HIGH-SPEED PROFILOMETRY

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The General Motors rapid travel profilometer has been evaluated by the Michigan Department of State Highways. It meets or exceeds all specifications for accuracy and reliability. It does not return a survey type of elevation map because long-wave features must be filtered out. For this reason, its profiles must be viewed as correct in the frequency domain but incorrect in the spatial domain. An inertial guidance system capable of recording long-wave features would solve the problem. Profile analysis in the frequency domain is confined to the 4 basic measures: mean squares, amplitude distributions, autocorrelation, and power spectral density. It is possible to extract some single number indexes based on the 4 standard measures. Power spectral density appears to be most interesting for highway work.

•THE RAPID TRAVEL PROFILOMETER (RTP) developed by General Motors (1) has ushered in a new era of road profile measurement. At the same time significant advances in data acquisition and signal analysis methods have provided powerful tools for profile study. Opportunities to use these new techniques became apparent during an evaluation of the RTP. This paper discusses the theory of the RTP, the outcome of the evaluation study, and the use of modern data acquisition and signal analysis on RTP profiles.

Profiles may be viewed as an elevation map for a narrow strip of roadway (width of wheel) or as a random signal with certain properties in common with all other random signals. Implications of this dual viewpoint are discussed.

THE GENERAL MOTORS RAPID TRAVEL PROFILOMETER (RTP)

The RTP is based on 2 systems. The first is hardware consisting of acceleration and displacement transducers. The second is software consisting of a signal-processing concept that can be implemented in various ways. The first system is relatively straightforward and consists of 2 transducers mounted in a vehicle. These are a linear potentiometer connected between a small road-following wheel and the vehicle body, and an accelerometer mounted in the vehicle body. Each transducer senses 2 components of vertical motion. The road-following wheel senses body bounce and changes in surface elevation that occur too rapidly to move the vehicle as a unit. The accelerometer picks up body bounce and elevation changes that occur slowly enough to move the entire vehicle as a unit. Acceleration data are then integrated twice to produce a displacement signal. When road-following wheel and accelerometer displacement signals are algebraically summed, the result is a road surface profile. Body bounce is canceled because it appears with equal magnitude but opposite polarity in each signal.

It is evident that long-wave features, such as hills or grade changes, are picked up by the accelerometer, and short-wave features are picked up by the road-following wheel. At this point, signals from the transducers, if processed as described, would

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yield a true elevation profile measured with respect to a reference established by the accelerometer when it was first turned on. Accuracy in recording long-wave, high-amplitude features such as hills would depend only on the quality of the accelerometer. If it responded to very low accelerations, even curvature of the earth would appear in long profile runs.

Explanation of the second system embodied in the RTP concept requires a digression into the nature of road profiles. Road profiles possess 1 characteristic that makes them difficult to measure. In terms of signal theory, profiles are said to exhibit a very high dynamic range of perhaps 80 dB (decibel) or more. In other words, it means that there is a great difference in amplitude between large features such as hills and surface details. For this reason, the attempt to measure surface detail, when it is accompanied by high-amplitude features, is similar to hearing a whisper next to Niagara Falls. Profile surface details will be invisible if the recording instruments are scaled to accommodate hills. If the instruments are scaled to make surface details visible, recorder overload will occur on the hills. This problem is avoided in surveying methods because instruments are continually moved to keep within range of the rod and the results are recorded numerically; this provides infinite dynamic recording capacity.

It is evident that some way had to be found to eliminate high-amplitude signals when profile is recorded on a medium of limited dynamic range. Fortunately, the nature of road profiles ensures that high-amplitude data will consist of long-wave features such as hills or grade changes. For this reason, a high-speed profilometer need only filter out the low-frequency signals induced in its sensors by high-amplitude hills and grade changes.

This filtering is accomplished by the second system associated with the RTP. It is actually a signal-processing concept that can be implemented in different ways depending on desired results. Basically, the fundamental operations of integrating acceleration twice and summing the result with road-following wheel displacement are combined with filtration. This is accomplished by forming the product of transfer functions for the operations desired and programming the result on an analog or digital computer. The computer then acts as a processor for the acceleration and road-following wheel signals. An illustration of this concept is as follows:

$$\left(\begin{array}{l}\text{transfer}\\ \text{function}\\ \text{for double}\\ \text{integration}\end{array} + \begin{array}{l}\text{road-following}\\ \text{wheel}\\ \text{displacement}\\ \text{signal}\end{array}\right) \times \left(\begin{array}{l}\text{transfer}\\ \text{function}\\ \text{for}\\ \text{filtration}\end{array}\right) = \text{profile}$$

The function labeled "filter" can be a transfer function for any third or higher order high-pass filter. Developers of the RTP chose the Butterworth design but could have used the Chebeyshev, Paynter, elliptical, or other type of design depending on needs. In practice the RTP operator chooses a filter cutoff frequency, feeds the transducer signals into the computer, and records a final profile that has all frequencies below the cutoff point attenuated. The filter not only removes the high-amplitude long-wave features but also permits use of a less-than-perfect accelerometer and eliminates concern over low-frequency noise contamination of the accelerometer signal. This contamination arises from drifts in the electronics and tilts of the accelerometer from a true vertical during the profile run.

It is valuable to note an important fact at this point. The transducer signals themselves do not span a great dynamic range. It is only after processing the accelerometer signal through double integration that high-amplitude hills and grade changes emerge. This is made clear by noting that double integration of a very small positive or negative acceleration over a long period of time results in a very large output. In other words, the second derivative of road profiles does not have a high dynamic range. Consequently, one could obtain long-wave, high-amplitude features by installing a near-perfect accelerometer on a nontilting mount and digitally processing the resulting signal. Digital processing provides a very high dynamic recording range, as was seen in the case of surveying. Filtration to remove the very lowest frequencies would probably still be needed, even with digital processing, because some low-frequency contamination is unavoidable.

The major effects of filtration depend on the intended use of the profile. If the profile is viewed as a random signal, the filter merely specifies the lower cutoff frequency of the data. The profile can then be analyzed by modern signal-analysis techniques without further difficulty. If the profile is viewed as an elevation map for a narrow strip of roadway, the filter introduces some problems. The main difficulty is lack of a fixed reference such as that used in surveying. This results in a final profile that does not look at all like the actual terrain. The filter introduces what might be called a piecewise linear reference for wavelengths up to one-tenth as long as the longest wave passed by the filter without attenuation. Thus, if the filter is passing 1,000-ft waves with no attenuation, waves up to 100 ft will be measured with respect to a linear reference. This reference is located at some arbitrary height and angle over the roadway. The next 100-ft segment, even if overlapping most of the first segment, will be measured with respect to a slightly different reference. Waves longer than one-tenth of maximum get shifted in phase and appear in the RTP profile ahead of their actual location on the roadway.

At present, the only way to produce a survey type of terrain map is by restoring long-wave features through a process called tipping. This requires transit shots at some predetermined interval, such as every 100 ft. When transit data and RTP profiles are processed by the tipping program, a true elevation map results with far less work than would be required by transit alone. With improved accelerometers, mounts, and digital processing, the required known elevation points could be thousands of feet apart.

EVALUATION OF RTP

We have seen how the RTP works and what it can do in theory. Evaluation of the device by the Research Laboratory Section of the Michigan Department of State Highways has shown close agreement between theory and practice. Accuracy under static conditions was easy to check and was found to be within specifications. Accuracy under dynamic conditions was considerably more difficult to determine.

Dynamic accuracy of any system is usually checked by feeding in a sine wave of fixed amplitude and noting the ratio of output to input for all frequencies of interest. Another method has recently been used that consists of feeding in broad-band random noise and measuring the power spectral density of the output. Random noise presents the system with all frequencies at once, thus providing a more realistic test. It was not feasible to apply either test to the RTP because very costly and complex drivers, generators, and delay networks would be needed.

Dynamic accuracy was determined by a technique developed in the early 1960's as part of a general attack on problems in signal theory. It is a statistical process defined by the expression

$$\gamma_{xy}^{2}(f) = \frac{\left| G_{xy}(f) \right|^{2}}{G_{x}(f)\, G_{y}(f)}$$

in which $G_x(f)$ and $G_y(f)$ are power spectral estimates for each of 2 signals, and $G_{xy}(f)$ is the cross spectrum at frequency (f). This coherence function statistic reveals the extent of agreement between 2 signals in a narrow frequency band centered at frequency (f). The result, after the function is evaluated for various (f), is a graph or table showing amplitude correlation (0:1) for all wavelengths in question. The analysis requires uniform and closely spaced, precise level readings from a test section containing equal intensity of roughness at all wavelengths. The RTP profile for the same test section was digitized, and the analysis was performed by computer. Analysis was complicated by the necessity to get RTP and precise level profiles in phase and by the arbitrary RTP reference that required tipping of the precise level profile to match the RTP reference. Analysis spanned wavelengths from 100 to 1 ft, and all coherence values were significantly high indicating high dynamic accuracy. Table 1 gives the wavelength, frequency in cycles per foot, and coherence value for each estimate.

TABLE 1

COHERENCE VALUES BETWEEN AN RTP PROFILE AND A PRECISE LEVEL PROFILE

Wavelength (ft)	Frequency (cycles per foot)	Coherence Value (correlation)
100.0	0.01	0.997
50.0	0.02	0.984
25.0	0.04	0.979
16.7	0.06	0.959
12.5	0.08	0.947
10.0	0.10	0.951
8.4	0.12	0.956
7.2	0.14	0.909
6.3	0.16	0.963
5.5	0.18	0.843
5.0	0.20	0.872
4.2	0.24	0.944
3.1	0.32	0.918
2.5	0.40	0.954
2.1	0.48	0.991
1.8	0.56	0.979
1.4	0.72	0.858
1.3	0.87	0.816
1.1	0.91	0.891
1.0	1.00	0.916

With accuracy established, the RTP was evaluated as a tool for highway work. The RTP itself has been found to be very reliable, easy to maintain, and straightforward to operate. Beyond this, its high speed is essential in view of ever-increasing traffic loads that make older devices too slow and hazardous to operate. Several small improvements were made in the underbody photocell that was originally intended to sense cracks and joints, but that is now used as a test section marker to sense reflective strips placed on the roadway. The road-following wheel was fitted with a distance-sensing pulse marker to aid in horizontally scaling the computer profile.

The most important aspect of evaluation concerns the question already mentioned. How is the profile to be used? If only signal analysis is desired, there are no difficulties with the RTP. If the elevation map view is held, there is strong impetus to develop a system that can handle very long waves, conceivably as long as 5,000 ft. This became an issue when more uses were found for the elevation map. One use, for example, was airport runway profiles requiring the recording of 2,000-ft waves. Another case involved estimates of bituminous material needed in resurfacing jobs. This problem has been studied at the Research Laboratory, and the general solution is evident. Recording of very long waves requires a very high-quality accelerometer on a stable platform and digital processing of the output. Experimentation along these lines using gyro stabilization has yielded encouraging results. Because the RTP is actually a small-scale inertial guidance system, it would be possible to install a true inertial guidance system, such as those used in missiles, if the proper security environment could be achieved. This would allow pickup of very long waves similar to true surveying.

PROFILE ANALYSIS

Research Laboratory findings indicate that the major impact of the RTP concept lies in the field of profile analysis. Again, the signal versus elevation map view of road profiles has a strong bearing on analysis considerations. If the profile is viewed as a random signal with properties common to all random signals, the analysis possibilities are limited to modern signal analysis techniques.

These methods of signal analysis that make it possible to rationally analyze random signals began to develop about 1958. To quote from Bendat and Piersol (2), "Four main types of statistical functions are used to describe the basic properties of random data: (a) mean square values, (b) probability density functions, (c) autocorrelation functions and (d) power spectral density functions." These 4 categories allow classification of the 2 traditional roughness measures: inches per mile and slope variance. Inches per mile is found to fit no standard classification and is, in fact, an undefined measure. It is not supported by signal measurement theory even though it may correlate with subjective ride quality or other objective measures. Slope variance is classifiable under mean square values and is a rudimentary measure of average intensity for the profile's first derivative. Neither measure provides any information about average intensity in a given wavelength band. This is vital information because it relates roughness to specific profile features. In addition, of course, current instruments used to produce the traditional roughness measures "see" a distorted version of the actual profile.

Power spectral density (PSD) alone, of the 4 available measures, supplies average intensity of the profile in given wavelength bands. For this reason, PSD is said to completely characterize the random process.

The RTP lends itself perfectly to a PSD analysis because an undistorted profile is recorded on magnetic tape and because vital filtering functions are performed. Long-wave, high-amplitude data would bias the PSD function if it were not removed by the profile process filter.

Research Laboratory work with PSD analysis led to the 4 following points:

1. A study of the available literature indicates that no measure is available that is more comprehensive or that is supported by a body of statistical and engineering expertise;
2. The investigator using PSD analysis must specify his statistical decisions so others may compare their work;
3. Data for which PSD analysis would be unreliable will not yield a statistically valid measure of any other type; and
4. PSD analysis must be done with great care because any contamination of the profile by even weak periodic or nonperiodic noise will seriously bias the analysis.

Even though PSD is the analysis of choice, there are at least 2 other possibilities for a single-number index that can then be used for correlation with other measures—contractor evaluations or the like. These 2 measures are statistically valid because they are derived from the 4 basic signal analysis measures. The first is merely mean squares but is computed for a narrow band of wavelengths important to the study at hand. The second is an amplitude distribution for a narrow wavelength band. This measure will usually form a Poisson distribution and is, therefore, fully specified by a single number. This is due to the fact that any Poisson distribution can be specified by its mean or variance, and, although this measure is not physically meaningful at this time, it is statistically valid.

If the profile is viewed as an elevation map for a narrow strip of roadway, another analysis viewpoint prevails. In this case the profile is used directly for a growing variety of purposes. In order to reproduce long-wave features or orient a profile segment to the true elevation, it is necessary to tip the profile as discussed previously. True elevation profiles have been used for a variety of maintenance purposes including joint blowups, potholed areas, and heaved slabs. They have been used in pavement studies involving comparison of profiles recorded at different times. A current use of elevation map profiles is in determining amounts of bituminous material needed in resurfacing jobs. In this case a computer simulation of the paving machine is passed over the elevation profile, and bituminous quantities are computed.

SUMMARY

The General Motors rapid travel profilometer embodies principles of inertial guidance that will undoubtedly underlie all high-speed profilometers to come. The device is best understood in terms of filter theory because the important feature of the RTP concept is its filter. Evaluation of the device by the Research Laboratory Section of the Michigan Department of State Highways has shown it to be accurate and reliable. It will, however, need improvement if very long waves are to be recorded. The RTP permits use of modern signal-analysis techniques. Of these, power spectral density analysis seems to be most important.

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