INSTRUMENT SYSTEM FOR MEASURING PAVEMENT DEFLECTIONS PRODUCED BY MOVING TRAFFIC LOADS

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This paper describes a feasibility study that has led to the development of a first-generation instrument system for measuring transient pavement deflections. Accelerometers embedded in the pavement structure are used to sense the basic motion. Dual analog integration is used to obtain and record output indications proportional to displacement. The circuit characteristics are such that dynamic vertical movements as small as 0.002 in. or horizontal movements as small as 0.0005 in. occurring within less than 2 seconds can be recorded. These characteristics allow the system to be used for vehicle speeds of more than 25 mph and for any normal pavement structure. These performance characteristics could be altered, if desired, to accommodate the larger, longer movements that occur on bridge decks.

•THIS PAPER covers an investigation of the feasibility of developing an instrument system for measuring the dynamic transient deflections that occur in pavement structures under normal traffic loading conditions.

Measurements of pavement deflections have heretofore been limited to observation of rebound on removal of a previously stationary heavy vehicle (Benkelman beam testing) or to measurements, such as those obtained with the Dynaflect, of cyclic loads of 1,000 lb applied 8 times per second or to tests, such as the plate bearing test, of static loads.

Direct observation of the deflections induced by moving traffic loads has, so far as is known, not been possible for lack of suitable instrumentation. The principal hindrance to the development of instrumentation for this purpose is unavailability of a reference location that is sufficiently fixed in position and sufficiently near the point where deflections are to be measured. Accordingly, the present study undertook to determine the feasibility of a measuring system that employs inertial sensors and therefore requires no external fixed reference point.

BACKGROUND

This research began with a proposal in response to the U.S. Department of Transportation's prospectus regarding the development of transducers capable of measuring the recoverable vertical deflections on and beneath the pavement surface. The desired measurement range was from 0 to 0.05 in., with precision of measurement to 0.0001 in., and the flat frequency response was from 0 to 100 Hz.

Consideration of these requirements in the light of present technology of motion sensing devices and of existing techniques for applying them led to the conclusion that an inertial reference should be used and that accelerometers were available having the requisite characteristics for measuring such displacements at frequencies above 1.0 or possibly 0.1 Hz.

A paramount consideration underlying this plan was the fact that one aspect of the objective is believed to be unattainable. Specifically it is not deemed feasible to mea-

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sure this wide span of small displacements over the entire frequency range down to and including 0 frequency. Any displacement measurement requires a reference point. If a physical tangible reference point is to be used, it must be sufficiently remote to remain undisturbed during the measurement to the extent set by the specified accuracy. In a pavement structure subject to normal traffic loading, suitable physical reference points are quite remote—at least as far as 50 ft distant on the surface and as deep as 20 ft or more from the load application point. The use of such reference points is considered incompatible with the specified performance, especially over a wide range of frequencies as great as 100 Hz or greater.

Accordingly, an inertial reference point, which may be regarded as the average position of the measuring point during the recent past, is believed to provide the most practical alternative. 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 vertical (velocity or acceleration) transducers, such as geophones or accelerometers (1). The principal limitation introduced by the inertial reference is that displacement response down to 0 frequency (static response) is not attainable. However, it appears fully feasible to obtain flat displacement response from below 1.0 Hz to above 100 Hz and with the desired displacement ranges by using this approach.

Accordingly, the basic measuring system was originally proposed in 1969, but that proposal was abandoned when the prospectus was canceled in 1970. In the belief that a need exists for instrumentation that can record the deflections 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 1-year feasibility study described here. Such instrumentation should permit the study of pavement deflection behavior with respect to loads varying in magnitude and distribution and in speed.

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 given in Table 1.

Early in the circuit development phase it became apparent that, in a system of 2 integrators in cascade, it is extremely difficult to obtain long-term stability. If 2 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 1 integrator to the other through a suitable capacitor that provides infinite attenuation at 0 frequency while passing all frequencies of interest (those above approximately 0.03 Hz in the present apparatus).

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 1 passenger car and 1 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 as heavy as 240,000 lb. At this location approximately 100 recordings were made of the passage of these 3-axle vehicles, some fully loaded, others empty, at approximately 25 selected sites. Although most of these recordings were satisfactory, it was learned during this series of measurements that the accelerometers must be implanted firmly and relatively deep in the pavement system to avoid initial shifts of position upon application of the first few loadings after installation.

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 on 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 relation:

$$a = g (\cos \theta - 1) \tag{1}$$

where

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

If the accelerometer were initially placed with its axis vertical, a quick nonrecoverable rotation through 1 deg would thus produce an apparent upward acceleration of 0.0002 g, which is approximately 0.08 in./s^2. The second integral of this acceleration corresponds to a displacement that reaches 0.040 in. (40 mils) at the end of 1 s and 160 mils at 2 s and continues to increase at an ever faster rate. The corresponding effect of rotation on a horizontally placed accelerometer is substantially less tolerable for 2 reasons. First, the apparent change in acceleration is given by

$$a = g \sin \theta \tag{2}$$

instead of by Eq. 1. Thus, it is nearly 100 times larger, or 0.018 g, for a 1-deg tilt. Second, the expected horizontal displacements in a pavement structure are generally on the order of 4 to 10 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 likelihood of incurring appreciable tilting movement after installation. This appears to be best accomplished by installation at an adequate depth, such as 6 or 8 in., 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 occur during the measurement interval can be further diminished by application of repeated vehicular loadings to the emplacement area before the transient displacements are measured. That the final positions of the accelerometers be truly vertical or truly horizontal is relatively unimportant because the errors incurred by a permanent misalignment of a few degrees will be relatively small.

After the sensors were re-implanted in a second flexible pavement at the A&M Research Annex, a series of recordings was made by using a variety of vehicle speeds and loadings. That activity, the data analysis, and the preparation of this report represent the final phases of this 1-year feasibility study.

APPARATUS

Accelerometers

The Kistler model 305T servoaccelerometer used in this study meets the most exacting specifications of any commercially available accelerometer known to the author (Table 1). Almost unique among instruments of any kind is its ability to respond throughout a range of 10 million to 1, that is, from 5 μg to 50 g. However, for this application it would be preferable if its response ranged instead from 0.5 μg to 5 g.

The operating principle of a force-balance servoaccelerometer is shown by Figure 1, which has been taken from the Kistler Company's literature. The seismic mass of a few grams is nonpendulously suspended by 3 pairs of flexible arms that 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. Inasmuch as 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 in. diameter by 2 in. long. However, for use in this study the accelerometers were placed in slightly larger waterproof housings, as shown in Figure 2. Each accelerometer was equipped with a 40-ft shielded multiconductor cable terminated in a plug that fits a receptacle on the panel of the dual integrator unit.

Dual Integrator Unit

This unit, shown in Figure 3, provides 2 channels that 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 that monitor the output of each integrator. The gravity-null control serves to center the pointer of the lower meter, and the bias control of the second integrator serves to center the upper meter. A push button below these controls restores the second integrator to 0. The circuit diagram of this unit is shown in Figure 4.

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 s and that the duration of the appreciable horizontal displacements will be somewhat shorter. To reproduce such displacements faithfully by twice integrating the corresponding accelerations requires that the integration time be extended 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 6.0 s for the vertical signal channel and 1.2 s 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 bidirectional and the vertical displacements are always downward.

The response characteristics of each 2 dual-integration channels are shown in Figures 5 and 6. Figure 5 shows 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. The upper portion of Figure 5 shows that the frequency range over which the gain diminishes at the rate of 100:1 per decade of frequency (the slope that corresponds to dual integration) extends from 0.05 to beyond 1,000 Hz for the vertical channel and that the maximum gain (2 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 shown in the lower portion of Figure 5.

In a channel having these characteristics, a change within the first integrating amplifier equal to 1 μV, or an equal change at the output of the accelerometer, necessarily results in an output signal that rises at the rate of 1 V/s. Should a change of this magnitude occur, while the system is being used to record pavement displacements, the pavement would falsely appear to have 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 μV. In practice 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 2 hours, provided the accelerometers are disconnected. However, random changes that occur in the accelerometer output signals make it impossible to maintain freedom from drift, except for brief periods ranging as high as perhaps 30 s. 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 that 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 s and 0.5 mil minimum for

Table 1. Specifications for accelerometer.

Item	Specification
Range, g max	±50
Dynamic range, g min	5,000,000
Resolution, g	0.000005
Sensitivity, A/g	0.00002
Damping factor	0.6 to 0.7
Output impedance, MΩ min	1.0
Frequency range	
dc, Hz	to 500
Flat, percent	±5
Power supply voltage, V dc	±15
Linearity (independent), percent full scale	0.01
Output at 0 g, A max	0.000001
Temperature, percent/F max	
Coefficient of sensitivity	0.03
Zero shift	0.05
Shock limit, any axis, g (ms)	100(5)
Suspension	Nonpendulous
Weight, oz	3.4
Length, in. max	$2\frac{1}{16}$
Diameter, in. max	
Body	1
Mounting flange	1.125
Estimated cost each, dollars	750

Note: Must be interchangeable with Kistler Instrument Company model 305T and equipped with isolated self-test coil and terminals and 40-ft long shielded cable.

Figure 1. Working elements of a force-balance servoaccelerometer.

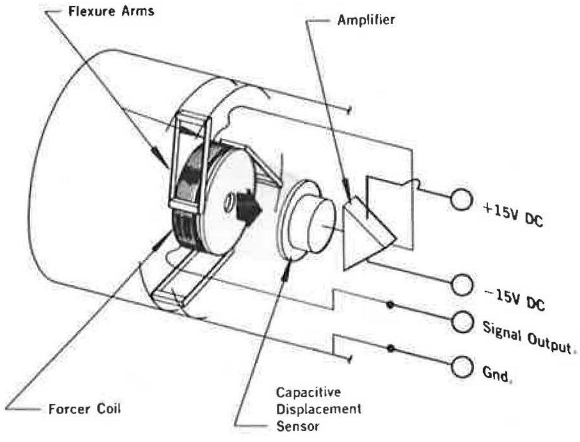


Figure 2. Accelerometer mounted in waterproof housing.

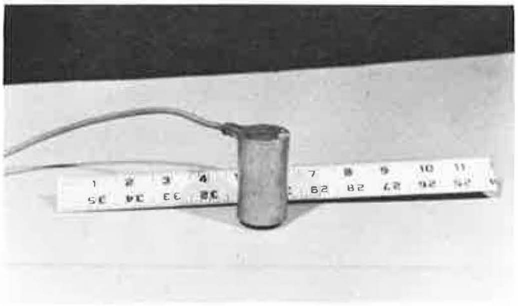
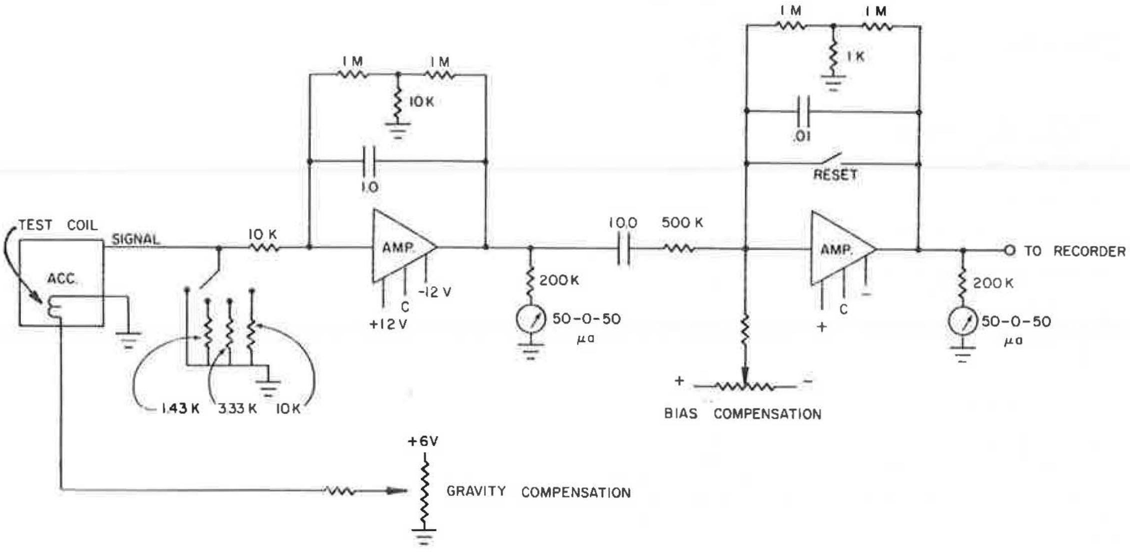
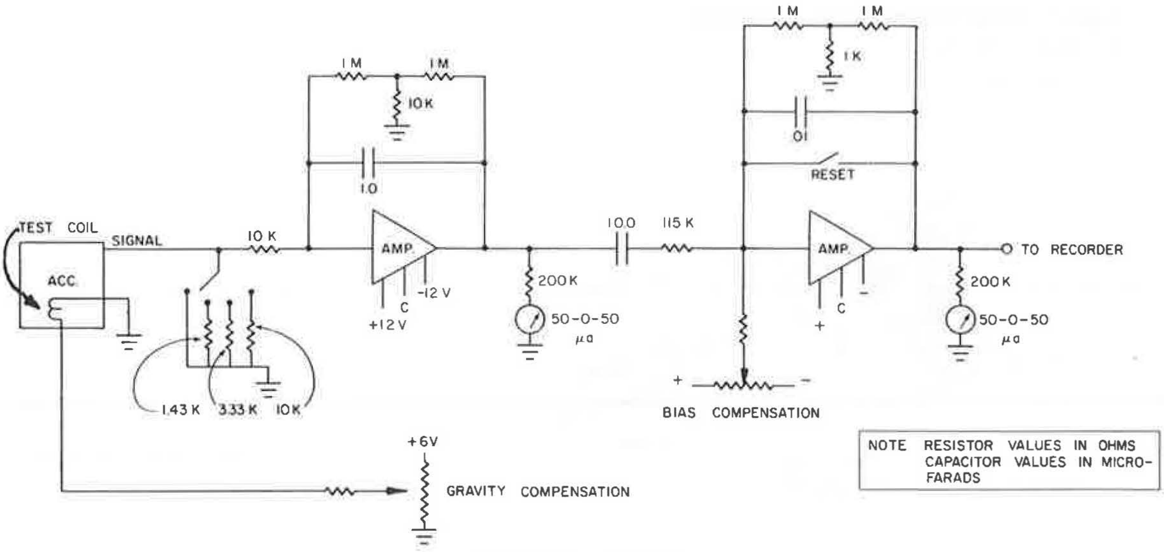


Figure 3. Pavement displacement measuring system.

Figure 4. Circuitry of 2-channel dual integrator.



VERTICAL CHANNEL



HORIZONTAL CHANNEL

horizontal displacements occupying 0.5 s. 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. Simple alterations of the circuitry can accommodate slower transient displacements, provided their magnitudes are correspondingly greater, and vice versa.

The impulse response of the vertical channel is shown in Figure 6 to indicate the type of distortion that is introduced by truncating the frequency response. (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.) Distortion of the signal is substantially negligible for impulses that are short compared with 1.0 s but becomes substantial as the impulse duration approaches or exceeds 5.0 s. Phase correction networks that diminish this effect during the initial 1- or 2-s 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 in the figure than for the rounded shapes represented by pavement deflections. Figure 7 shows typical pavement behavior. 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, produced by the passage of a 2-axle vehicle.

Recorder

A recorder found to be suitable for use in the field with the displacement measuring system is that shown in Figure 3. It is basically an Astro-Med model 102C modified to operate from batteries. A 2-channel recorder would make it possible to record from both channels of the integrator unit simultaneously.

System Configuration

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

SYSTEM CALIBRATION

Calibration of the overall displacement measuring system, comprising an accelerometer and dual integrator, cannot be done statically because the system response does not extend to 0 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 in. at frequencies within the range 1 to 10 Hz. The actual movements of the Dynaflect calibrator were verified and compared with "static" displacements by using the optical displacement tracker (4), as shown in Figure 8, to measure the dynamic as well as the static displacements of the calibration platform. The calibration factors for the system thus determined are as follows:

Gain Step	Vertical Channel (V/mil)	Horizontal Channel (V/mil)
1	0.1	0.460
½	0.0495	0.235
¼	0.0255	0.119
⅛	0.0130	0.0595

Figure 5. Integrator response in frequency domain.

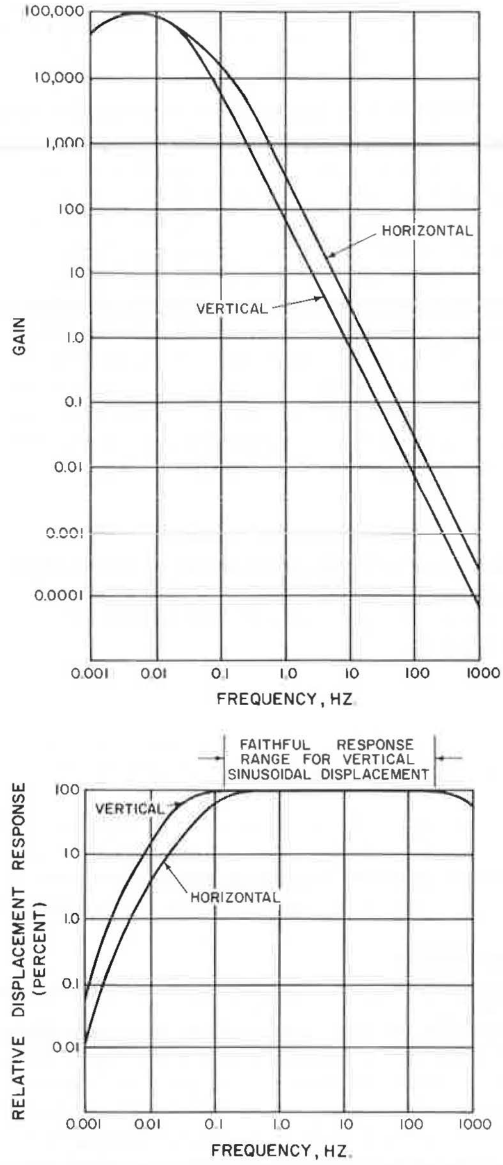


Figure 6. Integrator response in time domain.

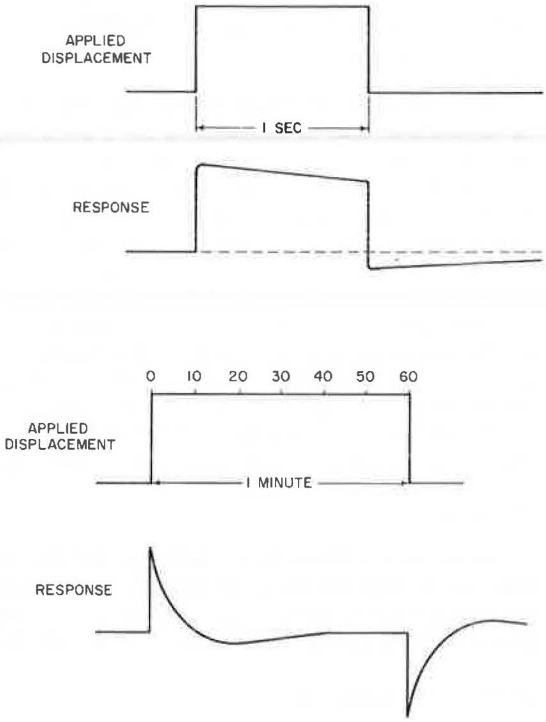
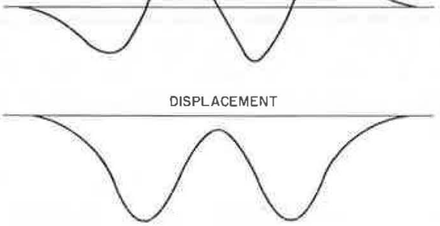


Figure 7. Shapes of dynamic vertical acceleration, velocity, and displacement versus time in a typical pavement on which a 2-axle vehicle passed.



The strip-chart recorder, as used with the system, has a sensitivity as great as 1,000 (chart divisions) mm/V. Thus the overall system recording capability extends as follows: 1-mm chart deflection = 0.1 mil (0.0001 in.) pavement deflections for the vertical channel, and 1-mm chart deflection = 0.02 mil (0.00002 in.) for the horizontal channel. The chart-paper drive speed is 10 cm/s; each 1-mm division along the record thus represents 0.01 s.

MEASUREMENTS

A typical record of the vertical deflection produced by a passenger car is shown in Figure 9a. The deflection basin, as measured by Dynaflect at the same location, is shown plotted to the same scale in Figure 9b.

Figure 10 shows 3 recordings obtained on a private haul-road during the passage of an exceptionally large heavy vehicle. These observations were later used in another study to evaluate the elastic constants of the pavement structure by comparison with deflections computed from elastic theory. When ⅔ loaded, this vehicle applies wheel loads of 26,500, 72,000, and 78,000 lb respectively at its front, drive, and rear wheels. Its overall wheelbase, 52 ft long, requires nearly 1.8 s to pass the measuring location at a speed of 20 mph. The recorded deflections necessarily occupy a slightly longer period. Two of the recordings are 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 that began shortly after the passage of the second wheel over the sensor. 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 or a shorter wheelbase or both.

Two recordings of the vertical deflections produced by a lightly loaded conventional truck are shown in Figure 11. The lower record shows the effects 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.

CONCLUSIONS

1. An instrument system has been developed that demonstrates the feasibility of the original approach and that is capable of recording pavement deflections under moving traffic loads.

2. It appears that, in its present form, this measuring system can be used 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. [Since completion of this work, a brief description of a similar instrument developed in Denmark has appeared in the appendix to a paper by Bohn et al. (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 on the order of 0.001 in., requires that, to be faithfully recorded, the transient deflections not exceed 1- or 2-s duration. With vehicles of conventional wheelbase, this necessitates travel at speeds of 20 mph or greater. Response to smaller and slower transient displacements requires accelerometers having characteristics beyond those known to be commercially 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 is adequate. Implantation of accelerometers at depths less than 6 in. in flexible pavement sections or less than 3 in. in rigid pavements is not recommended. Because 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.

Figure 8. Movement of Dynaflect calibrator unit, on which accelerometer has been mounted for calibration, verified by optical displacement tracker.

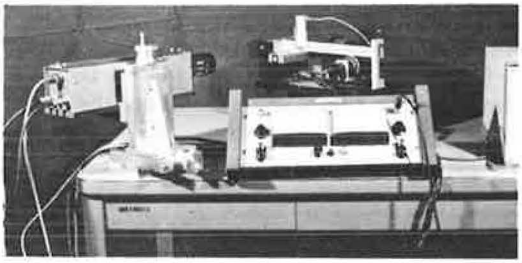


Figure 9. Deflection basins (a) produced by passenger car at 30 mph and 1,000-lb front 675-lb rear wheel loads and (b) measured by Dynaflect with 1,000-lb loading at 8 Hz.

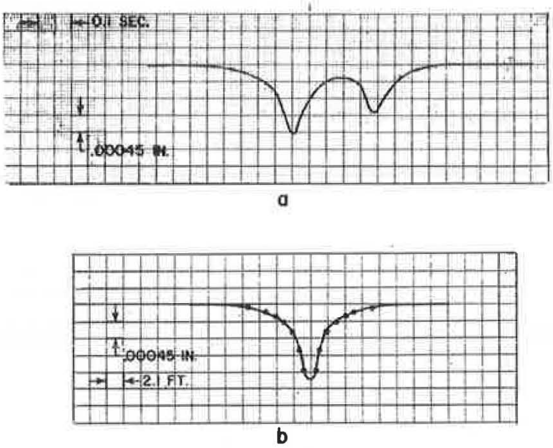


Figure 10. Records obtained on haul-road from passage of heavy vehicle.

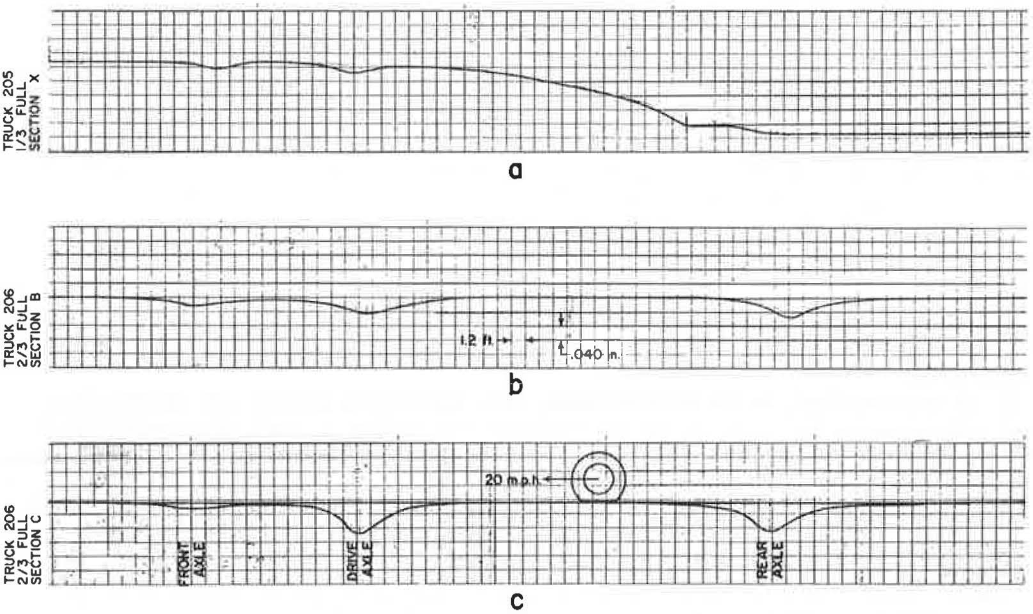
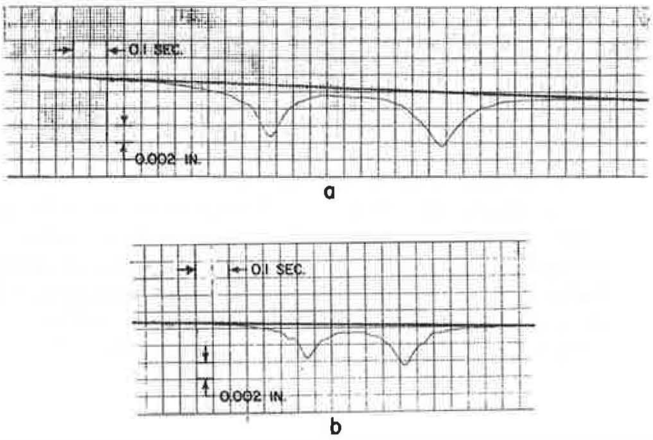


Figure 11. Deflection basin due to truck (a) traveling at 25 mph on relatively smooth pavement and (b) bouncing after passing over rough area 50 ft away.



d. Imperfections (drifts) of the accelerometer output signals represent the principle limitation to the measurement of small slow displacements. Occasionally (less than 50 percent of the time), a drift spoils the record of a given vehicular traverse. Accordingly, to record the deflections produced by a specific vehicle sometimes requires the vehicle to repeat its traverse.

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