GMR Road Profilometer—A Method for Measuring Road Profile

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Accurate road profiles are often required for the analytical study of vehicle ride and vibration phenomena induced by road irregularities. The desire to bring profiles of existing roads into the laboratory has led to the development of a road profilometer for the rapid measurement of such road profiles. The continued interest in this device by persons engaged in highway design, construction and maintenance encouraged the authors to further develop and simplify this instrument and to make it available to these highway groups. This paper discusses the basic operating principle of the GMR profilometer, describes the unit supplied to the Michigan State Highway Department, and presents some typical test results.

•AN AUTOMOBILE riding on a road can be considered a complex mechanical filter. The vertical displacements introduced at the tire contact patch are drastically modified by the filtering action of the tire, suspension, frame, body mounts, body and seat before they reach the passenger. To assist in the analytical and experimental study of vehicle ride, the GMR road profilometer has been developed to produce accurately measured road profiles to be used as an input into the simulation of this complex filter. An earlier profilometer (1) physically established a reference which was used to measure the displacement of a road-following wheel. This system involved an analog computer, a hydraulic system and two cumbersome trailers on the rear of the towing vehicle. In the new GMR road profilometer, the road-following wheels are located under the towing vehicle, the hydraulic system has been eliminated, and the analog computer has been replaced by an inexpensive analog computation package. During the development work, the Research Laboratories worked closely with highway engineers, both at the General Motors Milford Proving Ground and in other highway engineering groups. A by-product of this activity was the request by highway engineers that the GMR road profilometer be made available for their use. As a public service, the authors have assisted the Michigan State Highway Department in a Bureau of Public Roads research project to evaluate the GMR road profilometer for highway department use.

MECHANICAL VIBROMETER

One of the principal problems in measuring road profile with reasonable flexibility and speed is establishing a reference from which to measure deviations. Optical systems such as used in surveying and light beam references are slow and not readily applicable to curved roads. In addition, it is desirable to obtain a continuous record for ride simulation purposes. After consideration of many alternative possibilities, a system with an inertial reference was chosen for development. This system has the

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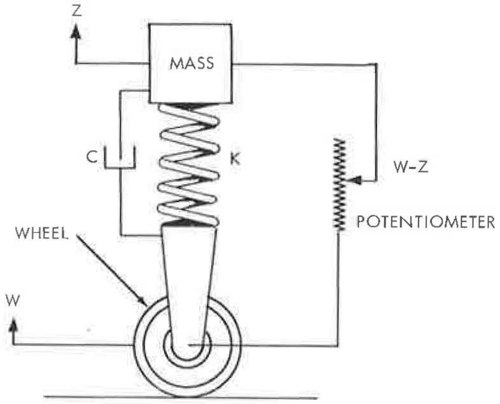


Figure 1. Mechanical vibrometer.

ability to measure the range of road wavelengths significant to vehicle ride. The principle of the inertial reference system is illustrated by the mechanical vibrometer (Fig. 1). At very low frequencies the motion of the mass follows the wheel motion, but at higher frequencies the motion of the mass is small and the relative motion between the wheel and mass (W-Z) is essentially the road profile. This simple mechanical filter can be described by a block diagram (Fig. 2), where the road profile or wheel displacement W enters from the left. The output of the mechanical filter is the displacement of the mass Z. The potentiometer, represented in Figure 2 by a summer, measures the relative motion between the wheel and the mass to produce the output W-Z. The behavior of the mechanical vibrometer system is shown in the frequency response curve of Figure 3. (The analysis of the GMR profilometer is based on a frequency response approach; a brief discussion of frequency response is included in Appendix A.) This curve is for a system having a natural frequency of 6 rad/sec. Mechanical systems with natural frequencies lower than 6 rad/sec are difficult to design. Equivalent road wavelengths at different vehicle speeds are shown along the abscissa in addition to frequency. Shorter wavelength disturbances which produce frequencies above the natural frequency of the mechanical system can be measured by the relative displacement of the wheel and sprung mass. However, lower frequency components are attenuated.

MECHANICAL AND ELECTRONIC VIBROMETER

The road profile can be measured exactly with a mechanical vibrometer (Fig. 2) if the motion of the mass Z is measured and added to the measured motion $(W-Z)_m$. The motion of the mass can be determined from its acceleration by double integration. This is the operating principle of the GMR road profilometer as shown in the system block diagram (Fig. 4). The left side is recognized as the block diagram of the mechanical vibrometer. The remainder is the addition of an accelerometer, the double integration of the accelerometer signal to obtain the measured displacement of the mass Z_m, and the summation of $(W-Z)_m$ and Z_m to produce the measured road profile W_m.

Frequency response plots on a log-log scale of the individual operations (Fig. 4) aid in the understanding of the principles. The frequency response of the mechanical filter is shown in Figure 5. If for low frequencies (long wavelengths) the motion Z and the motion W could be measured from the same reference, the output of the mechanical filter Z would equal the input W. The amplitude ratio (Z/W) would be unity. As the frequency increases above the natural frequency of the mechanical filter ω_n, the motion of the mass Z becomes smaller than the input W. This frequency response curve is,

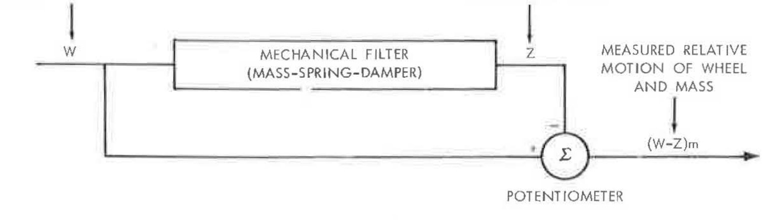


Figure 2. Block diagram of mechanical vibrometer.

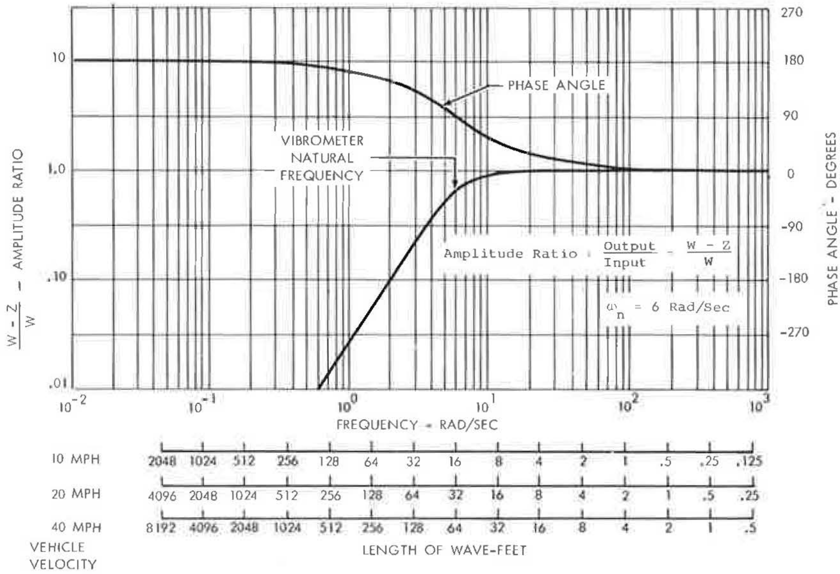


Figure 3. Frequency response of mechanical vibrometer.

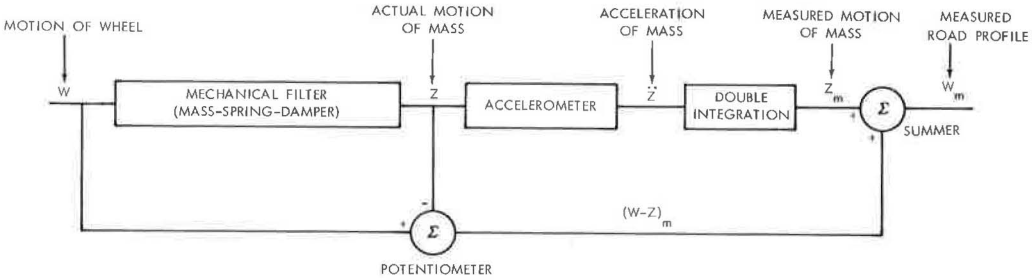


Figure 4. Block diagram of mechanical and electronic vibrometer.

of course, consistent with our observations as an automobile passenger. We have much less motion than the wheel and tire on short wavelengths (washboard road) but tend to go up and down with the wheel and tire on long wavelengths (hills and valleys).

The next element in Figure 4 is the accelerometer. This transducer converts displacement of the mass to its acceleration. An ideal accelerometer would have the characteristic plotted in Figure 6. The acceleration, for a fixed displacement amplitude, varies directly as the square of the frequency.

The frequency response of the double integration following the accelerometer (Fig. 7) is exactly the inverse of the accelerometer characteristic. The computed amplitude of the mass Z for a constant acceleration amplitude input varies inversely as the square of the frequency.

Figure 8 is the same block diagram as Figure 4 with the amplitude of the signals after each operation shown as a function of frequency. The measured road W_m theoretically exactly equals the real road W. The low frequency (long wavelength) road waves are reproduced through the accelerometer branch; the high frequency (short wavelength) road waves are detected by the potentiometer with the dividing point being the natural frequency of the mechanical filter ω_n.

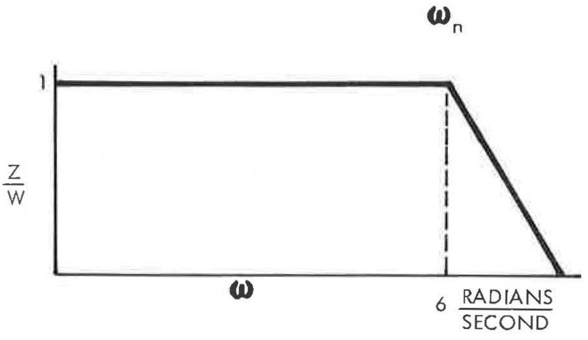


Figure 5. Frequency response of mechanical filter.

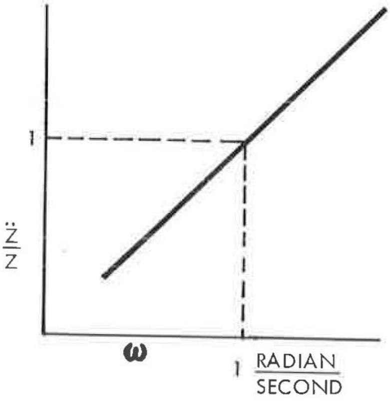


Figure 6. Frequency response of an accelerometer.

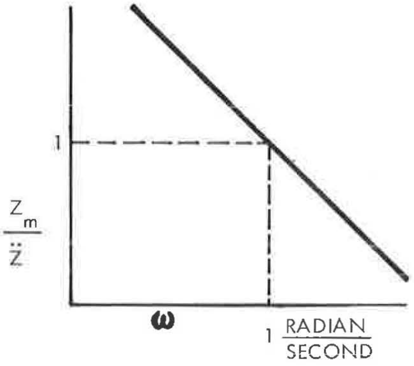


Figure 7. Frequency response of double integration.

HIGH PASS FILTER

The GMR profilometer is theoretically capable of measuring the road profile exactly at all frequencies. Practically, this is neither possible nor desirable for most applications. Usually, a person who is interested in road profile for vehicle ride or road condition purposes is not interested in the long wavelengths (hills and valleys). However, it is considered desirable to allow the user to determine what wavelength information he wants to collect. This is accomplished by use of a high pass filter which attenuates amplitudes at all frequencies below the filter frequency, ω_f. The frequency response for the high pass filter is shown in Figure 9. Adding a high pass filter to Figure 8 produces the block diagram of the complete GMR profilometer (Fig. 10). The operations of double integration, summation and filtering are enclosed and separated from the rest of the system (Fig. 10) by a box described as "analog computations." The inputs to the analog computation box are the transducer signals from the potentiometer and accelerometer. The output from the analog computation box is the filtered, measured road profile.

COMPLETE SYSTEM PERFORMANCE

For ease of explanation, the frequency response characteristics of the various signals in Figure 10 are represented by straight line approximations on log-log scales. The actual frequency response of the complete system is shown in Figure 11. The abscissa is again expressed as both frequency and wavelengths at various recording vehicle speeds. The amplitude is shown as a ratio of measured road profile W_f to the

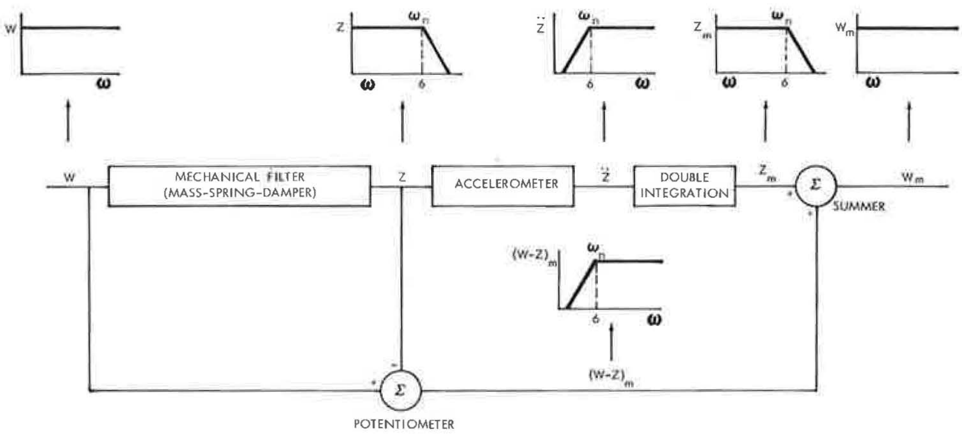


Figure 8. Block diagram of mechanical and electronic vibrometer.

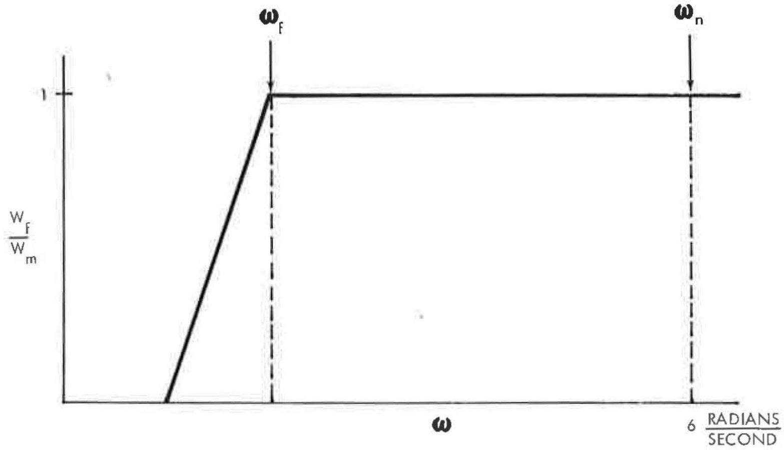


Figure 9. Frequency response of high pass filter.

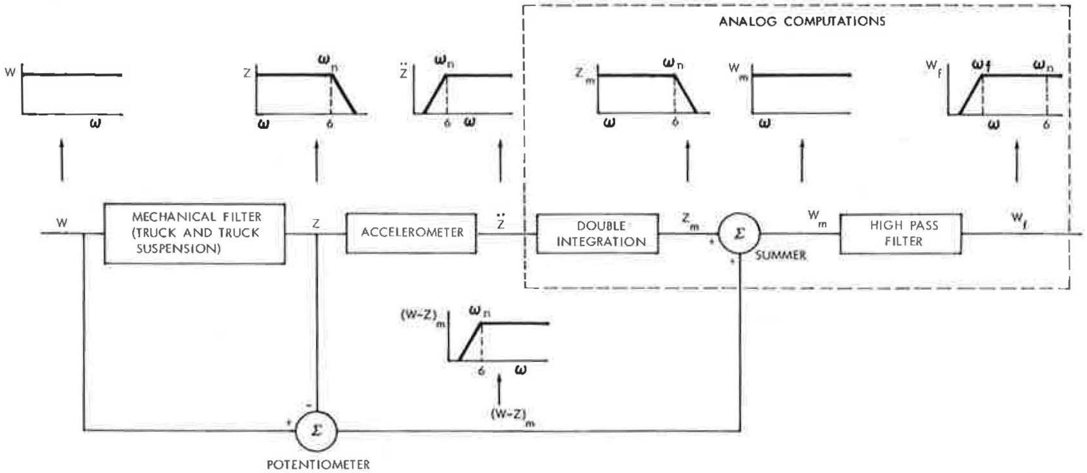


Figure 10. Block diagram of complete GMR profilometer.

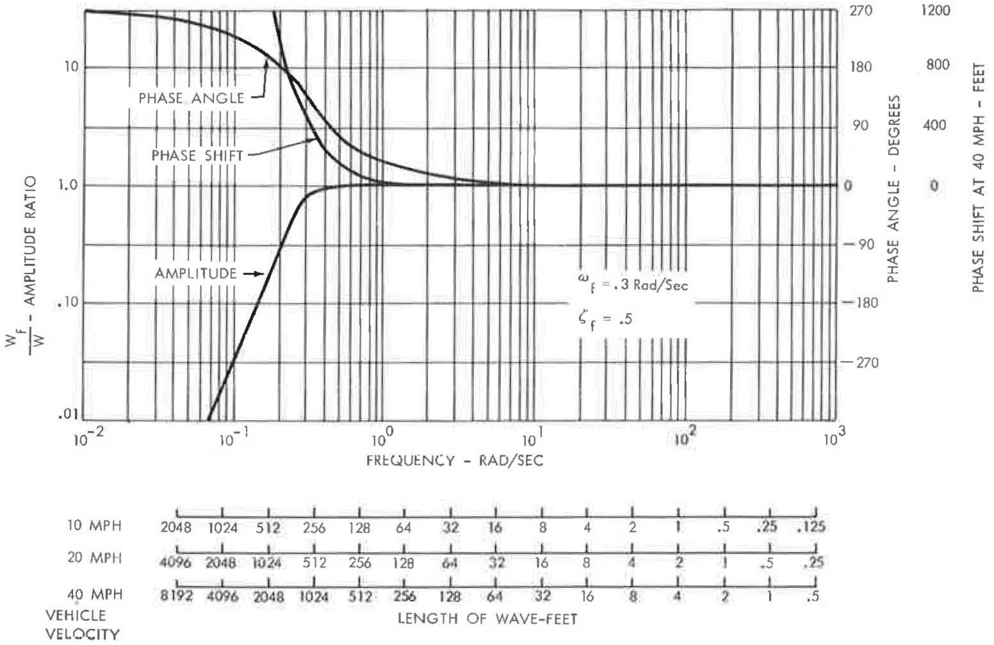


Figure 11. Frequency response of complete system.

actual road W. Note the similarity between the frequency responses of Figures 11 and 3. The response of the mechanical and electronic vibrometer is similar to the response of the mechanical vibrometer except that longer wavelengths can be measured with the former.

As an example of the influence of wavelength on amplitude, a 100-ft sinusoidal wave measured at 40 mph would be measured with an amplitude ratio of one (Fig. 11). The measured wave would have the same amplitude as the actual wave. However, the

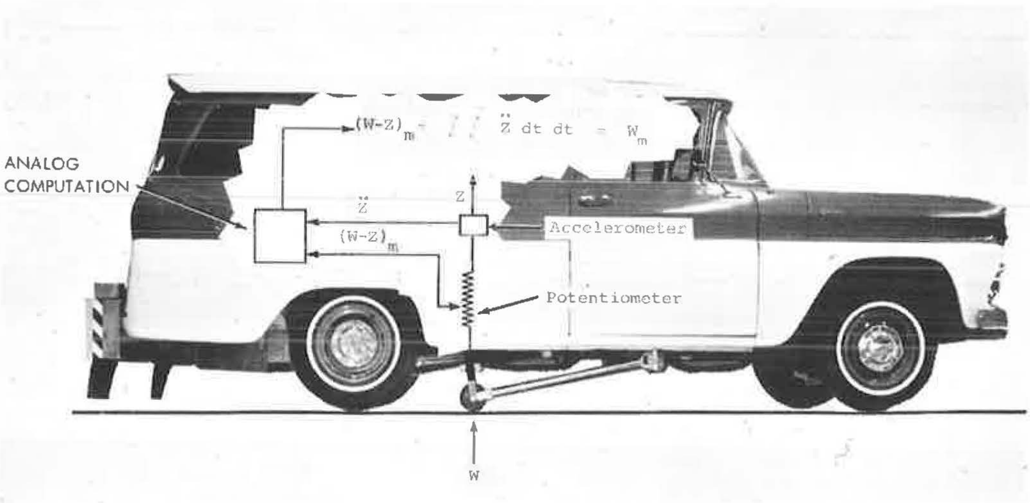


Figure 12. GMR road profilometer.

amplitude of a 2,000-ft sinusoidal wave would be measured with an amplitude of one-tenth its actual value. A second characteristic of the system is the measured road phase shift. In filtering, whether electronic or mechanical, the output of the system is shifted along the wave form or road profile from where it actually should be (Figs. 3 and 11). The attenuation and phase shift must exist if the hills and valleys are rejected by the measuring system. From Figure 11, there is practically no phase shift in the measurement of the 100-ft sinusoidal wave measured at 40 mph, but the 2,000-ft wave as measured leads the actual wave by 180°, half a wavelength or 1,000 ft. Normally, the 2,000-ft waves are not of interest. The wavelengths of interest are measured without amplitude change or phase shift. Figure 11 shows that higher recording vehicle velocity produces better fidelity. A 100-ft sinusoidal wave is measured at 40 mph with practically no phase shift but a phase shift of 45°, one-eighth of the wavelength, or 12 ft, is introduced if the recording vehicle velocity is 10 mph.

The selection of the filter natural frequency ω_f is based almost exclusively on the road amplitude and the road frequencies of interest. It would be desirable, of course, to have the filter natural frequency as low as possible at all times to provide accurate reproduction of all wavelengths. But, if the road being measured has large-amplitude, long-wave components, the voltage capacity of the analog computation components may be exceeded. This would suggest 2 courses of action. The filter natural frequency ω_f may be raised or the voltage scaling of the analog computation may be reduced. This latter course will result in reduced accuracy on small amplitude components. The flexibility to change quickly both filter natural frequency and analog computation scaling to suit requirements has been built into the GMR profilometer.

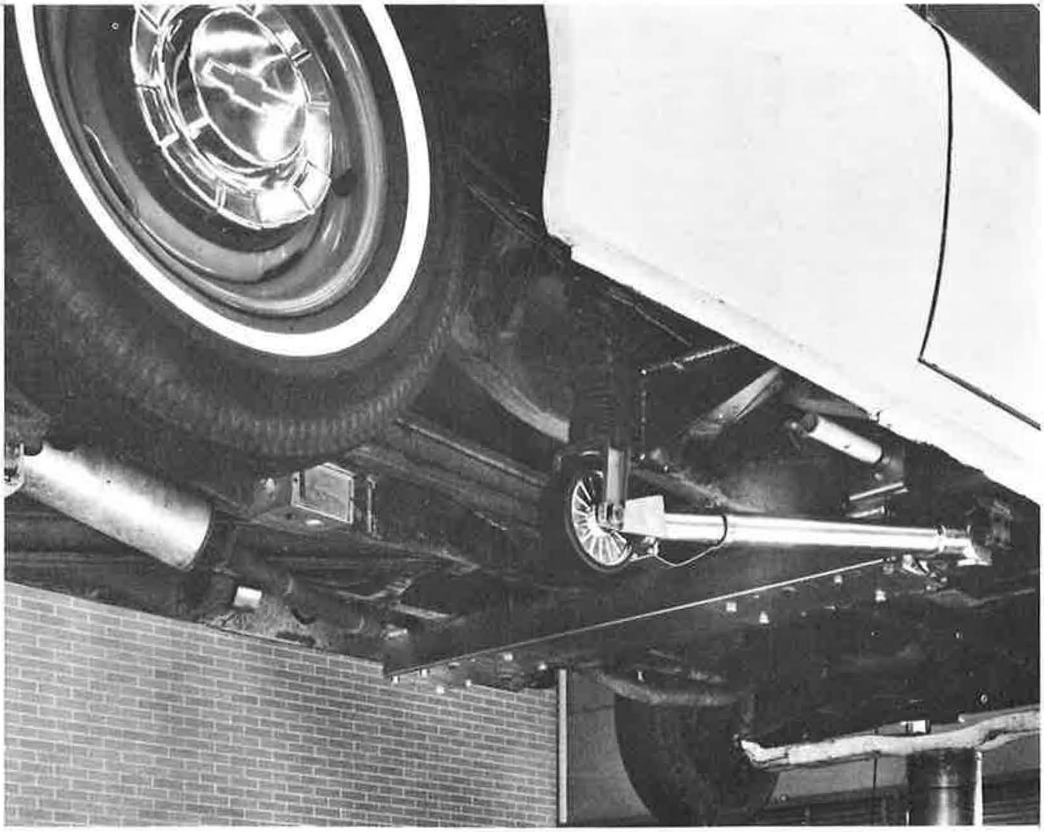


Figure 13. Road wheel assembly mounted on truck.

GMR ROAD PROFILOMETER

The road wheel of the GMR road profilometer (Fig. 12) is mounted on a trailing arm underneath the measuring vehicle. The wheel is held in contact with the ground with a 300-lb spring force. The truck mass and truck suspension form the mechanical filter between the road and accelerometer. The relative motion of a location on the vehicle body and the road wheel $(W-Z)_m$ is measured with a potentiometer. The accelerometer is mounted on the vehicle body above the road-following wheel at the point where the potentiometer fastens to the body. The 2 signals $(W-Z)_m$ and $\ddot{Z}$ are inputs into an analog computer; the output is W_m.

Road Wheel Assembly

The wheel and wheel hold-down mechanism are mounted under the measuring vehicle on the frame (Fig. 13). Figure 14 shows the general arrangement of the parts in the assembly. The road wheel is supported on a trailing arm which is free to rotate about a transverse axis located in a transverse tube which attaches to the vehicle. A torsion bar applies a torque from the transverse tube to the trailing arm to keep the road wheel in contact with the road surface. A kingpin in the trailing arm allows for misalignment and prevents scrubbing of the road wheel during turning maneuvers.

The road wheel (Fig. 15) is a lightweight, small-diameter wheel with a thin natural-rubber tire. The considerations in selecting the small wheel size are (a) a small wheel is easier to keep in contact with the ground than a wheel with more mass, (b) a small wheel performs less geometric filtering on the road profile than a large wheel,

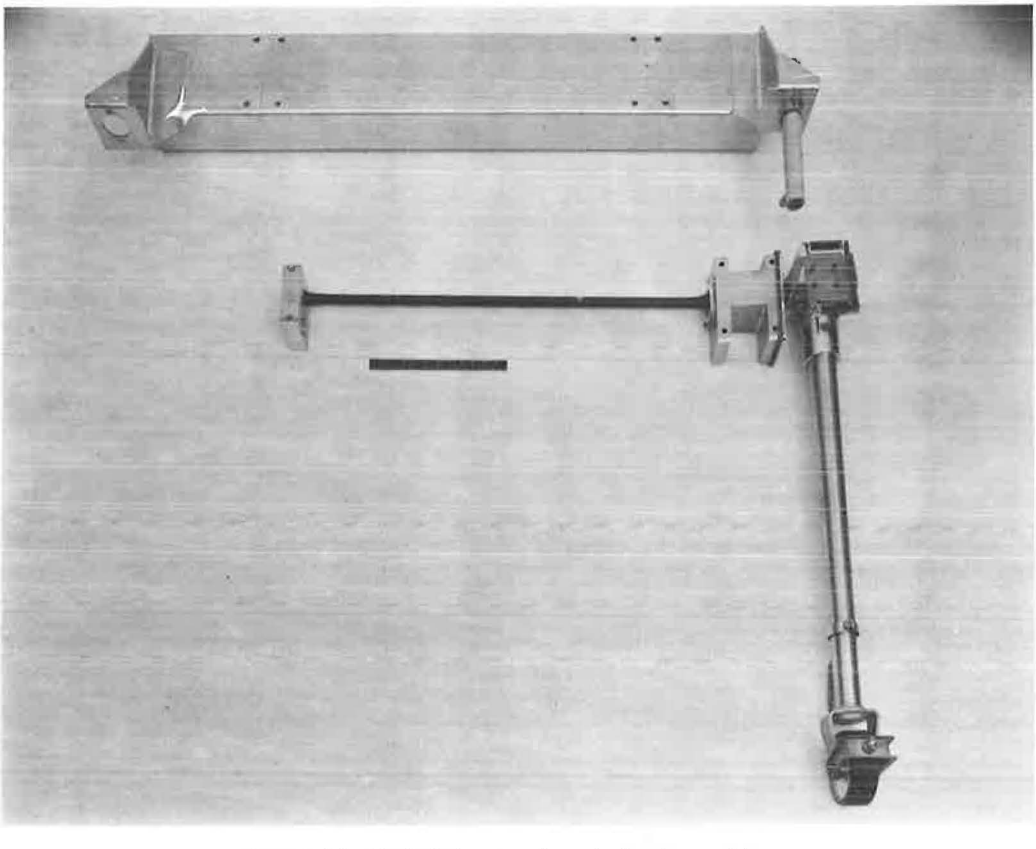


Figure 14. Exploded view of road wheel assembly.

and (c) the signals due to wheel out-of-roundness will introduce errors at shorter wavelengths. The shorter wavelength disturbances in the road do not excite appreciable vehicle vibrations and introduced errors may be disregarded.

A small road wheel also has several disadvantages. The wheel is small enough to get lost in a pothole in the road and be pulled off the towing vehicle. To overcome this difficulty, a skid is mounted on the trailing arm that will allow the wheel to drop no lower than 1.75 in. below a point 5 in. ahead of the wheel centerline (Figs. 13 and 14). A second difficulty is the high rotational speed, which is approximately 2260 rpm at 40 mph. The factors which dictated the choice of a thin natural-rubber tire molded to the wheel rim are (a) wear, (b) high temperature bond strength, and (c) low hysteresis which results in a lower operating temperature.

Figure 16 shows the recorded wheel displacement resulting from a wheel passing over a wedge at 40 mph. The natural frequency of 80 cps of the wheel and wheel hold-down system can be determined by the number of wheel bounces per unit time after the wheel has passed over the wedge. At a vehicle recording speed of 40 mph, wheel bounce would produce waves approximately 9 in. long. This low-amplitude, short-wavelength wheel bounce will not interfere with any road profile analysis presently contemplated.

A hydraulic piston and lever arrangement allows the road-following wheel to be raised off the ground when not in use. The vehicle driver controls this with a hand pump or the switch of an electric motor-driven pump. This accessory makes possible the rapid transit from one test site to another without concern about the road wheel.

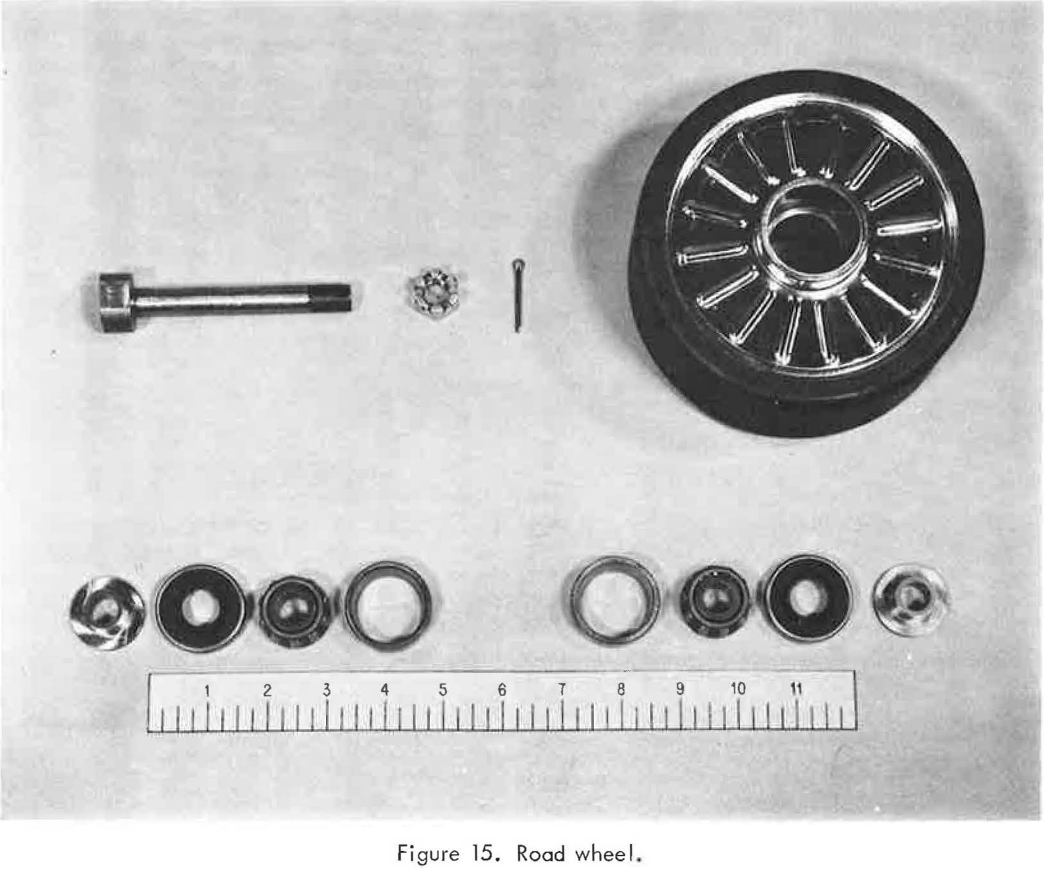


Figure 15. Road wheel.

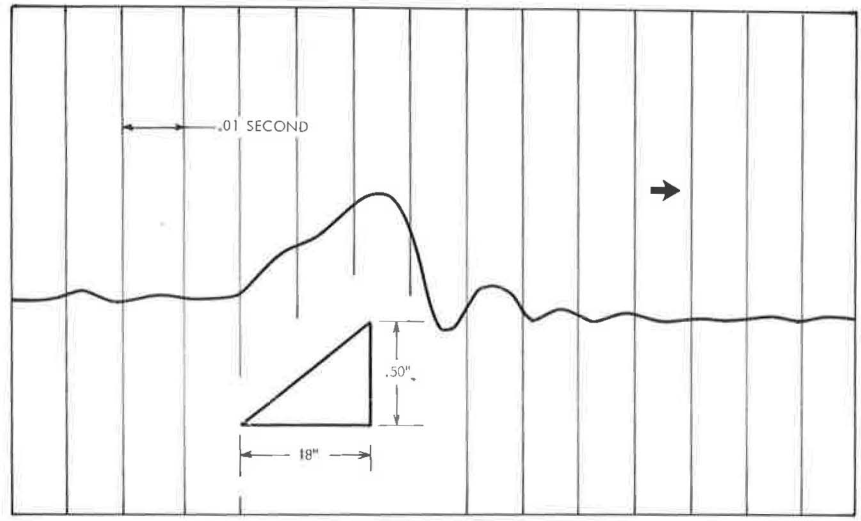


Figure 16. Transient response of road wheel passing over wood wedge at 40 mph.

Figure 17. Systron-Donner accelerometer and Markite potentiometer.

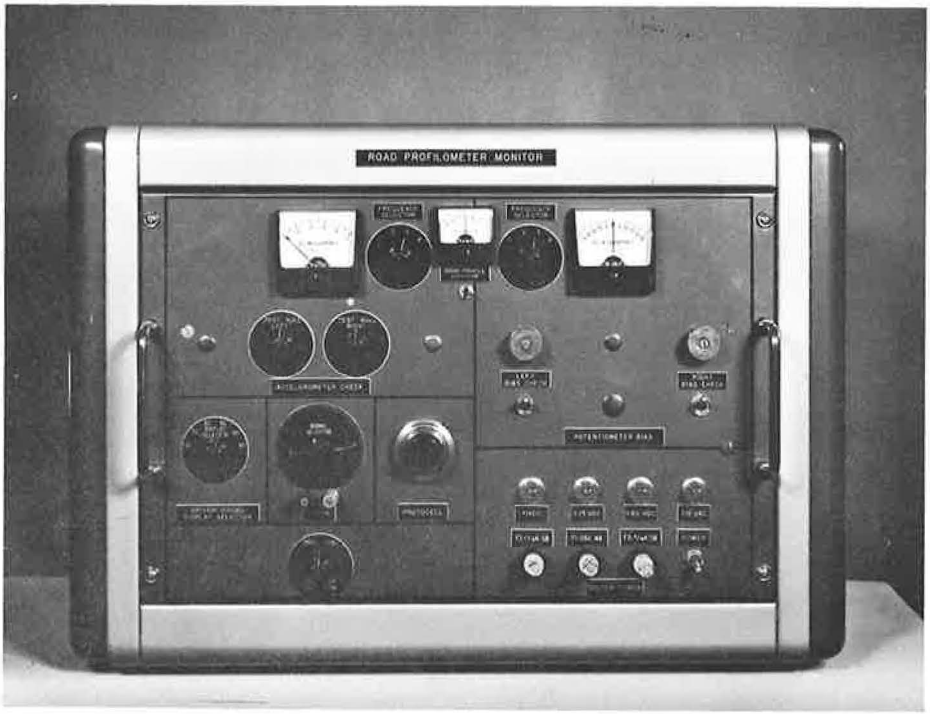


Figure 18. Monitor for road profilometer system.

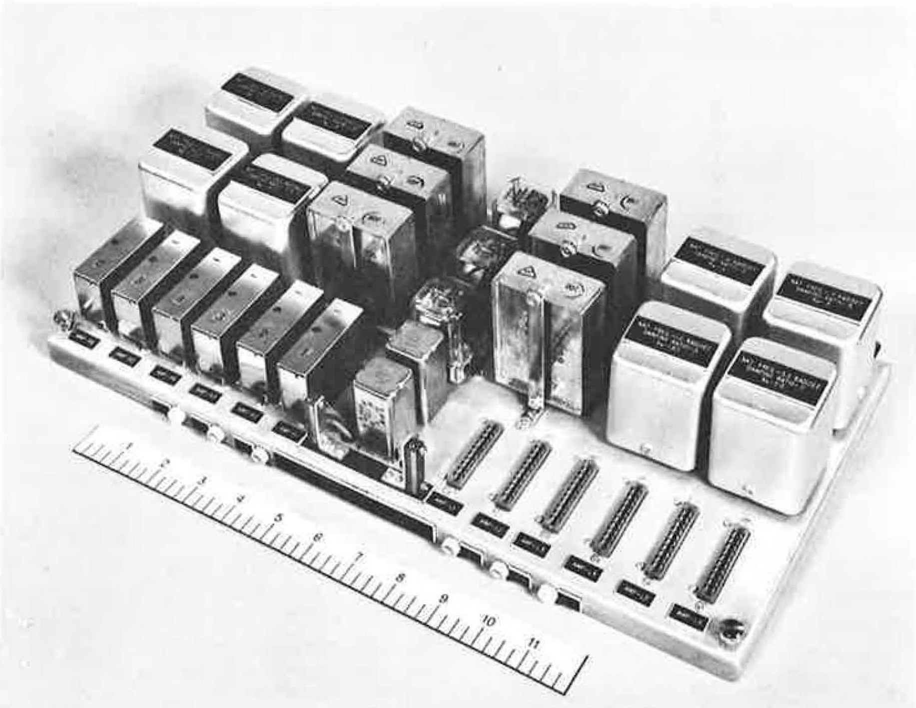


Figure 19. Analog computation package.

Transducers

Two important components in the road profile measuring system, the linear potentiometer and the accelerometer, are shown in Figure 17. The linear potentiometer is manufactured by the Markite Corporation. It has 15 in. of mechanical travel, 14 in. of electrical travel and is excited with a ±7-v DC power supply. This produces a road profile scaling of 1 in. of wheel displacement equal to 1 volt of output from the potentiometer.

The acceleration transducer is a Donner Model 4310 servo accelerometer. This is a force-balance instrument which has an improvement in linearity of 10 over conventional strain gage accelerometers. In addition, the accelerometer output signal is large enough that no signal amplification is required for use in the analog computation or for recording on a magnetic tape recorder. A ±2-g accelerometer range was found to be sufficient to handle the accelerations encountered at the mounting location on the vehicle body. The output signal for this range accelerometer is 3.75 v/g.

Precision excitation voltages must be supplied to both the potentiometer and accelerometer. A monitor box that performs this and several other functions is shown in Figure 18. The monitor box allows the operator to check quickly the condition of the transducers and to scale the signals for use in the analog computation or for recording on the tape recorder. A more complete description of the monitor box is given in Appendix B.

Analog Computation

The monitor box also contains a small, special-purpose analog computer (Fig. 19). A four-position selector switch (Fig. 20) mounted on the face of the monitor box allows the operator to select a variety of filter natural frequencies and voltage scaling. Corresponding to the positions on the selector switch are plug-in components inside the monitor box (Fig. 21) that actually establish the filter natural frequency and voltage scaling. Figure 22 shows the frequency response curve for 4 possible filter plug-in components. The filter natural frequency ω_f, the filter damping ratio ζ_f, and the voltage scaling in volts per inch of road profile K_w are indicated for each selection. A description of the analog computing components is given in Appendix B.

RECORDING EQUIPMENT

A large variety of equipment is available for recording road profiles as they are measured and computed. A direct-writing oscillograph is very valuable for an on-the-spot look at the road profile just measured. But it does not lend itself to more extensive data processing. For this purpose, a magnetic tape recorder is essential.

SYSTEM TRANSIENT RESPONSE

In addition to frequency response curves, information about the system performance can be obtained from the response of the system as a function of time, or transient response. Figure 23 shows the system transient response to a step input of displacement at the wheel which would occur if the road abruptly increased a unit in elevation. From a frequency standpoint, a step input is composed of all frequencies. The step is measured exactly at time equals zero indicating that the short wavelengths are almost unaffected by the filter. As time increases, the displacement returns to zero as the filter acts on the longer waves.

Figure 24 shows the transient response of the system to a ramp input such as would occur if the road abruptly increased in elevation at a rate of 1 unit per sec. This would simulate the transition from a level road to an uphill grade. The initial transition is measured exactly but, as time increases, the displacement again returns to zero. It now becomes obvious that this filtering action is necessary from a displacement storage standpoint; it is impossible to scale the problem to measure accurately both the small amplitude road features and the large amplitude hills.

The transient response to one wave of a sinusoid bump D ft long with flat road before and after the bump is shown in Figure 25. This transient response is for 40-mph

ROAD PROFILOMETER MONITOR

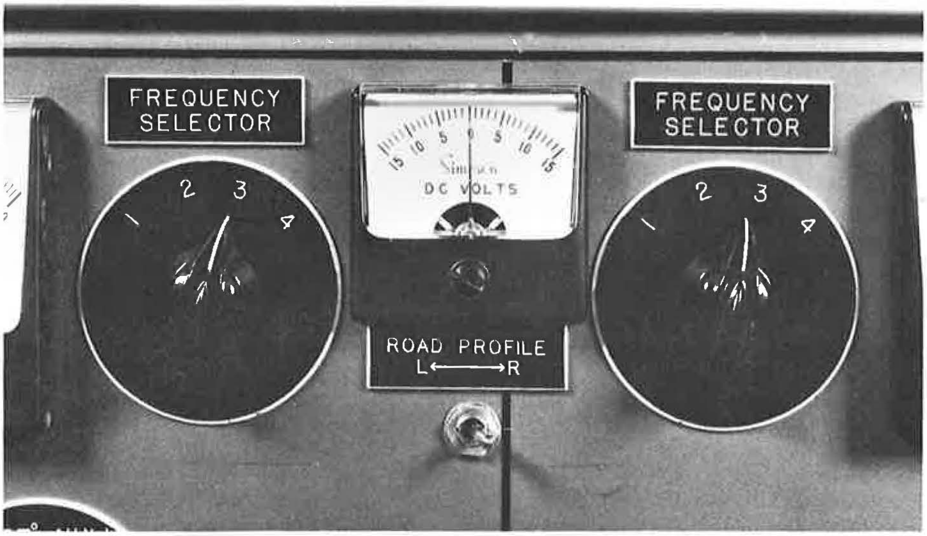


Figure 20. Frequency selector switch.

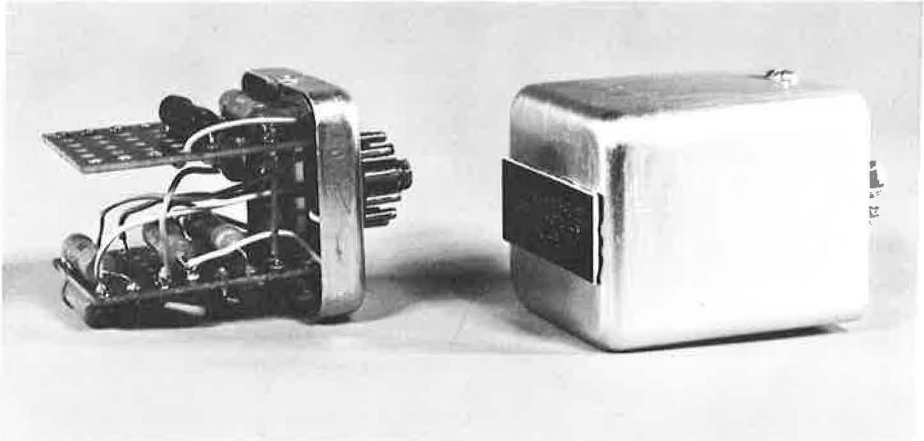


Figure 21. Frequency determining components.

recording velocity, a filter natural frequency of 0.3 rad/sec and a damping ratio of 0.5 for various values of D. As would be expected, the shorter bumps are measured with greater fidelity. Each bump is attenuated as the result of the filtering action on the longer wave components present in the bump.

The transient responses of Figure 25 can be determined for arbitrary values of recording vehicle speed, filter frequency and bump length as in Figure 26. Greatest fidelity is obtained when the quantity $(\omega_f D/V)$ is small. Again, the conclusion is that the long wavelength bumps are best measured with a high recording vehicle speed and low filter frequency.

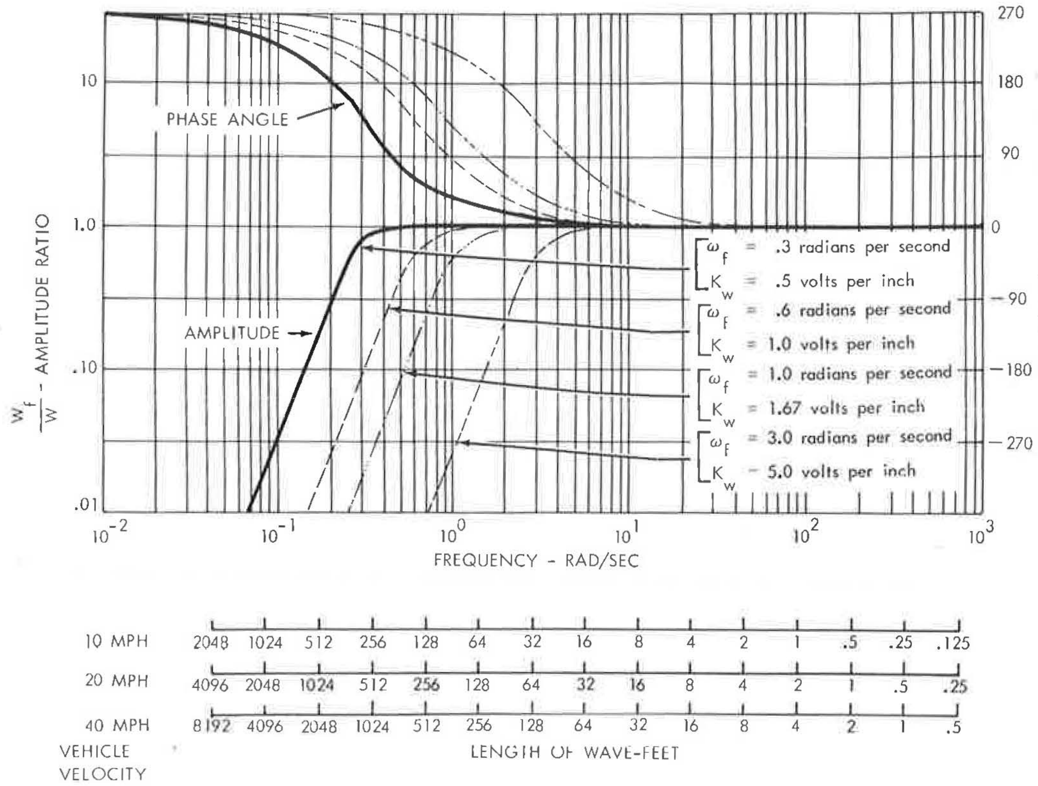


Figure 22. Typical frequency response selections.

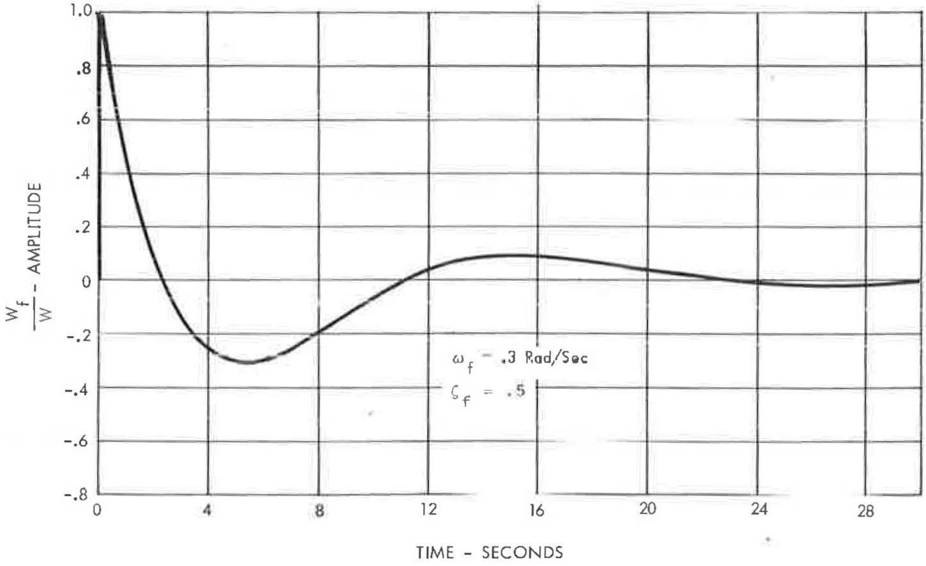


Figure 23. Transient response to a unit step input.

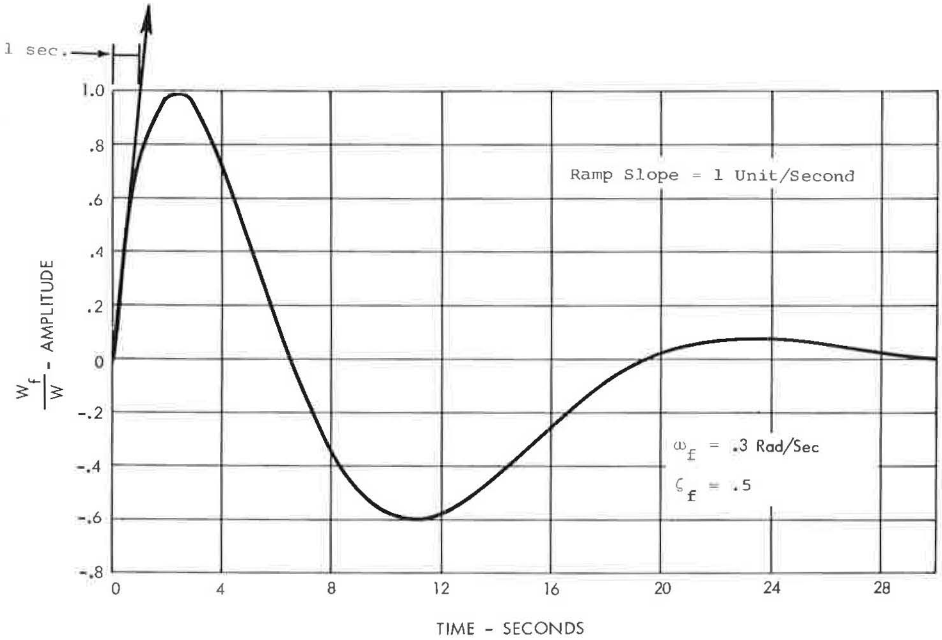


Figure 24. Transient response to a ramp input.

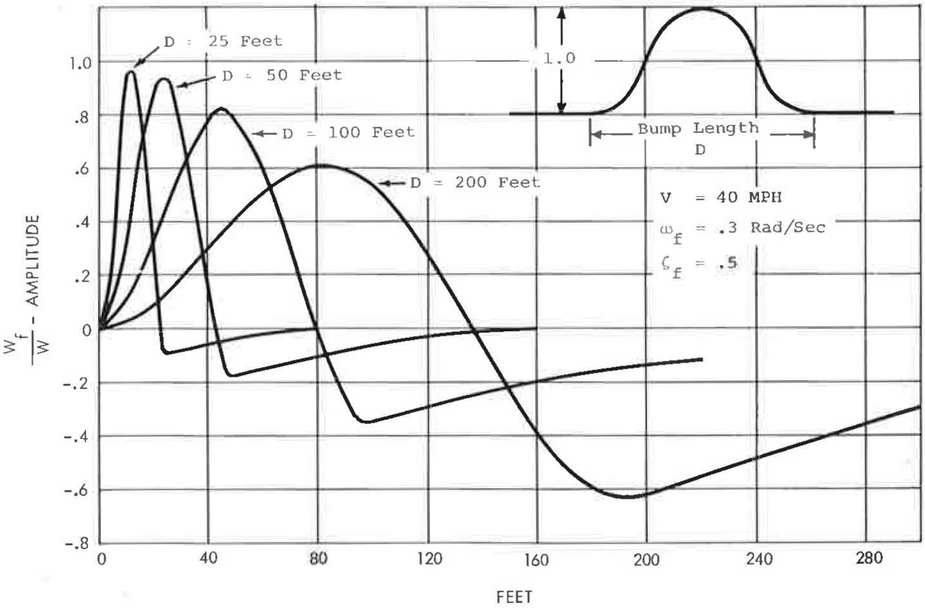


Figure 25. Transient response to a single sinusoid bump.

TYPICAL APPLICATION OF GMR PROFILOMETER

The GMR profilometer has been used on many projects, both within the General Motors Corporation and in cooperation with other groups. To illustrate the versatility

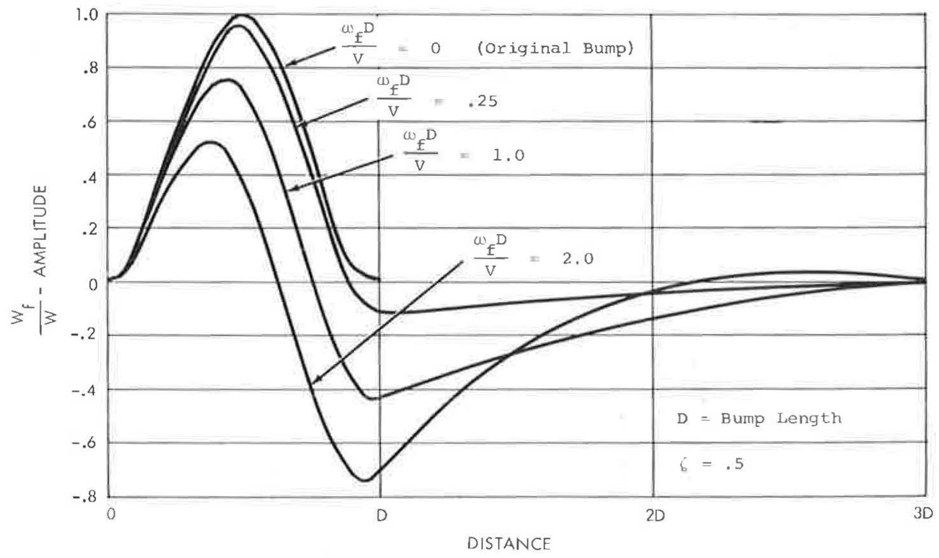
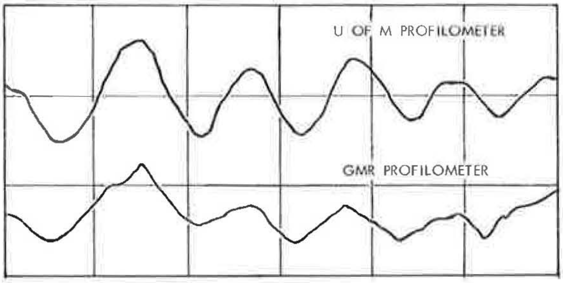
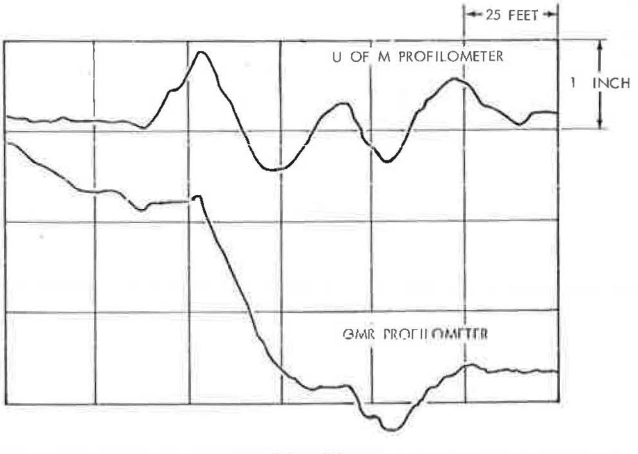


Figure 26. Measuring fidelity for a single sinusoid bump.

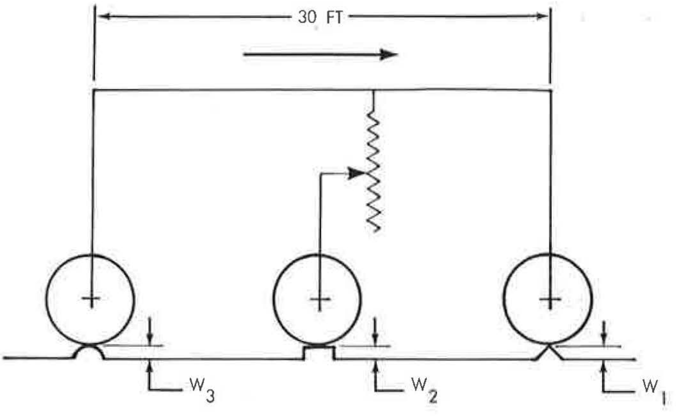


FIRST ROAD SECTION



SECOND ROAD SECTION

Figure 27. Comparison of profiles obtained with University of Michigan truck profilometer and GMR profilometer.



UNIVERSITY OF MICHIGAN PROFILOMETER

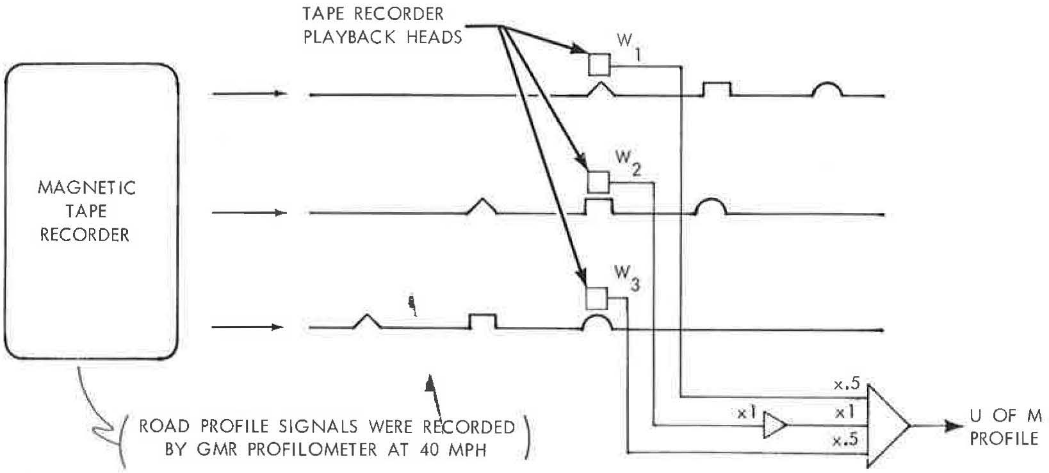


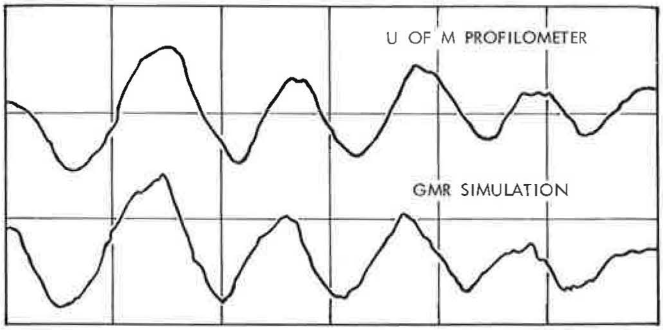
Figure 28. Simulation of rolling straightedge.

of the GMR profilometer, 3 applications are discussed showing how the profilometer was used and how the profiles were processed to produce meaningful test results.

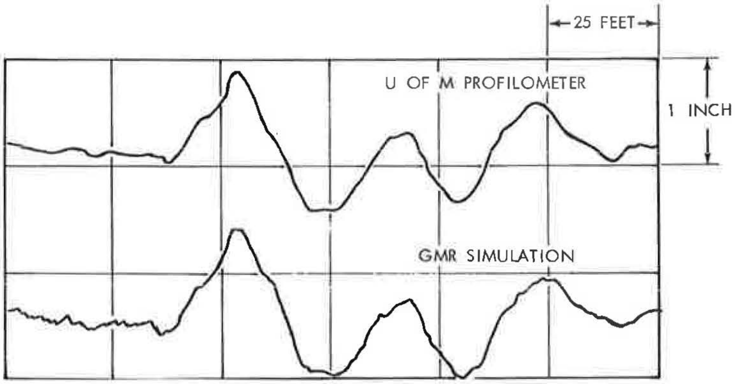
Simulation of Moving Straightedge

In the first application the road profiles obtained with the GMR profilometer were compared with profiles obtained with the University of Michigan truck profilometer. This comparison consisted of measuring the same section of road with the 2 devices at the same time. Figure 27 compares profiles as obtained directly with the GMR profilometer and the University of Michigan truck profilometer for 2 sections of road. The comparison of the first section is surprisingly good and can readily be identified as the same road. The agreement of the 2 directly measured profiles for the second section is poor.

Better agreement is obtained in this comparison if a simulation is made of the University of Michigan profilometer being driven over the GMR measured road profile for the same section of road. The Michigan profilometer measures the difference between the height of its center wheel and the average height of its front and rear wheels. The simulation was implemented by using a magnetic tape recorder and several operational amplifiers (Fig. 28). The GMR road profile was recorded on the first track as it was measured. It was then played back from the first track onto the second track with a



FIRST ROAD SECTION

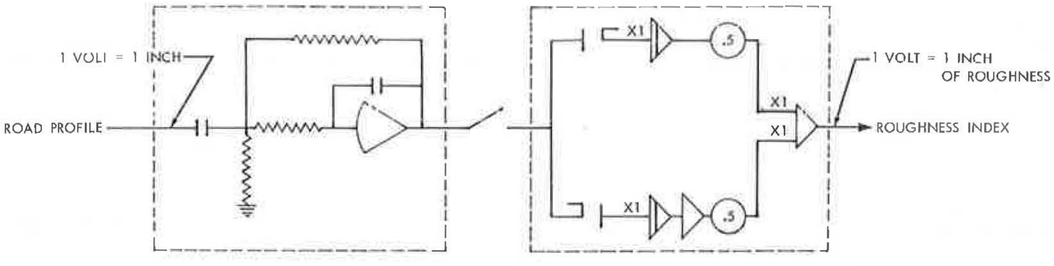


SECOND ROAD SECTION

Figure 29. Simulation of University of Michigan profilometer.

time delay proportional to the distance between the first and second wheels of the moving straightedge. The third track was produced in a similar manner from the second track. The end result from this recording procedure is the availability of 3 signals that represent what each of the 3 wheels sees at any one time. The simulation is completed by the use of operational amplifiers to form

$$\text{U of M Profile} = W_2 - \frac{W_1 + W_3}{2}$$



DIFFERENTION CIRCUIT

ABSOLUTE VALUE AND INTEGRATION CIRCUIT

Figure 30. Road roughness index simulation.

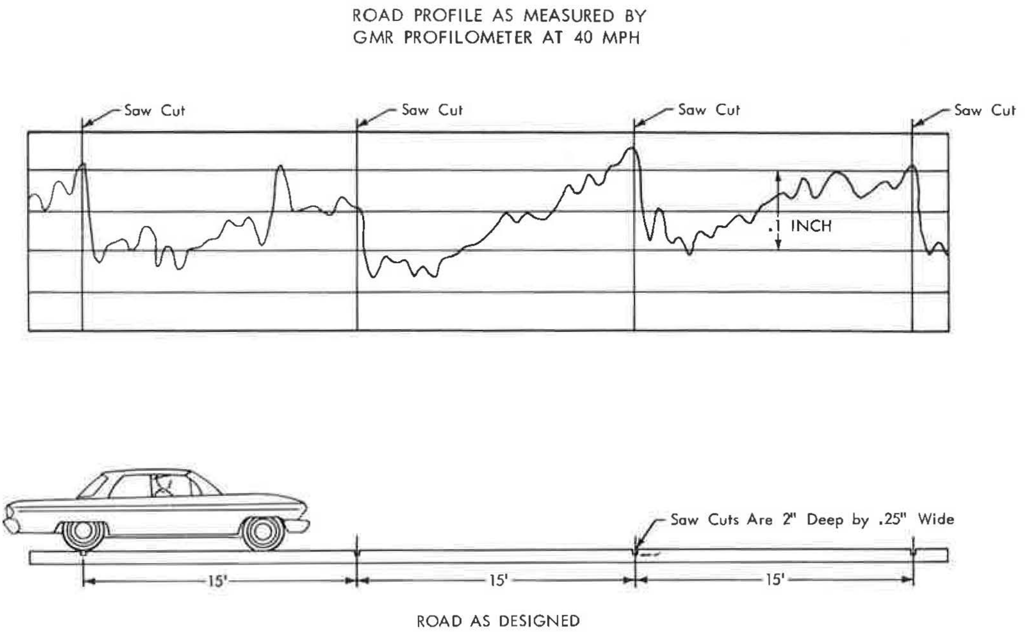


Figure 31. A road that induces automobile body shake.

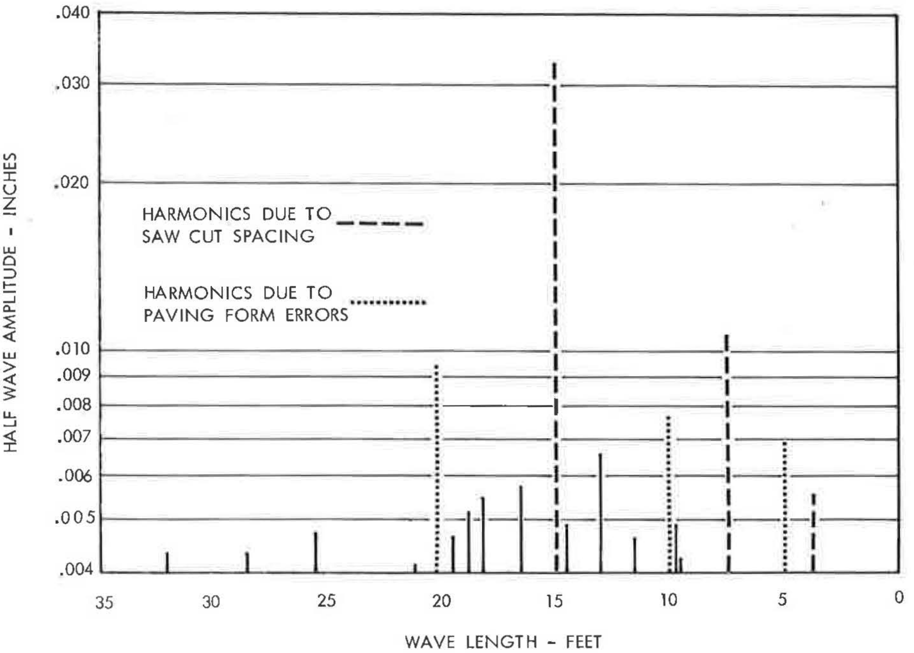


Figure 32. Harmonic analysis of a road that causes automobile body shake.

The comparison of the simulated moving straightedge profile with the actual moving straightedge profile as obtained with the Michigan profilometer is shown in Figure 29 for the 2 sections of road previously considered. The comparison is almost exact. This profilometer tends to amplify 30-ft wavelength components in the road profile

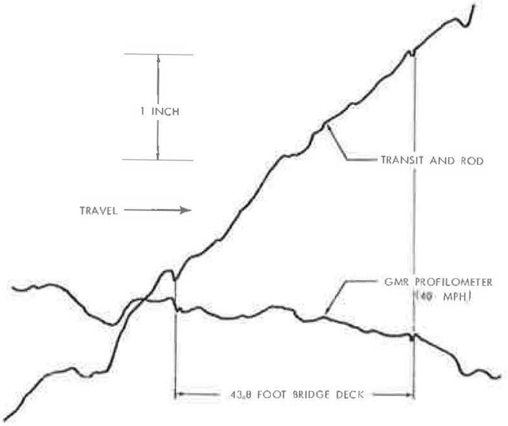


Figure 33. Bridge deck profiles as measured.

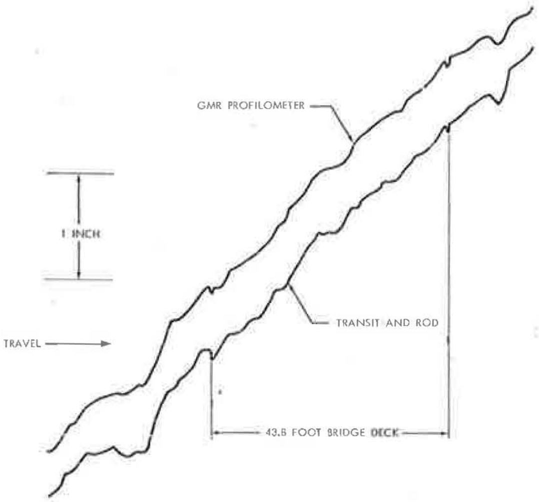


Figure 34. Comparison of bridge deck profiles after conversion of GMR profilometer reference.

(Figs. 27 and 29). The comparison in Figure 29 clearly indicates that the long wavelength components of the road profile, which are rejected by the GMR profilometer, are also rejected by the Michigan profilometer.

It is also possible to extend the simulation of the moving straightedge to obtain a roughness index (Fig. 30). Since the roughness index is an integration of vertical road displacement per unit distance, it can be obtained by differentiating the profile signal, integrating the plus and minus signals separately, dividing these signals by 2 and adding them together. Roughness indexes obtained by this simulation compared favorably with roughness indexes measured by the University of Michigan truck profilometer. In similar ways, other profilometers and roughness indexes can be simulated from the measured road profile.

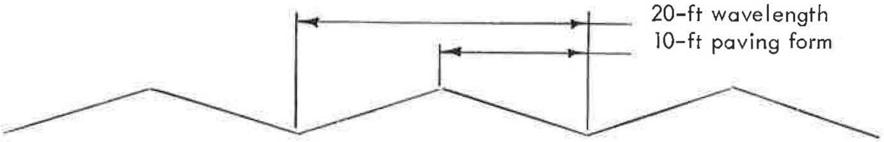
Roughness indexes, of which currently there are several, are dependent only on the road profile and the method of measurement. Clearly, all the information about a road profile can only be obtained from its actual profile. Any of the roughness indexes currently available from other apparatus can be obtained from the measured GMR profile by simulation of the method of measurement.

More work is required to determine an index, or indexes, which will highly correlate with subjective ride observations. Any new index can be determined from the measured road profile.

Analysis of a Road Profile

The second application is more typical of the projects on which the GMR profilometer is used within General Motors Corporation. Figure 31 is a very much expanded profile of a road measured with the GMR profilometer. This road was laid continuously and then saw cut every 15 ft to provide weakened planes for cracking. The profile of this road appears to indicate that faulting has occurred at the saw cuts causing as much as $\frac{1}{8}$-in. discrepancy between adjacent slab heights. It is very difficult to assess mentally the seriousness of a wave form of this type on automobile ride. We do know from experience that this particular periodic wave form induces automobile body shake. Figure 32 illustrates one method used by Research Laboratories for analyzing a complex wave form to break it down into its frequency components or wavelength components. From this harmonic analysis (2), it becomes apparent that there is a rather large 15-ft component from the saw cut spacing with smaller second and third harmonics at 7.5-ft and 3.75-ft wavelengths. It was the 7.5-ft component near the speed limit of 60 mph that caused the body shake frequency of 11 cps. The harmonic analysis of Figure 32 gives us some additional information about this road. The next most prominent frequencies are

20-ft, 10-ft, and 5-ft wavelengths. The 20-ft wavelength is a form-laying-induced profile as shown below:



The 10-ft and 5-ft wavelengths are the second and third harmonics of the 20-ft wave. The 10-ft wavelength at 75 mph causes the same 11-cps body shake frequency.

Measurement of a Bridge Deck

The third application illustrates the use of the GMR profilometer to measure the profile of an interstate highway bridge deck. This bridge deck was measured by the Michigan State Highway Department as part of a Bureau of Public Roads research project to evaluate the GMR profilometer for highway department use. In this evaluation the profile of a bridge deck as measured with the Michigan State Highway Department's GMR profilometer was compared to the profile of the bridge deck as obtained with a transit and rod. The bridge deck profile measured by the 2 methods is shown in Figure 33. At first glance, it would appear that the comparison is poor, but a more detailed examination, keeping in mind the method of measurement, will show an excellent correlation. The most obvious discrepancy between the profiles is that the actual bridge rises approximately 2 in. in its length while the profile as measured with the GMR profilometer shows that it is dropping. This is due to the use of 2 different reference systems—a horizontal line for the transit and rod and a moving reference which is a function of the previous road profile for the GMR profilometer. The reason for this was discussed in the section on system transient response. Since the GMR road profile is always a function of the previous road profile, the GMR road profile will rarely show the correct slope.

A more direct comparison of the 2 profiles can be obtained by converting the reference of the GMR profile to a horizontal reference by the process in Appendix C, which requires knowing the actual elevation of 2 points along the road. Figure 34 compares the 2 profiles using the same horizontal reference system. In both profiles, there are small discontinuities where the bridge deck meets the road. There are also prominent profile characteristics that identify the profiles as being from the same road. The amplitude of local profile details is small, which demonstrates the resolution of the GMR profilometer. Since this bridge deck is relatively smooth and causes little disturbance as a car passes over it, the GMR profilometer appears to have more than adequate resolution for bridge deck measuring purposes.

The process of converting the reference system (Appendix C) is another example of data processing at a later time to put the original information into more meaningful form. Whether this form be road profile, roughness index, moving straightedge profile, slope variance, harmonic analysis, power spectral density, or any other, it is felt that this final form can be obtained from the GMR profilometer data. The authors are not proposing that any of the data processing methods discussed be adopted by the highway industry, but rather are indicating the wide variety of information which can be obtained from the measured road profile with later data processing techniques.

CONCLUSIONS

1. The GMR road profilometer developed by the General Motors Research Laboratories is simple to operate and produces an accurate and repeatable road profile quickly and safely.
2. The measured road profile when recorded on magnetic tape can be reproduced easily for data processing at a later date.

3. The road profile and roughness index as measured by the University of Michigan profilometer can be obtained from the profile measured with the GMR road profilometer.

4. All of the roughness indexes currently in use can be obtained from the profile measured with the GMR road profilometer.

5. The operating characteristics of the GMR road profilometer are variable and can be changed to adapt to the conditions of the road being measured.

6. Additional work is required to determine a roughness index, or indexes, which will correlate highly with subjective ride observations. These various indexes can be determined from the profile measured with the GMR road profilometer.

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Appendix A

FREQUENCY RESPONSE THEORY

Analysis by the frequency response (3) approach is based on the fact that any complex wave form can be represented by the summation of several sinusoidal waves. For example, the wave form at the top of Figure 35 can be manufactured by the algebraic summation of 2 sinusoidal waves as shown at the bottom of the figure. The first sinusoid wave is called the fundamental or first harmonic. The length of the second wave is one-half the first wave and is called the second harmonic. At time equals zero, both sinusoid waves are passing through zero amplitude going in the same direction (upward); thus there is no phase shift between these 2 sinusoid waves in this complex wave form. To illustrate the effect of phase shift, Figure 36 shows the same 2 sinusoidal waves with the fundamental only shifted 45°. The resulting wave form is, of course, also modified. In the frequency response approach it is then assumed that a system can be analyzed by observing how the system responds to the individual sinusoidal waves that make up the complex wave form.

A simple method of performing a frequency response measurement on a system

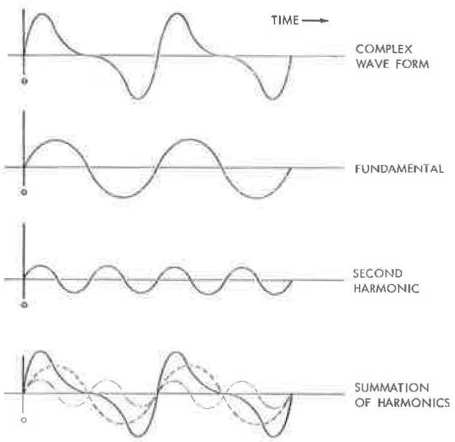


Figure 35. Frequency composition of wave form.

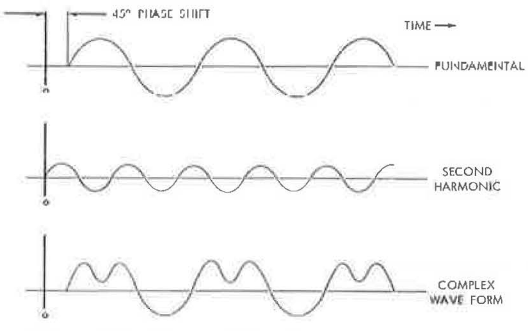


Figure 36. Phase shift effect on wave form.

is to use a sinusoidal signal as an input to the system and observe its output. The output from this test is usually presented as amplitude ratio and phase shift. The amplitude ratio is the amplitude of the output signal divided by the amplitude of the input signal. The phase shift can also be determined by observing how much the output signal leads or lags the input signal. As an example, the frequency response of the GMR profilometer system (Fig. 11) could have been obtained by driving the truck over many different sinusoidal wave roads and recording amplitude ratio and phase shift for each wave. This is not practical because these sinusoid roads do not exist, and it is not necessary because the frequency response of this system can be computed.

Appendix B

GMR ROAD PROFILOMETER MONITOR

Analog Computation

In the early GM profilometer, the analog computation was performed in a rather large general purpose analog computer carried in the measuring vehicle. However, once the analog computer requirements were more specifically determined, a special analog computation package was designed to fit the job exactly. This analog computation package (Fig. 19) is mounted on a separate sub-chassis in the monitor box. The main analog computing components are small solid-state operational amplifiers manufactured by Philbrick Research Incorporated. The operational amplifiers are converted to an integrator by the addition of a good quality capacitor between the output and input of the amplifier. The operational amplifiers form a network that performs the functions of double integration, signal summation and high pass filtering. The analog computation package has 4 plug-in frequency determining components which can be individually selected by the switch (Fig. 20). The operator can select the filter natural frequency and voltage scaling used in the analog computation. A simple test has been built into the analog computation system to check the condition of the analog components. The test is performed by rotating the calibration switch on the face of the monitor box. The calibration switch replaces the output from the linear potentiometer, $(W-Z)_m$, with a 1-v signal. Since the potentiometer is scaled to 1 v = 1 in. of road profile, the 1-v calibration signal will always represent a 1-in. step of displacement. The output W_f should resemble the step transient response of Figure 23. The time for the transient response to first cross the zero axis and the amount of overshoot are good checks on the operation of the circuit. The overshoot for a 0.5 damping ratio will always be approximately three tenths of the step value. The time in seconds required for the transient response to first cross the zero axis can be expressed as a function of the filter natural frequency in radians per sec by

$$t = \frac{0.74}{\omega_f}$$

From Figure 23, the time is 2.5 sec as predicted by this equation.

Other Monitor Functions

Although the basic system of the GMR road profilometer is simple, the associated functions necessary to make everything work become a bit complex. It is desirable to reduce this complexity to the point where it is reliable and can be operated by a person with limited technical background. Other than analog computation, the purpose of the monitor is to:

1. Convert 110-v 60 cycle AC power into suitable DC power supplies for transducer excitation;
2. Supply checks to determine if all power supplies are working;
3. Check on the operation of all transducers;
4. Receive all transducer signals and convert them into signals suitable for analog computation to produce road profile; and
5. Supply properly scaled road profile signals for recording on a 1-v RMS range tape recorder.

The monitor has a power supply cable which can be plugged into any 110-v 60 cycle power supply. In a vehicle this may be the same converter used to supply power to an oscillograph or a tape recorder. The monitor has a power switch which interrupts the 110-v supply when it is in the OFF position; when the switch is ON, the 110-v alternating current is converted into ±60-v DC, ±15-v DC, and + 1-v DC. The monitor control panel (Fig. 18) is equipped with yellow indicator lights which light if there is an output from each of the DC voltage regulators. The indicator light only shows that the DC voltage regulators have an output. However, experience shows that if a regulator has any output, it almost always is the correct voltage. These DC voltages are necessary for successful operation. If a light is out, the reason should be determined before proceeding further.

In addition to supplying transducer excitation, the monitor unit supplies excitation for a photocell sensor. A light shines on the pavement from under the vehicle. A photocell aimed at the light spot senses changes in pavement reflectivity. With this device, areas of interest on the road can be marked with contrasting paint, which then produce signals as they are passed over. In addition to indicating painted areas, the photocell has been found to indicate tarred pavement joints, saw cuts and cracks. Preliminary results indicate that this device could be used by highway people in pavement condition checks.

Connectors have been supplied on the back of the monitor (Fig. 37) for all the transducer cables. After connecting the transducers, the condition of each transducer can be evaluated by a few simple checks. In the ACCELEROMETER CHECK area of the

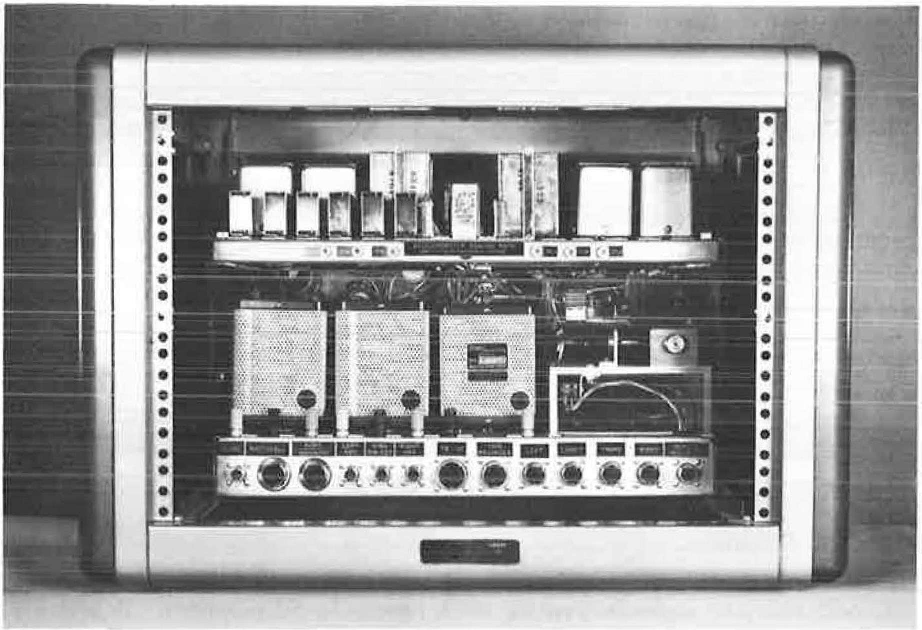


Figure 37. Transducer connectors on rear of monitor box.

monitor control panel (Fig. 18) is a rotary switch for the accelerometer check. Turning the switch counterclockwise to TEST should deflect the meter 1 milliampere which indicates that a test is being performed. Turning the switch clockwise to NULL should cause no meter deflection. Readings different from these indicate the accelerometer is not functioning properly. The rotary switch is spring loaded to return to the normal operating position.

In the POTENTIOMETER BIAS area of the monitor control panel is a biasing pot for the potentiometer. A potentiometer output results from the brush of the potentiometer being located at a non-zero voltage spot on the element. The voltage output of the potentiometer can be observed on the meter by pressing down the toggle switch and the output càn be made zero by adjusting the biasing pot with a screwdriver. It is desirable to have the potentiometer output nearly zero prior to recording so that the signal fluctuates around zero. The output of the potentiometer changes as the vehicle load changes since this changes the linear potentiometer arm position.

The remaining transducer inputs into the monitor box are a photocell output and a rotating cable from the measuring vehicle's transmission output speed. To supply the rotating flexible cable to the monitor box it is necessary to install a tee on the transmission where the vehicle's speedometer cable is attached. The flexible cable from the transmission has a receptacle on the monitor box into which it fits during operation. Inside the monitor box, the rotating cable drives a tachometer generator and a distance measuring device.

In the center of the monitor control panel is an adjustable potentiometer labeled PHOTOCELL. This is an adjustment on the photocell voltage output for various road reflecting conditions.

To the left of the monitor control panel is an area labeled DRIVER VISUAL DISPLAY SELECTOR. This selector switch is used in conjunction with a driver display box (Fig. 38) located in front of the driver on the vehicle's instrument panel. The driver display box is connected by electrical cables and connectors to the monitor box. There are 2 meters on the driver display box. One meter, labeled SPEED, will read zero when the driver is driving at the speed selected on the monitor panel. This meter is in effect a more sensitive speedometer. In Figure 18, the selector switch is set at 40 mph. Other speeds are available from 10 mph to 60 mph in steps of 10 mph. The second meter on the driver display box, labeled INFORMATION, is a monitor of the information signal. The information signal display is the output of a tachometer-generator which is vehicle velocity. Distance is indicated by a reversal in sign of the voltage every tenth mile traveled. The voltage level can be reduced to zero

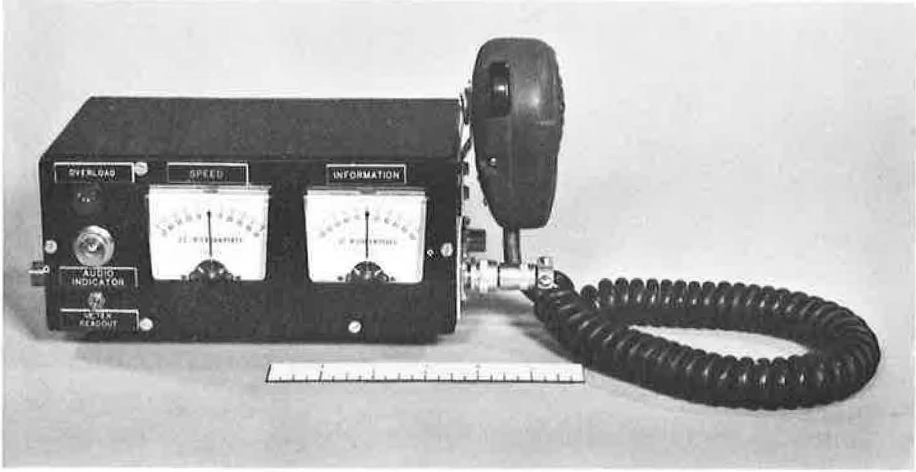
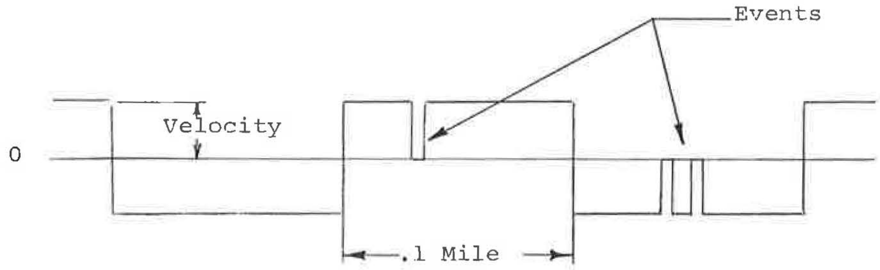


Figure 38. Driver display box.

with a driver-operated remote switch to mark events of interest. A typical output of this device is:



The driver also has available a microphone with which he is able to record voice comments on the tape recorder. As an indication that the voice signal has been supplied to the tape recorder, an AUDIO INDICATOR in the form of a light bulb is mounted on the driver display box. This bulb glows as signal amplitude increases.

The monitor box has 3 outputs. One output is a connector to a tape recorder or oscillograph. The signals to the recorder are scaled not to exceed 1 volt RMS. A second connector contains the outputs from the transducer for use in an external analog computer. A third output is a SCOPE connection and a SIGNAL SELECTOR switch which allows the signals going to the tape recorder to be observed on an oscilloscope.

Appendix C

REFERENCE SYSTEM CONVERSION

Because there is no direct relationship between the slope of the road profile from the GMR profilometer and the actual slope of the road, it is sometimes difficult to compare the GMR road profile with the real road. This comparison can be simplified by converting the reference on the GMR profile to a horizontal reference. Figure 39 establishes the geometry to be used in the development of the conversion process.

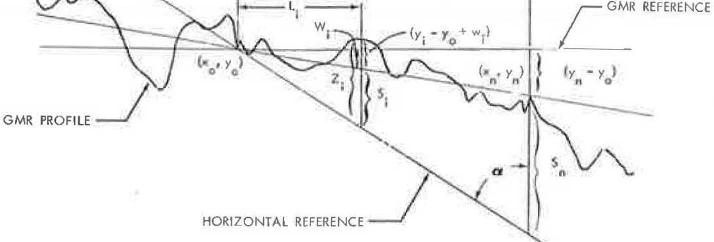


Figure 39. Reference conversion geometry.

The following notation is used in this appendix:

(x_i, y_i) = the location of a point on the GMR profile, the elevation of which is to be determined;
(x_o, y_o) = the location of the first point on the GMR profile at a known elevation;
(x_n, y_n) = the location of a second point on the GMR profile at a known elevation;
S_n = difference in elevation between two points (x_o, y_o) and (x_n, y_n) on the road surface as measured by a transit;
L_n = horizontal distance between two points (x_o, y_o) and (x_n, y_n) of known elevation;
Z_i = elevation of a point on the road profile; and
L_i = horizontal distance from point (x_o, y_o) to point (x_i, y_i).

Figure 39 is greatly compressed in the horizontal direction and makes the angle α appear much smaller than 90°. Actually, it is very near 90° and will be considered 90° for this analysis.

By observation the following relationships can be written:

$$S_i = S_n \frac{(x_i - x_o)}{(x_n - x_o)}$$

$$W_i = (y_n - y_o) \frac{(x_i - x_o)}{(x_n - x_o)}$$

$$Z_i = (y_i - y_o + W_i + S_i)$$

$$L_i = x_i - x_o$$

This reference conversion can be performed in a variety of ways depending upon the frequency of its use. The simplest and slowest method is to measure the distances Z_i directly from the oscillographic recording (Fig. 39). A digital computer program could be used to obtain fast, but possibly complex, conversion of the reference. In the bridge deck problem the Michigan State Highway Department recorded the bridge profile on an oscillograph chart and the profile was digitized using a Benson-Lehner digitizer.

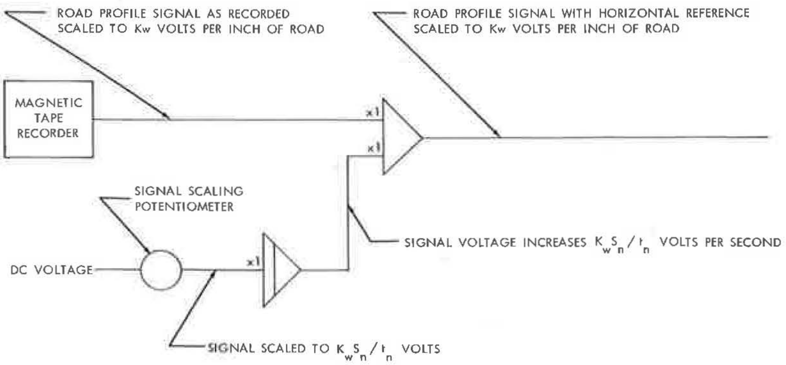


Figure 40. Analog reference conversion.

If the road profile is recorded on magnetic tape, this reference conversion can be accomplished on the analog signal as shown in Figure 40. S_n (Fig. 39) is the difference in elevation between 2 points on the road surface in inches as measured by a transit and t_n is the time in sec required by the magnetic tape recorder to play back the road distance L_n. K_w is the road profile scaling in volts per inch as it is played back from the tape recorder. If the analog signal is available, the analog method of reference conversion is the simplest.