Servo-Seismic Method of Measuring Road Profile

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• AT THE GENERAL MOTORS Research Laboratories a ride simulator is used for the study of ride characteristics of the many different General Motors' products. The input to this ride simulator is the road profile of actual roads whose measurements have been stored on magnetic tape. This paper is about the method that was developed for measuring this road profile.

Before starting on the discussion of the measuring, a broader understanding of the Research Laboratories' ride simulator program may be helpful. Figure 1 shows a view of the ride simulator installation. Using the road profile as an input, an analog computer produces voltages proportional to the calculated movements of the car body for any selected suspension characteristics. These voltages then are fed into electro-hydraulic valves and actuators which then produce car body movements of the desired magnitudes. With the actuators shown, the car body can be subjected to bounce, pitch, and roll. Intuitively, it can be seen that the road profile input from two tire tracks is required to obtain body roll.

With this brief background, it is apparent that accurate recording of the road profile of two tire tracks is a very important part of the ride simulator program. This paper describes the method used to measure road profile and techniques used to establish the accuracy of these measurements and attempts to correlate the frequency characteristics of the road profile signal with road roughness as experienced through a car suspension.

At the beginning of the ride simulator program, it was realized that it was necessary to measure the profile of many miles of the country's roads. The results of the usual literature search paralleled F. N. Hveem's report presented at the 39th Annual Meeting of the Highway Research Board. It soon became apparent that the methods developed by the highway people for measuring road roughness were not capable of measuring the road wave lengths required for the ride simulator program.

The methods used by the U. S. Air Force to measure runway roughness were also investigated. These included transiting and the use of a stationary projector that casts a highly collimated light beam onto an optical head moving along the runway. The optical head consisted of an array of photoelectric cells which sensed the light beam's vertical position. Both of these methods allowed the measurement of the long waves but did not have the speed and flexibility desired for continuous measurement of miles and miles of the country's roads.

It was soon concluded that a new method would have to be developed. The results of the first attempt are shown in Figure 2. This method consisted of a road following wheel held against the ground by a spring that used the towing vehicle as a reaction. An accelerometer mounted on the wheel produced an electrical signal that was integrated twice to obtain an electrical signal representing the movement of the accelerometer and thus through the wheel a representation of the road profile. However, difficulty was experienced measuring the long waves. The inadequacy of this method can be attributed to the large maximum accelerations which required the use of a 30-g accelerometer and the resulting poor accelerometer signal to noise ratio for the subtle low-frequency long-wave operation; that is, the signal representing the long-wave displacement contained so much instrument noise that the road profile signal could not be separated. Considerable time was spent trying to develop this method but it was finally abandoned.

In effect, the double integration of the accelerometer signal was the measuring of accelerometer displacement with respect to an inertial reference. Using an inertial reference appeared desirable, and this concept was carried over to the second attack

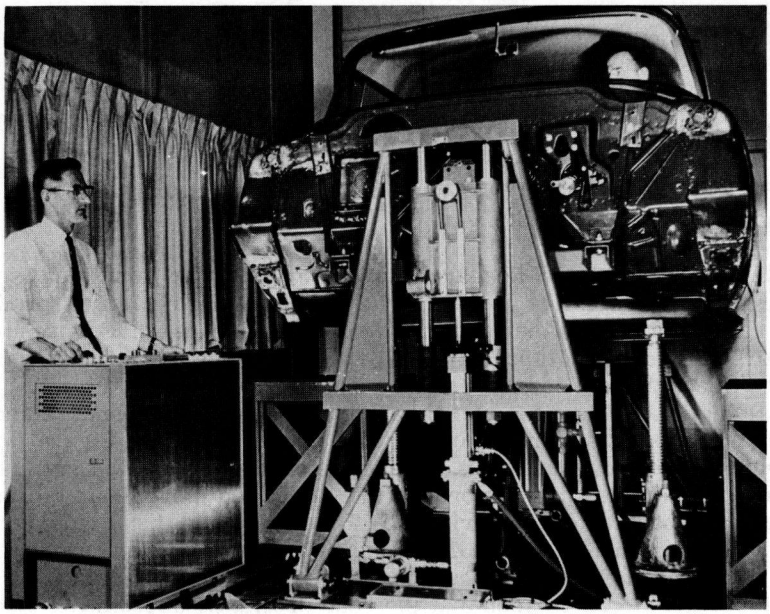

Figure 1. The General Motors vehicle ride simulator.

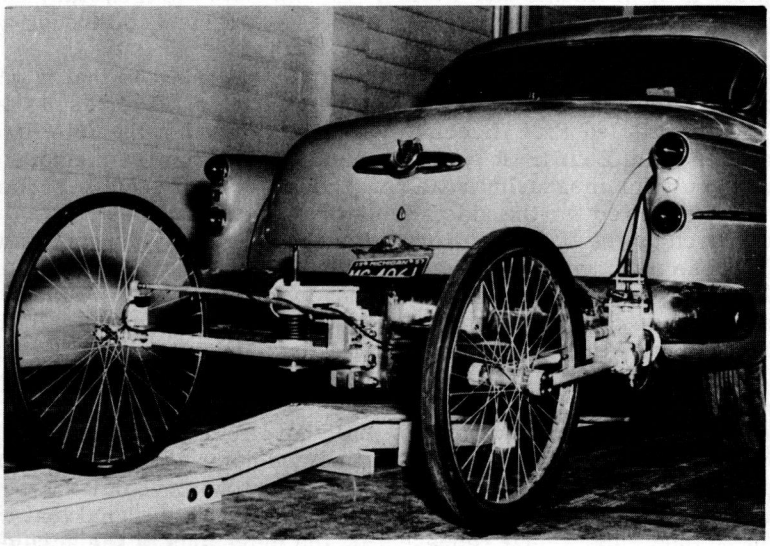

Figure 2. A device for measuring road profile using an accelerometer.

on the problem. In this approach it was decided to establish an inertial reference platform and measure the vertical displacement of the road following wheel with respect to this platform. This reference platform must, therefore, be held stationary with respect to the universe. To determine if the platform has moved, an accelerometer was placed on the platform. An acceleration signal from the accelerometer indicates the platform has moved and the double integration of the accelerometer signal shows how much. If this information can be used to move the platform physically back to its

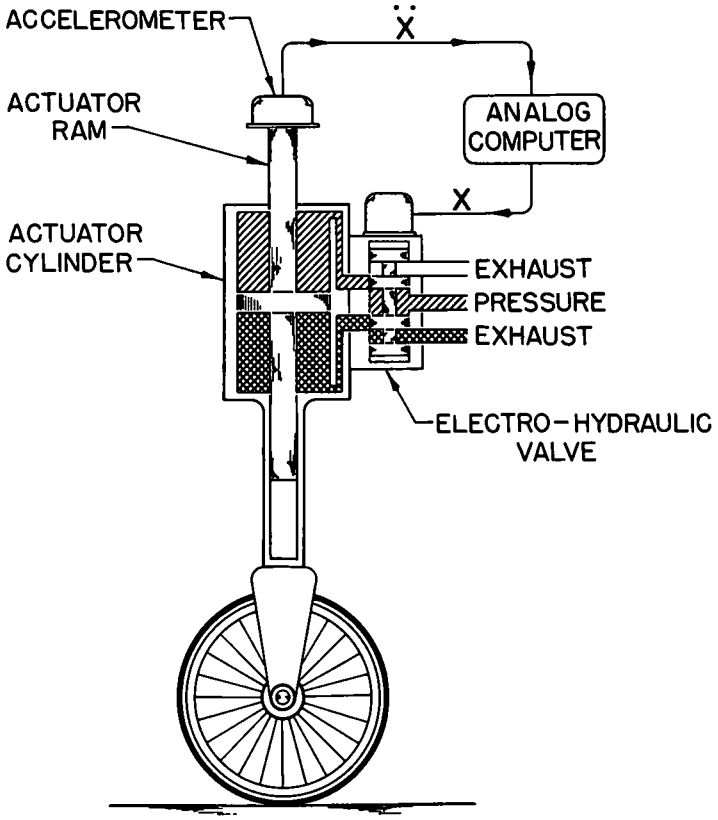

Figure 3. Schematic of Servo-Seismic road profile recording device.

original location, the inertial reference platform has been established. This platform positioning was obtained by use of an electrohydraulic valve and hydraulic actuator which produce a movement of the actuator ram that is proportional to the electric voltage supplied to the valve. Figure 3 shows how these components were combined to accomplish this. The actuator ram with the accelerometer mounted on the end is the inertial reference platform. The analog computer integrates the accelerometer signal and feeds a signal proportional to the platform displacement to the electrohydraulic valve. The valve then causes an oil flow to the appropriate chamber in the actuator. However, this is an oversimplification of the system.

Figure 4 shows a sequence with the road profile measuring wheel going over a bump. As the wheel goes up the bump, the wheel, actuator and accelerometer are accelerated upward. This accelerometer signal is integrated twice, to determine the upward displacement of these components. This displacement signal is used to cause an oil flow in the electrohydraulic valve. The signal is scaled so that the oil flow into the top chamber of the actuator and exhausted oil out of the bottom chamber causes a relative movement of the actuator cylinder and ram exactly equal to the upward movement of the actuator cylinder, thus causing the ram to remain stationary. The road profile can be obtained by measuring the displacement of the actuator cylinder with respect to the ram. The oil ports in the valve are reversed when the wheel goes down the bump. Again, this is an oversimplification of the system, but it illustrates the principle.

Figure 5 is a simplified block diagram of the control system. The circles are summing junctions either mechanical or electrical, and the blocks represent the various components. The input to the system is the actual road profile, Y, as represented by the vertical movement of the wheel hub and actuator cylinder. The first summing junction is the mechanical relationship between the actuator cylinder and the actuator ram.

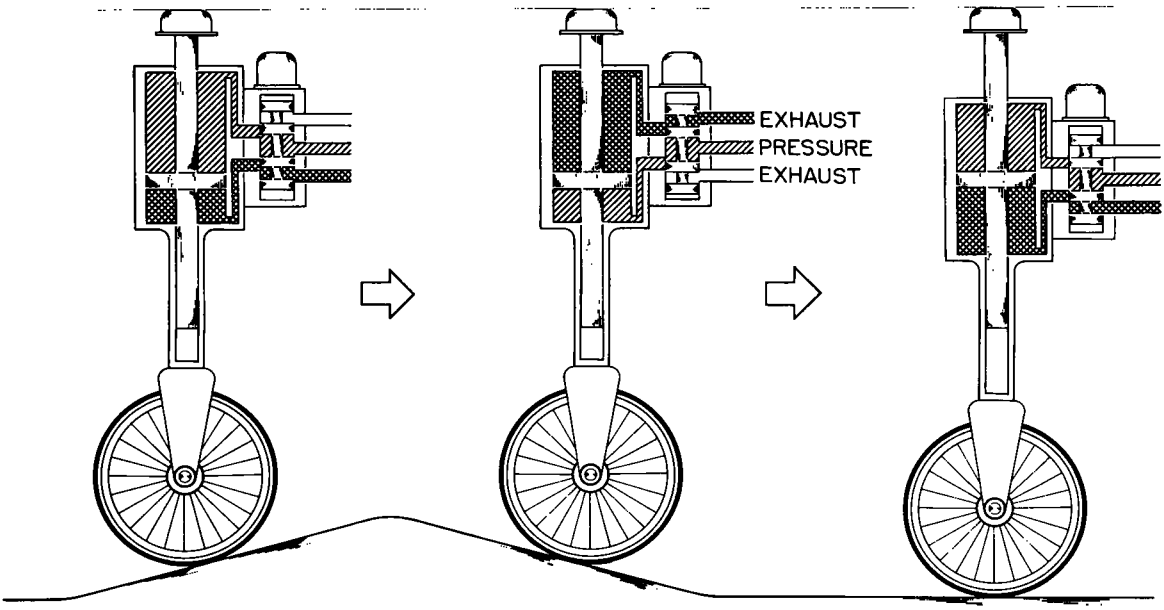

Figure 4. Sequence showing Servo-Seismic device passing over bump.

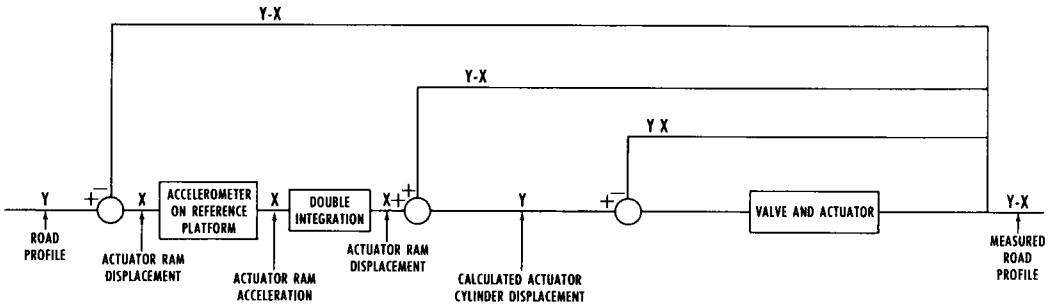

Figure 5. Simplified block diagram of Servo-Seismic system.

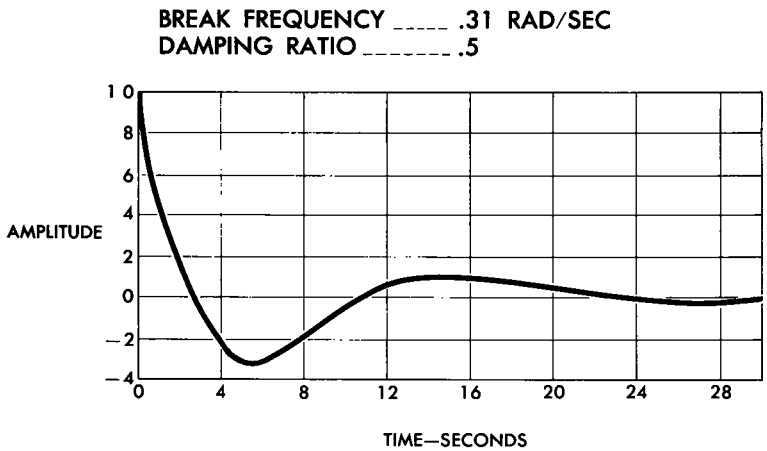

Figure 6. Transient response of third order filter to unit step input.

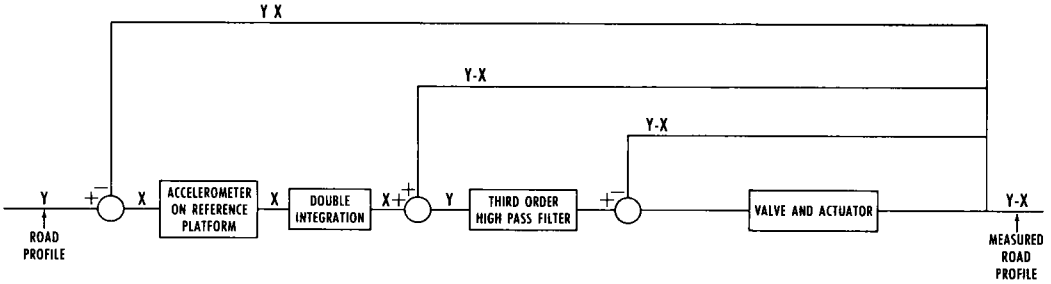

Figure 7. Block diagram of system showing addition of third order filter.

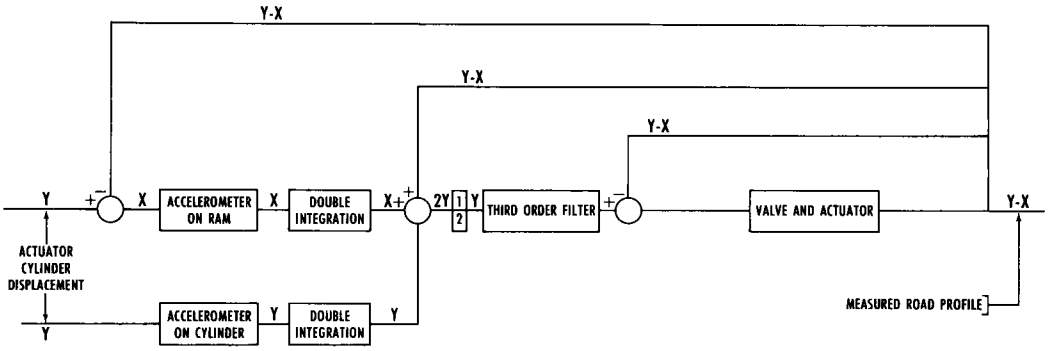

Figure 8. Block diagram of Figure 7 with parallel open loop added.

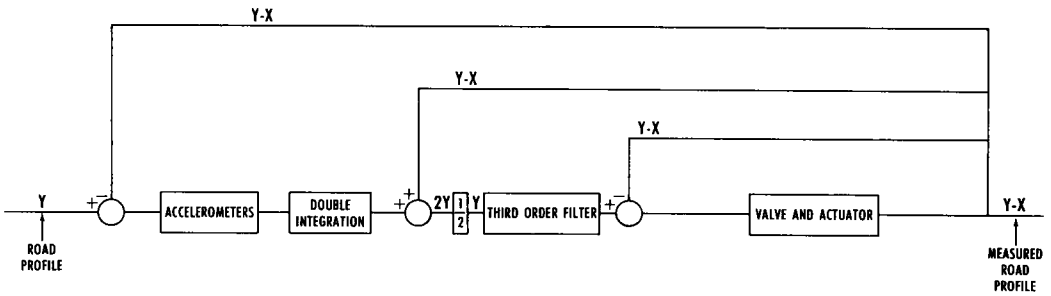

Figure 9. Simplified block diagram.

The movement of the ram, X, is the result of this summation. Because the displacement of X with respect to an inertial reference cannot be measured directly, an accelerometer is used to measure $\ddot{X}$ and a double integration performed to obtain X. The second summing junction is electrical and adds the measured absolute movement of the ram to the relative movement of the cylinder and ram, Y-X, to determine the movement of the cylinder. Using the valve and actuator as a position feedback servomechanism, an oil flow is caused in the actuator that will allow the actuator cylinder to move a displacement, Y, with respect to the actuator ram. If the measurement of X and resulting computer calculation of Y are correct, it can be seen that the reference platform returns to its original position. In fact, if the system has no time lags, the reference platform might never move.

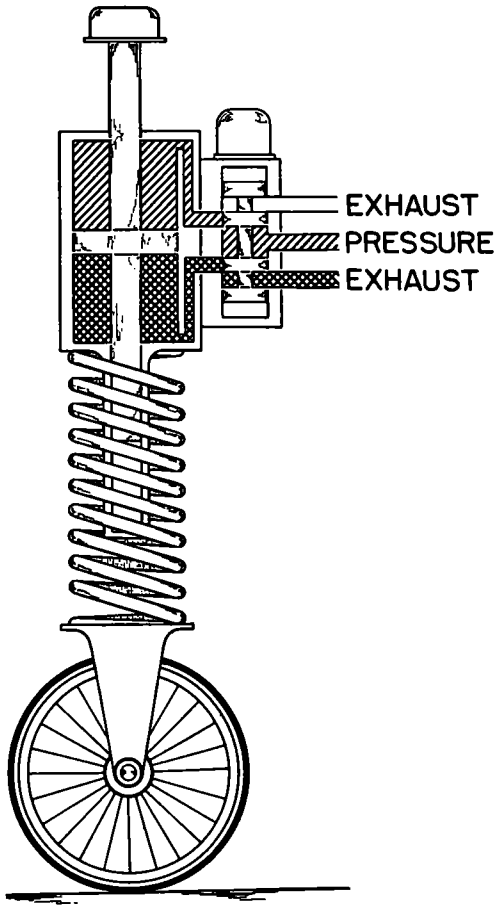

Figure 10. Servo-Seismic device incorporating spring between wheel and actuator.

It may be apparent by now that the reference platform could plow into the side of a hill or at any rate run out of actuator travel if the road amplitude were large. With the road profile trailer towed down the road at a fixed speed, it is necessary to hold the reference for a certain period of time to measure road waves of a certain length. Conversely, it is necessary to return the actuator ram to the center of the cylinder as a function of time. In effect, it is desired to filter the low frequency components or provide a "high-pass filter." Figure 6 shows the transient response of a third order filter to a step input. The 0.31 rad per sec break frequency and 0.5 damping ratio were used in some of the work presented later. Figure 7 is the same block diagram as shown before with the addition of this high-pass filter on the signal to the valve. This block diagram can be described as a closed-loop system because it strives to hold the reference platform stationary and has an error signal if it is unsuccessful. In parallel with this closed-loop system, there is also an open-loop system which converts the block diagram to a multiple input system. Figure 8 is the same block diagram as Figure 7 with the lower branch added. In this system in addition to forming Y as the result of measuring X, an accelerometer is mounted on the parts of the system which follow the road profile and obtain Y directly by integrating this signal. The signal after the second summing junction then is 2 Y and must be halved to maintain proper scaling. Various other proportions of the signal sources can be used as conditions require. This second branch or second source of Y was added to improve the low frequency characteristics of the system by allowing the measuring of an acceleration signal that was considerably larger than the accelerometer noise.

By making the assumption that the two accelerometers are identical, the block diagram can be further simplified as shown in Figure 9. By mounting an accelerometer on the actuator cylinder, large amplitude accelerations are again a problem. To reduce the acceleration level, a spring was inserted between the wheel and the actuator which, in effect, acted as a second order low pass filter. Figure 10 shows the final configuration with the road profile being measured as the relative movement of the wheel hub and actuator ram. Figure 11 shows the complete system including road profile trailer; towing truck; a 20-amplifier, transistorized analog computer; and various other components. The road profile trailer includes the road-following wheel, accelerometers, the electrohydraulic valve, hydraulic actuator, and the road-measuring potentiometers. Figure 12 shows a block diagram of the complete system with the transfer functions for the individual components shown as functions of the LaPlace operator, s. The input to the system is the road profile, now called W, and the output is the measured road profile, X-W. The quantity X-W can be obtained as the summation of two potentiometer signals Y-W and X-Y. It is obtained more directly by a potentiometer between the reference platform and wheel hub.

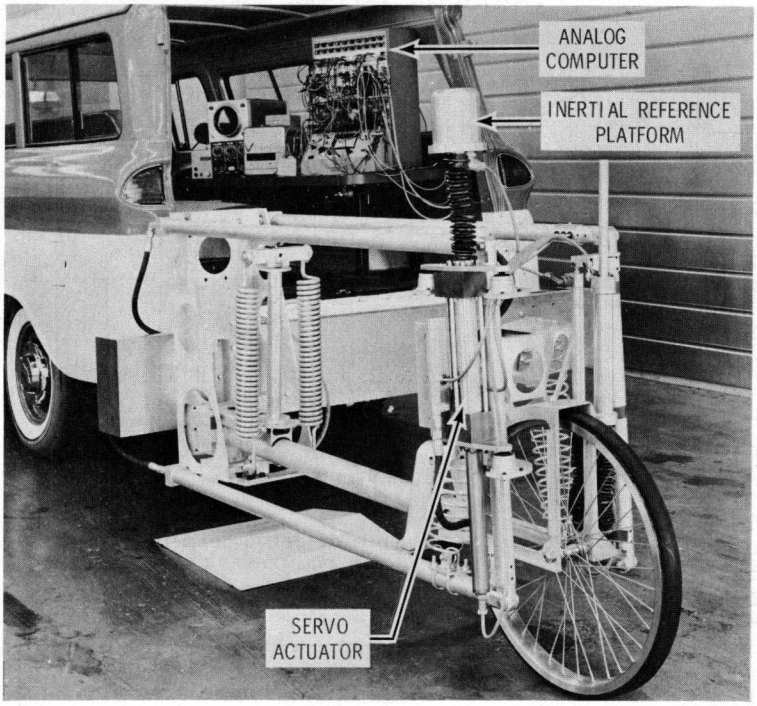

Figure 11. Photograph of complete Serve-Seismic road profiling system.

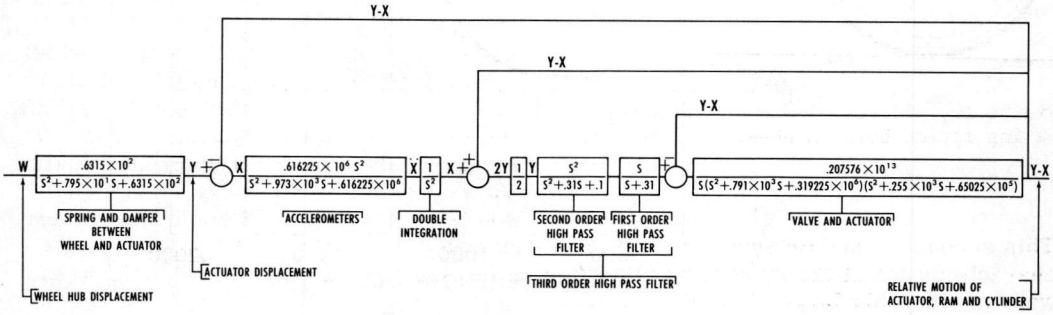

Figure 12. Block diagram showing transfer functions of system components.

A digital computer program was used to obtain the frequency response of the complete system. The frequency response in the form of a "Bode" plot is shown in Figure 13. Both amplitude and phase lag are plotted as a function of frequency. The amplitude is the ratio of the output of the system, X-W, to the input, W, expressed in decibels (db). The phase lag is the amount the output lags the input in degrees. The amplitude is 0 db or an amplitude ratio of 1 above the break frequency of 0.31 rad per sec. For the amplitude ratio to be 1, the reference platform movement, X, must approach 0. Figure 13 also shows the same system without the spring between the wheel hub and actuator cylinder for comparison. The addition of the spring produced a noticeable improvement in amplitude ratio and phase relationship at higher frequencies. At the break frequency of 0.31 rad per sec, the output leads the input by 135^0. At 10 rad per sec and above, there is no appreciable phase difference for the system with the actuator

SYSTEM FREQUENCY RESPONSE

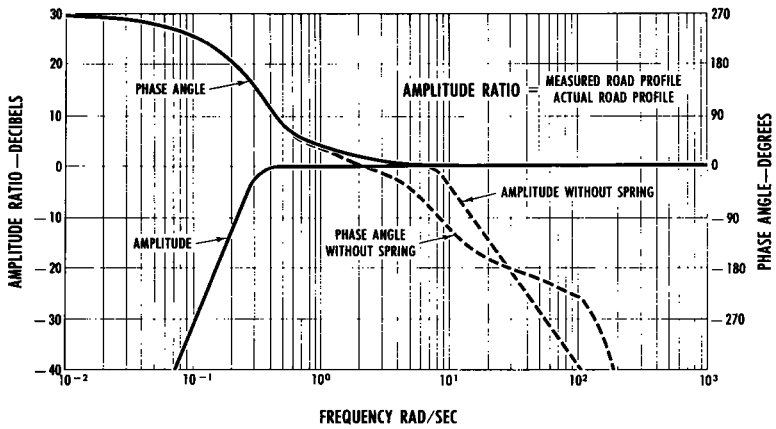

Figure 13. Frequency response of Servo-Seismic system.

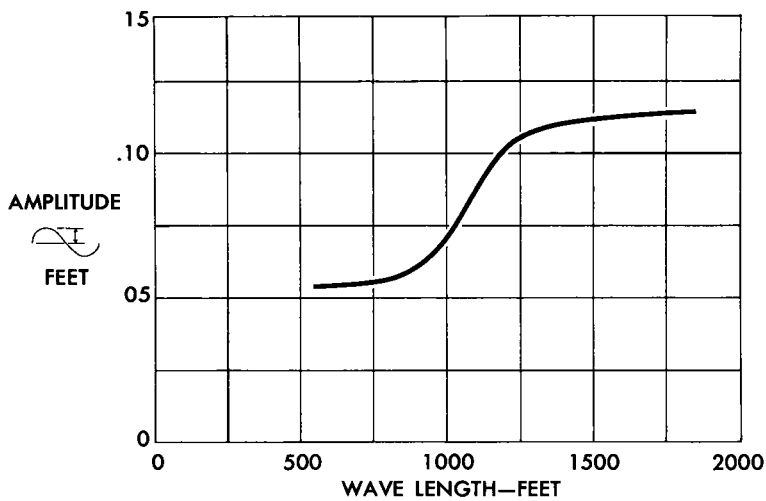

Figure 14. Sensitivity of vehicle passengers to sinusoidal road disturbances at 100 mph.

$$\frac{Y-X}{W} = \frac{38914 \times 10^{10} S^3}{[S^2 + 7.95 S + 63.15]\ [S^2 + 981.8 S + 609674]\ [(S^2 + 31 S + 1)(S + 31)]\ [S^2 + 796.2 S + 276201]\ [(S^2 + 53.86 S + 26325)(S + 289.1)]}$$

$$\frac{Y-X}{W} = \frac{KS^3}{\text{[WHEEL SPRING]}\ \text{[ACCELEROMETER]}\ \text{[THIRD ORDER HIGH PASS FILTER]}\ \text{[SERVO VALVE]}\ \text{[HYDRAULIC ACTUATOR]}}$$

[WHEEL SPRING]	[ACCELEROMETER]	[THIRD ORDER HIGH PASS FILTER]	[SERVO VALVE]	[HYDRAULIC ACTUATOR]
$\omega = 7.95$ RAD/SEC	$\omega = 780.8$ RAD/SEC	$\omega = 31$ RAD/SEC	$\omega = 525.6$ RAD/SEC	$\omega = 162.3$ RAD/SEC
$\zeta = .50$	$\zeta = .63$	$\zeta = .50$	$\zeta = .76$	$\zeta = .17$
				$\omega = 289.1$ RAD/SEC

Figure 15. System transfer function.

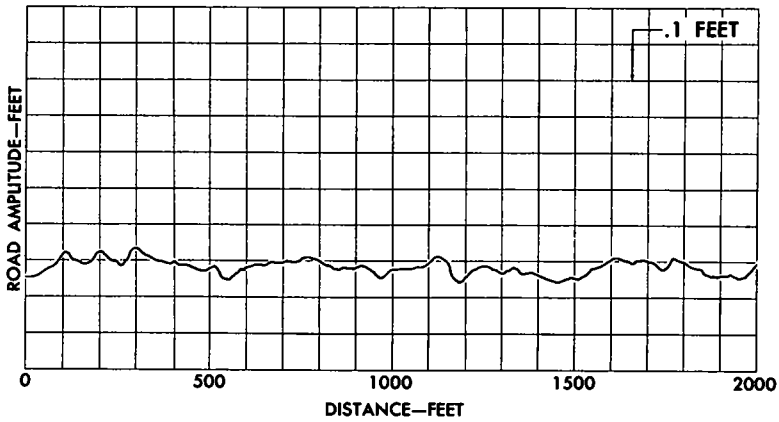

Figure 16. North-South Straightaway, G.M. Milford Proving Ground, Servo-Seismic method.

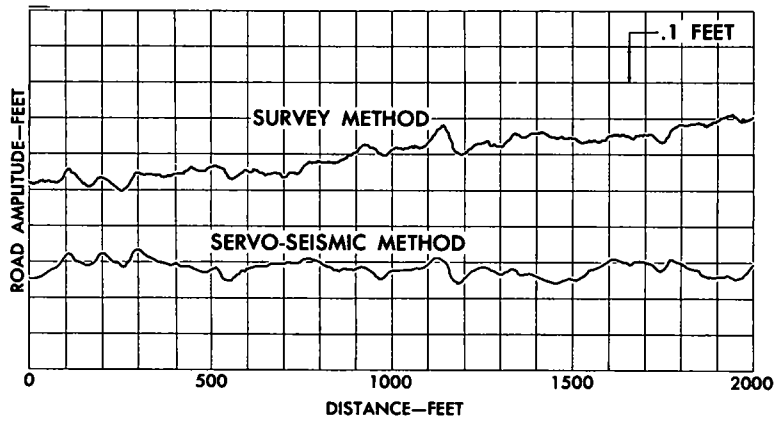

Figure 17. North-South Straightaway, G.M. Milford Proving Ground.

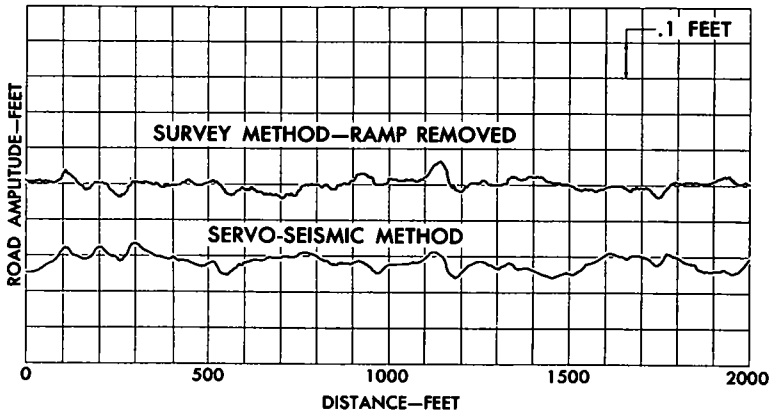

Figure 18. North-South Straightaway, G.M. Proving Ground.

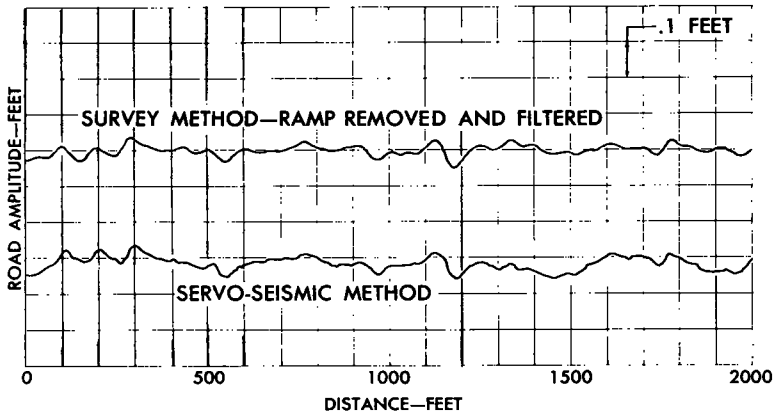

Figure 19. North-South Straightaway, G.M. Proving Ground.

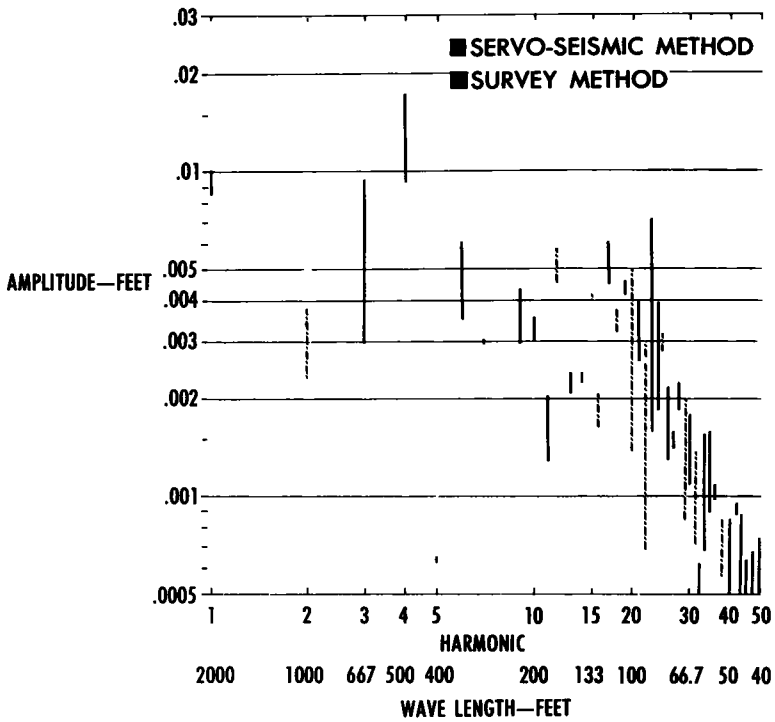

Figure 20. Harmonic analysis, 2,000-ft sample, North-South Straightaway. On this and figures following that compare harmonic analyses of two roads, the ends of each bar mark the amplitudes of the corresponding wave-length components of the two roads. Length of bar represents difference in amplitude. Shading indicates which road contains the larger amplitude. For example, at the 500-ft wave length, the "surveyed" road amplitude is 0.009 ft and the Servo-Seismic, 0.018 ft.

sprung. The effect of the low-frequency phase difference on the accuracy of the system was considered but was found to be insignificant. Figure 13 shows that the selection of the 0.31-rad per sec break frequency for the third order filter was one of the more important decisions.

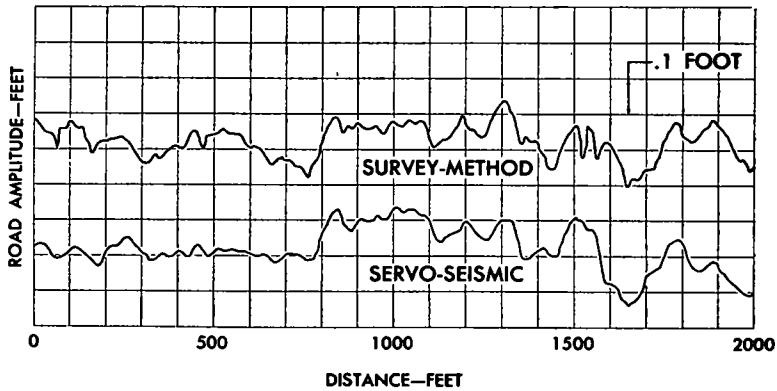

Figure 21. Military Straightaway, G.M. Milford Proving Ground.

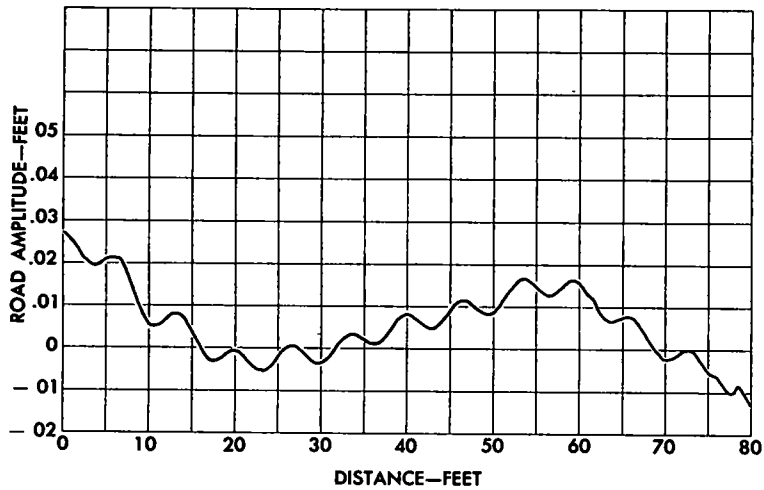

Figure 22. North-South Straightaway, G.M. Milford Proving Ground, with out-of-round wheel.

Some of the considerations that enter into the decision are maximum road wave length to be measured, the amount of travel available in the ram, the ability to hold the wheel on the road, and the ability of the human body to sense change in position as a function of time. In effect, the reference platform is held stationary for a certain period of time after which the ram returns to the center of the cylinder. As a result, the length of wave measured with respect to this reference platform is a function of the filter time constant and the velocity at which the wheel and reference platform are moved down the road. Now the problem of actuator ram travel is apparent. If the wave amplitude exceeds the actuator travel, the trailer velocity must be reduced or the filter break frequency increased. An actuator travel of ± 5 in., which is the maximum commercially available, is used on the trailer shown in Figure 11. The ability to hold the wheel on the ground and the wheel strength appear to be the limits on top trailer recording velocity. A wheel hold-down force of ten times the weight of the wheel assembly is currently being used. No difficulty is experienced in measuring most roads at 20 mph. The fourth consideration is the human body's ability to sense change in position as a function of time. This was determined subjectively using the ride simulator.

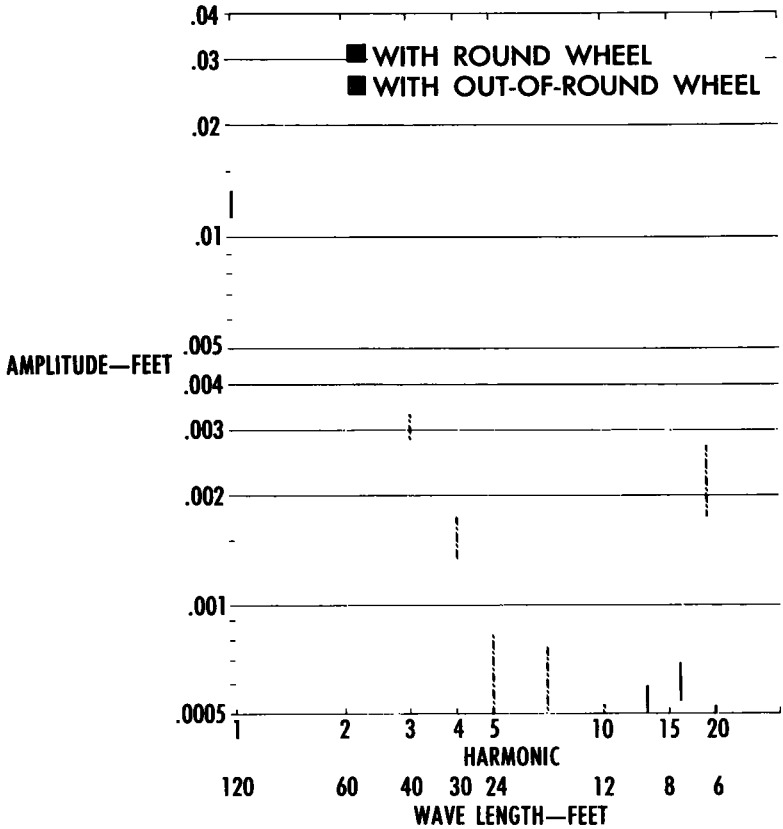

Figure 23. Harmonic analysis, 120-ft sample of North-South Straightaway. (See caption, Fig. 20).

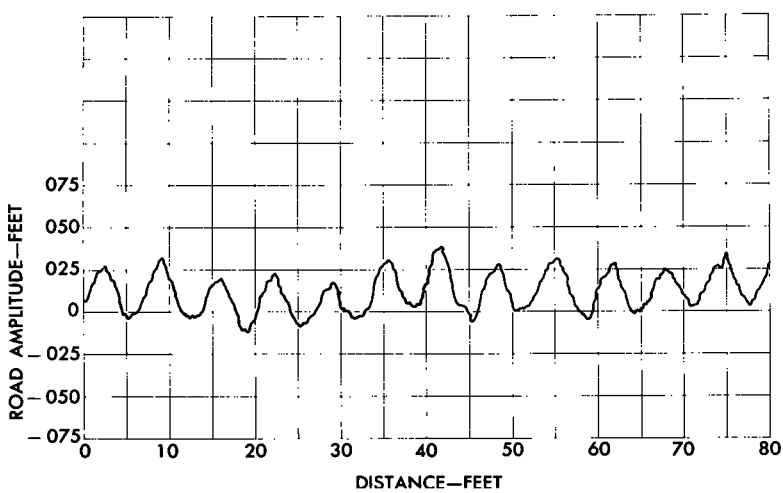

Figure 24. Sine Road, G.M. Milford Proving Ground; wave length—6 ft, wave amplitude—0.03 ft peak to peak.

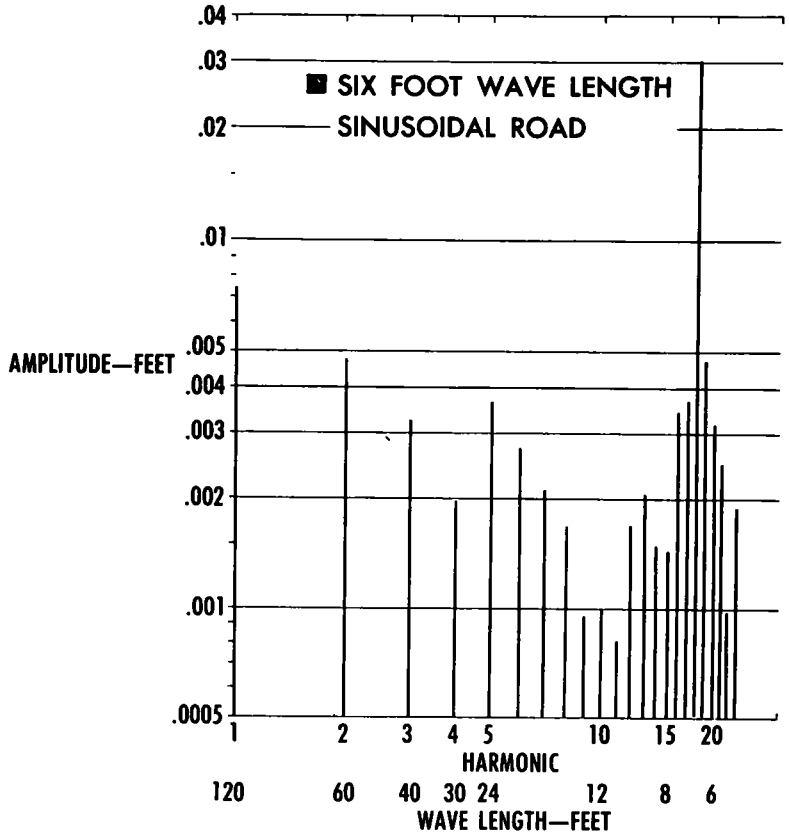

Figure 25. Harmonic analysis, 120-ft sample.

A passenger in the car body of the ride simulator was subjected to an input of sine waves to determine what wave amplitude could be perceived at an equivalent car speed of 100 mph. The test was run by holding wave frequency constant and increasing wave amplitude until the subject could tell he was moving. Superimposed on these low-frequency waves was a low-amplitude white noise which was held constant. Figure 14 shows the preliminary results of this study. This curve indicates that at car velocities of 100 mph, a 500-ft wave with an amplitude in excess of 0.05 ft is of importance in vehicle-ride studies. The subject becomes less conscious of wave amplitude as the wave length increases but is still aware of a wave amplitude in excess of 0.12 ft in 1,800-ft waves.

The requirement to measure wave lengths of this magnitude is certainly severe but it may be possible on roads designed for 100-mph traffic where wave amplitude is low. However, for the initial work, it appears that a recording velocity of 20 mph, break frequency of 0.62 and a damping ratio of 0.5 will allow the measurement of most roads with the actuator travel available. This will allow the measurement of wave lengths up to 300 ft which at 100-mph car velocity produce input frequencies to the car below the natural frequencies of all current road vehicle suspensions.

Now that this servo-mechanism network has been developed to measure road profiles, its stability must be considered. The transfer function for the entire closed loop is shown in Figure 15 with the denominator or characteristic equation factored. Because the characteristic equation has no positive roots, the system is stable. The damping ratio of the roots corresponding to the hydraulic actuator appears rather light, but has caused no stability problem. If necessary, actuator damping can be increased by

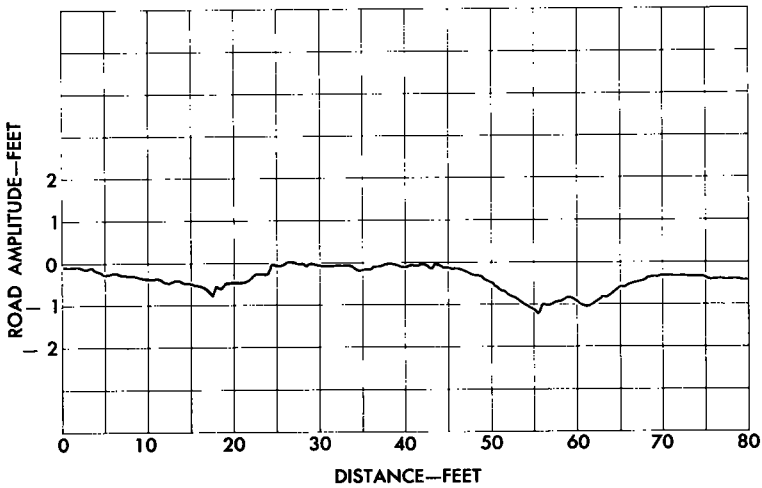

Figure 26. Military Straightaway, G.M. Milford Proving Ground.

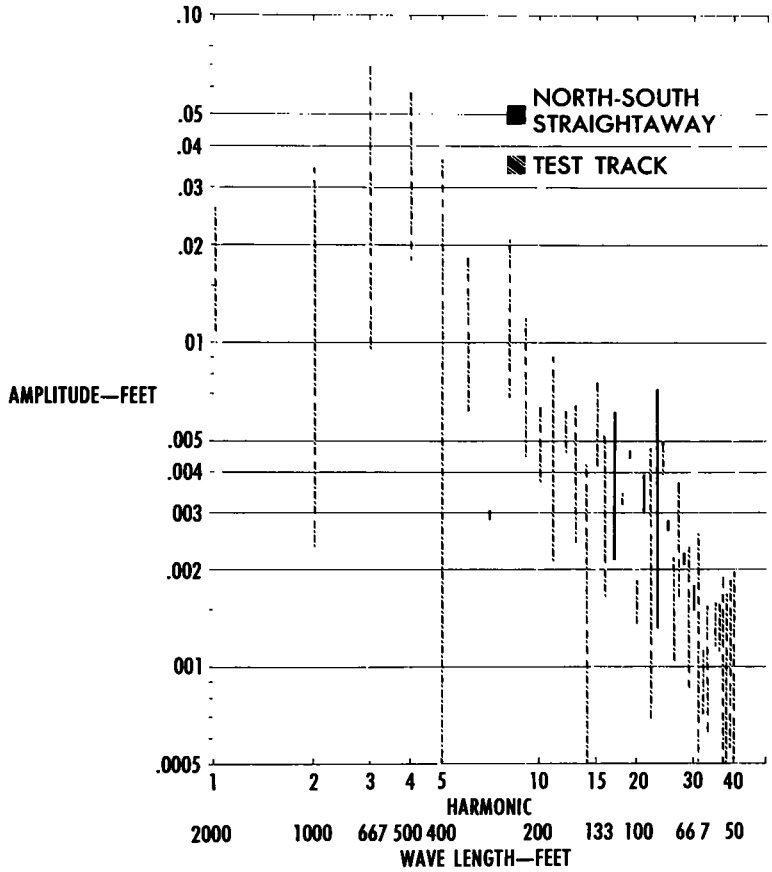

Figure 27. Harmonic analysis, 2,000-ft sample. (See caption, Fig. 20.)

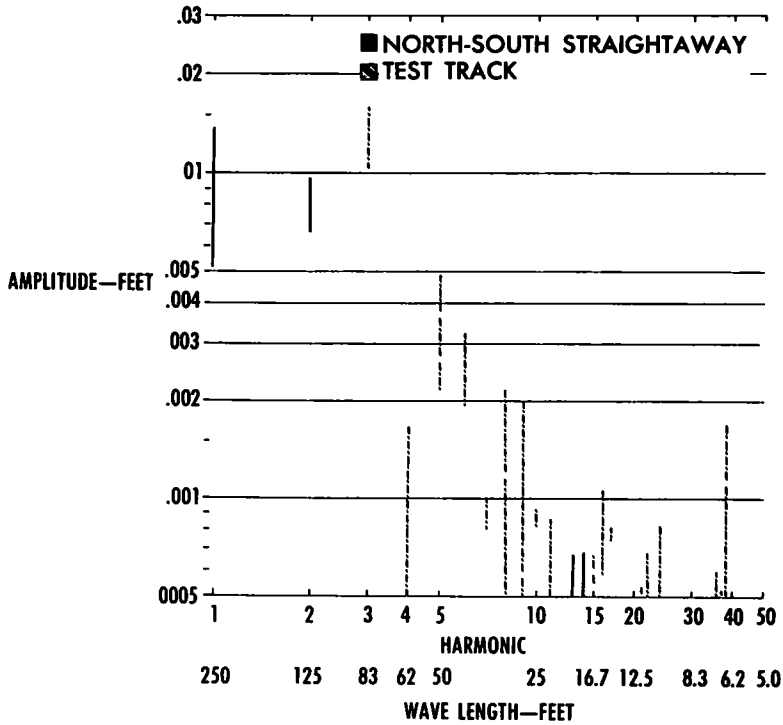

Figure 28. Harmonic analysis, 250-ft sample. (See caption, Fig. 20.)

reducing the valve gain with little effect on the over-all system. The actual stability analysis was more complete than this and included root locus plots from a digital computer program.

In the over-all evaluation of the profiling device to determine its ability to capture true road profiles, the philosophy was adopted that no better test could be made than to compare the record made by the device directly with a profile of the same road as obtained by conventional surveying methods. This procedure would take into account extraneous effects that could otherwise be overlooked, such as the pitching and bouncing of the towing vehicle, electronic disturbances, bouncing of the contour-following wheel, and tilting and vibrating of the accelerometers. A satisfactory result over a large enough sample of roads would be a sufficient demonstration of the adequacy of the system.

Some difficulties existed, such as ensuring that the recorded path was the same as that surveyed, and accounting for the intentional filtering by the Servo-Seismic method. Variations in the profiles produced by these factors should not be attributed to system error.

Figures 16 through 19 show the results of a comparison test, in this case, a 2,000-ft stretch of the very smooth "North-South Straightaway" at the General Motors Proving Ground in Milford, Mich. Figure 16 shows the profile as recorded by the Servo-Seismic method. In Figure 17, the profile of the same stretch exactly as surveyed has been added to the first plot. Elevations were taken at 5-ft intervals. It is apparent that an over-all slope exists in the real road that is not picked up by the Servo-Seismic device. This was to be anticipated and Figure 18 shows a comparison of the two profiles after removing this "ramp" characteristic from the surveyed profile. In addition, wave components less than 40 ft in length have been eliminated. This facilitates examination of the longer wave components that were of concern in this instance. In Figure 19, the surveyed profile has been further subjected to a computer approximation of the third

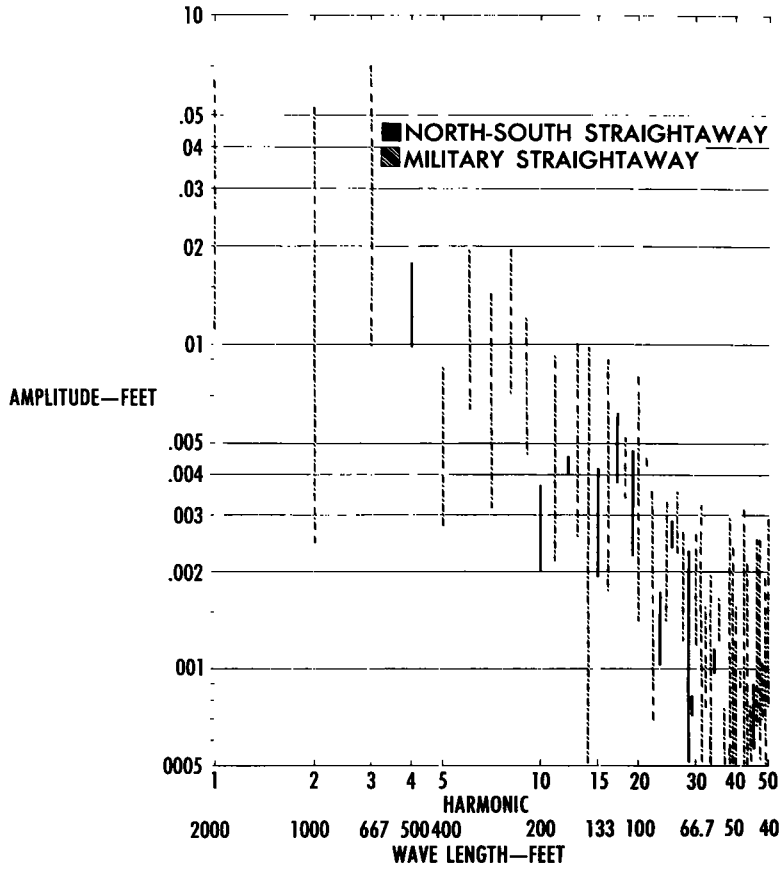

Figure 29. Harmonic analysis, 2,000-ft sample. (See caption, Fig. 20.)

order filter of the Servo-Seismic system. This has the effect of diminishing the amplitude of road components longer than approximately 600 ft.

The agreement appears to be fairly good. The sensitivity of the Servo-Seismic to long waves of small amplitude has been demonstrated here. In this range, the response is due primarily to the servo-portion of the system. Harmonic analyses of the two 2,000-ft lengths are shown in Figure 20 and also compare favorably.

Figure 21 compares the recorded and surveyed profiles of a considerably rougher stretch of road than the North-South Straightaway, 2,000 ft of the Military Straightaway at the Proving Ground. Amplitudes of the irregularities range up to three times as great as in the previous, smooth road. Here again the agreement is seen to be fairly good. In this run, the vehicle and trailer were subjected to more roughness than in the first, providing an indication of the magnitude of these effects. However, on the rougher road, small variations in path followed can result in considerable differences in profiles. Differences of this type cannot be distinguished from errors produced by deficiencies of the profiling systems.

To obtain a surveyed profile that would include a reasonable representation of the sharper irregularities of the order of 2 to 20 ft in wave length, it would have been necessary to take readings at intervals of approximately $^1/_{10}$ of the shortest wave length, which for 2-ft waves would be 0.2 ft. Furthermore, amplitudes in this range tend to be smaller than in the longer wave lengths and more resolution is required than is readily available in conventional surveying procedure. Instead, to verify the performance of the Servo-Seismic system for these shorter wave lengths, a recording wheel

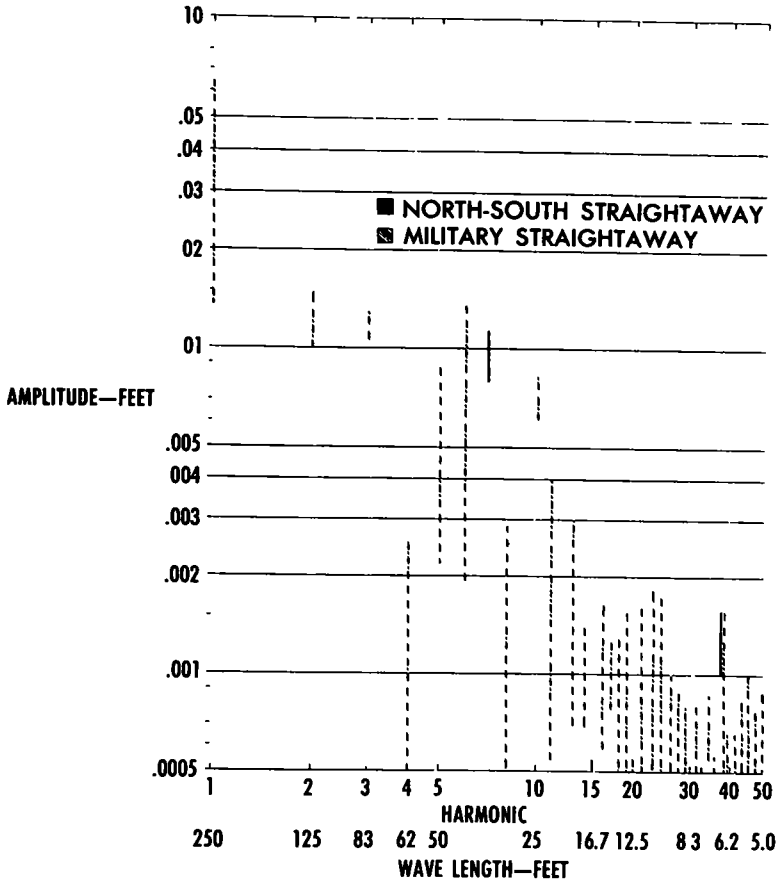

Figure 30. Harmonic analysis, 250-ft sample. (See caption, Fig. 20.)

that was made deliberately out of round was installed. The resulting effect, a repeating wave approximately 6 ft long, equal to the wheel circumference, is clearly shown in Figure 22, a 120-ft section of the North-South Straightaway. A spike in amplitude also appears at the 6-ft wave point in the harmonic analysis of this section (Fig. 23). The installed out-of-roundness of the wheel totaled 0.120 in. but was modified during the run by the compression of the rubber tire. Lesser out-of-round effects can be noted even in runs with supposedly round wheels.

A second check of system performance for the shorter wave lengths was made by attempting to record the profile of the Proving Ground "Sine Road." The profile of this road consists of continuous sine waves 6 ft long and approximately ½ in. high. These waves are faithfully reproduced in the recorded profile, 120 ft of which is shown in Figure 24. Their presence is also clearly reflected in the harmonic analysis of this section (Fig. 25). An 80-ft section of the Military Straightaway to expanded scale in Figure 26 shows typical shorter wave length irregularities.

Figures 27 through 32 compare various types of road surfaces with the North-South Straightaway as a standard. In each case, harmonic analyses of 2,000- and 250-ft stretches are presented. Characteristic differences can be discerned. The general slope appears to be about the same on all plots and suggests that the average amplitude of the wave components falls off as the square of the wave length. This implies that the acceleration amplitude introduced by these waves as input to a traversing vehicle is constant for a particular road for all wave lengths. This has also been suggested in previous investigations.

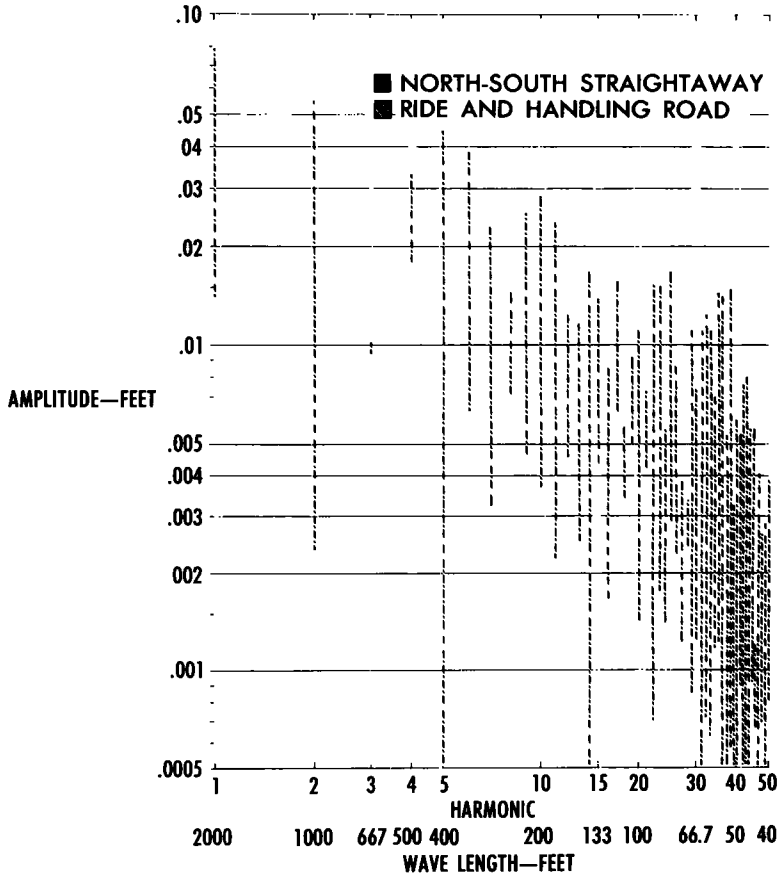

Figure 31. Harmonic analysis, 2,000-ft sample. (See caption, Fig. 20.)

In general, amplitudes contained in the test track plot (Figs. 27 and 28) appear to be somewhat larger than those in the Military Straightaway (Figs. 29 and 30). Ride and Handling Road amplitudes (Figs. 31 and 32) are clearly greater than either. Of course, the North-South Straightaway amplitudes are the smallest of all. This order conforms to the general impression of relative riding quality gained by driving an ordinary passenger car over these roads. Every plot shows a small spike of amplitude at the 6-ft wave length point. This can probably be attributed to inaccuracies in the contour-following wheel as previously mentioned, but it is also possible that actual components present in the roads may be partially responsible. Refined techniques of analysis may isolate these and other differences more distinctly.

The authors feel that the Servo-Seismic system offers a quick, reasonably accurate method of obtaining road profile data in a form convenient to rapid computer analysis. Future plans include study to develop the correlation between the recorded profile and various properties of the road itself, particularly its "riding" qualities. Hopefully, statistical, frequency, or similar methods of analysis will yield an easily interpreted mathematical criterion by which roads may be quickly and objectively evaluated.

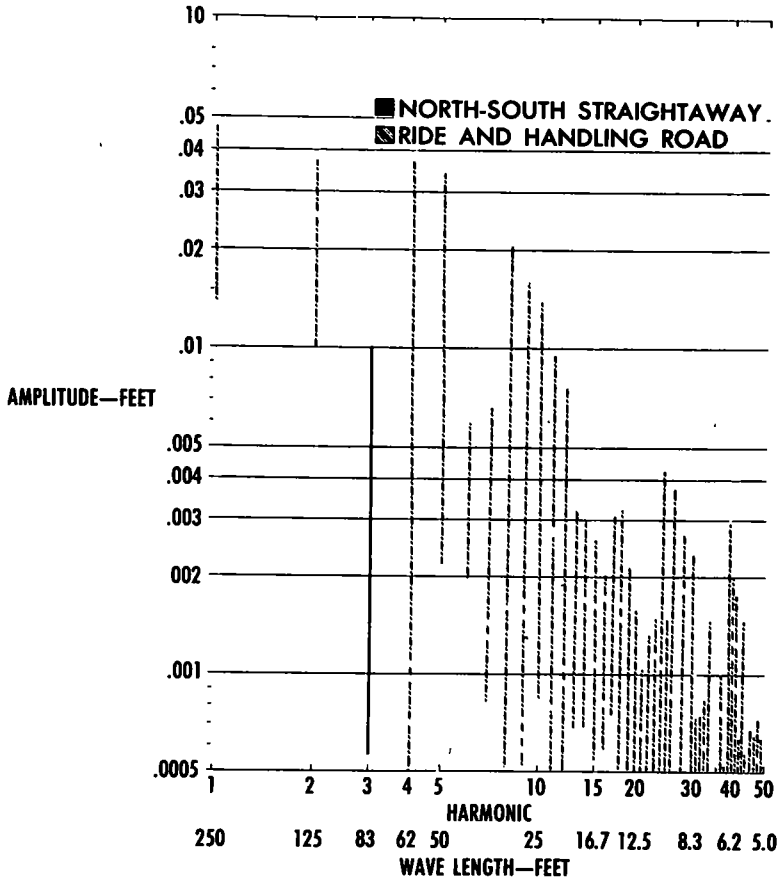

Figure 32. Harmonic analysis, 250-ft sample. (See caption, Fig. 20.)