix to the paper listed as reference (5).

APPENDIX A

This appendix contains purchase specifications for the accelerometer used in the measuring system.

Purchase Specifications for Accelerometers

Interchangeable with Kistler Instrument Company's Model 305T: Technical requirements which must be met are as follows:

Range: $\pm$ 50g maximum

Dynamic range: 5 x 10^6 minimum

Resolution: 0.000005g.

Sensitivity: 2 x 10^{-4} amperes/g.

Damping factor: 0.6 to 0.7

Output Impedance: 1.0 meg. minimum.

Freq. Range: DC to 500 Hz, flat $\pm$ 5%

Power Supply Voltage: $\pm$ 15 volts DC

Linearity (independent): 0.01% Full Scale

Output at zero g: 10^{-5} amperes maximum

Temperature Coefficient of Sensitivity: 0.03%/°F maximum

Temperature Zero Shift: 0.05%/100°F maximum

Shock Limit: 100g (5 milliseconds) any axis

Suspension: Non-pendulous

Weight: 3.4 oz.

Length: 2-1/16 inch maximum

Diameter (body): 1 inch maximum (1.125 Mounting Flange)

Equipped with isolated self-test coil and terminals.

Equipped with 40 ft. long shielded cable.

Est. Cost: $750.00 each

APPENDIX B

This appendix contains a discussion of the effect of a sudden axis shift on the output signal from an accelerometer and a description of the embedment technique developed to minimize the liklihood of such shifts.

Suddenly shifting the sensitive axis of an accelerometer from the vertical to a slightly off-vertical position, at which it then remains fixed, produces an effect identical to that of introducing a continuous upward acceleration. This occurs because the accelerometer no longer has the earth's gravitational field directed along its sensitive axis, but instead, is acted upon by the component of gravity in the direction of its axis. Such a shift of the axis produces a change in the apparent acceleration expressed by the following relationship:

$a = g\ (\cos\theta - 1)$, where: equation (1B)

a is the apparent change in acceleration
g is the acceleration due to gravity, and
θ is the angle between the sensitive axis and the vertical.

Assuming that the accelerometer was initially placed with its axis vertical, a quick non-recoverable rotation through one degree will thus produce an apparent upward acceleration of 0.0002 g, which is approximately 0.08 inches/sec^2. The second integral of this acceleration corresponds to a displacmment which reaches 0.040 inch (40 mils) at the end of one second, 160 mils at two seconds, and continues to increase at an ever faster rate. The corresponding effect of rotation on a horizontally placed accelerometer is substantially less tolerable for two reasons:

first, the apparent change in acceleration is given by:

$a = g \sin\theta$ equation (2B)

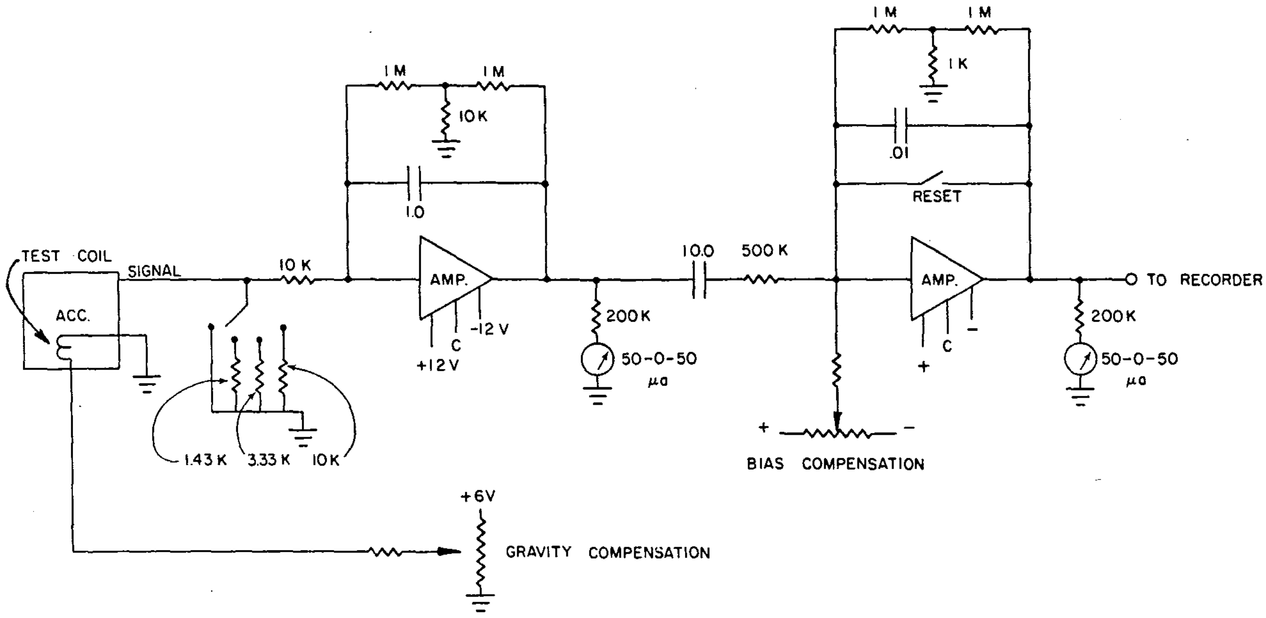
instead of by equation (1B). Thus it is nearly one hundred times larger, or 0.018 g, for a one degree tilt. Second, the expected horizontal displacements in a pavement structure are generally on the order of four to ten times smaller than the vertical displacements.

Accordingly, placement of accelerometers within the pavement structure, especially a horizontal accelerometer, must be done in such a way as to minimize the liklihood of incurring appreciable tilting movement after installation. This appears to be best accomplished by installation at an adequate depth, such as 6 or 8 inches and by surrounding the accelerometer with a rather rigid material such as plaster of paris before filling the remainder of the hole. The tendency for a tilting movement to o ccur during the measurment interval can be further diminished by application of repeated vehicular loadings to the emplacement area before attempting to measure the transient displacements. It is relatively unimportant that the final positions of the accelerometers be truly vertical or truly horizontal since the errors incurred by a permanent misalignment of a few degrees will be relatively small.

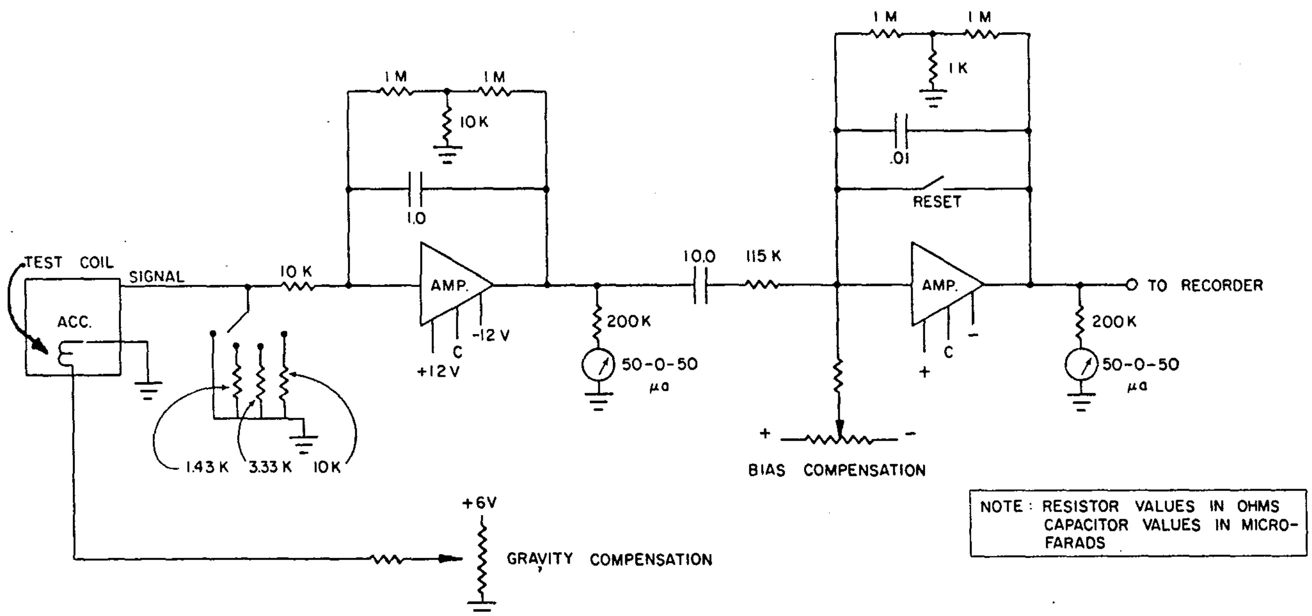
An implantation technique which was utilized successfully for the later measurements comprised drilling a 2 inch diameter core hole 6 inches deep, then using an abrasive wheel to cut a slot for the cable 1/4 inch wide by 1 inch deep, from the hole to the shoulder. The accelerometer was embedded in plaster of paris, the upper surface of which was left 1 inch below the pavement surface. The slot and the remainder of the hole were then filled with asphalt to complete the installation.

APPENDIX C

This appendix contains a schematic circuit diagram of the Dual Integrator Unit and also a table listing the Dynaflect observations from which Figure 12b was derived.



VERTICAL CHANNEL



HORIZONTAL CHANNEL

Figure C-1: Two-channel dual-integrator schematic diagram.

Table C-1

Dynaflect measurements at accelerometer installation site, Texas A&M Research Annex, adjacent to Pavement Test Facility.

Distance From Load Application Point (inches)	Vertical Deflection (mils)/1000 lb. force
10	2.14
15.6	1.47
26	0.88
37.4	0.55
49	0.34
60.8	0.24
72.7	0.178
84.6	0.132
96.5	0.088
120.4	0.067
144.3	0.044
180.3	0.034
216.2	0.026