HIGH SPEED PROFILOMETRY

MICHIGAN DEPARTMENT OF STATE HIGHWAYS

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ABSTRACT: The General Motors Rapid Travel Profilometer (RTP) 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 elevation map because long wave features must be filtered out. For this reason RTP 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 four basic measures, mean squares, amplitude distributions, autocorrelation and power spectral density. It is possible to extract some single number indices based on the four standard measures. Power spectral density appears to be most interesting for highway work.

KEY WORDS: profilometers, analysis, data systems, road profiles.

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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 Michigan's evaluation of the RTP under the Highway Planning and Research program. 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.

(1) Spangler, Elson B. and Kelly, Wm. J., "GMR Road Profilometer Method for Measuring Road Profile." General Motors Research Publication GMR-452.

The General Motors Rapid Travel Profilometer

The RTP is based on two 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 two transducers mounted in a vehicle. These are a linear potentiometer connected between a small follower-wheel and the vehicle body, and an accelerometer mounted in the vehicle body. Each transducer senses two components of vertical motion. The follower-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 follower-wheel and accelerometer displacement signals are algebraically summed, the result is a road surface profile. Body bounce is cancelled since 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 by the follower-wheel. At this point signals from the transducers, if processed as described, would 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 disgression into the nature of road profiles. Road profiles posses one 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 decibels or more. In other words it means 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. Surveying methods avoid this problem because they continually move their instruments to keep with range of the rod and record the results numerically which provides infinite dynamic recording capacity.

It is evident that some way had to be found to eliminate high amplitude signals when recording profile on a medium of limited dynamic range. Fortunately the nature of road profiles assures 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 follower-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 follower-wheel signals. A block diagram of this concept appears in Figure 1.

Transducer Signals — Filter

([Transfer function for double integration] + [Follower-wheel displacement signal]) X ([Transfer function for filtration]) = Profile

The block labelled "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 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 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 for a long period 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 very long wave, high emplitude features by installing a near perfect accelerometer on a non-tilting mount and digitally processing the resulting signal. Digital processing provides 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, since 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 doesn't 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 1000 foot waves with no attenuation, waves up to 100 feet 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 foot segment, even if overlapping most of the first, 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 terrain map is by restoring long wave features through a process called tipping. This requires transit shots at some predetermined interval, every 100 feet for example. 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 the 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 employed which 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 since very costly and complex drivers, generators and delay networks would be needed.

Dynamic accuracy was determined by a technique developed in the early nineteen sixties 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 two signals and $G_{xy}(f)$ is the cross spectra at frequency (f). This coherence function statistic reveals the extent of agreement between two signals in a narrow frequency band centered at frequency (f). The result, after evaluating the function for various (f), is a graph or table showing amplitude correlation (zero to one) 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 performed by computer. Analysis was complicated by the necessity to get RTP and precise level profiles in phase and by the arbitrary RTP reference which required tipping of the precise level profile to match the RTP reference. Analysis spanned wavelengths from 100 to 1 foot and all coherence values were significantly high indicating high dynamic accuracy. Table 1 shows the wavelength, frequency in cycles per foot and coherence value for each estimate.

With accuracy established, the RTP was evaluated as a tool for highway work. The RTP itself has been found very reliable, easy to maintain and straightforward to operate. Beyond this, its high speed is essential in view

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

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 follower-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 signal analysis only 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 five thousand feet. This became an issue when more uses were found for the elevation map. One use, for example, was airport runway profiles requiring recording of 2000 foot 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. Since 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 missles, 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 pretty much limited to modern signal analysis techniques.

These methods of signal analysis began to develop around 1958 to enable rational analysis of random signals. To quote from page 13, reference (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 four categories allow classification of the two 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 profiles first derivative. Neither measure provides any information about average intensity in a given wavelength band. This is vital information since 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 four 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 since 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 not removed by the profile process filter.

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

1. A study of the available literature indicates that there is not a more comprehensive measure available which 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 unrealiable will not yield a statistically valid measure of any other type.

4. Great care must be employed when doing PSD analysis. Any contamination of the profile by even weak periodic or non-periodic noise will seriously bias the analysis.

While PSD is the analysis of choice, there are at least two possibilities for a single number index which can then be used for correlation with other measures--contractor evaluations or the like. These two measures are statistically valid because they are derived from the four basic signal analysis measures. The first is merely mean squares, but 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 earlier. True elevation profiles have been used for a variety of maintenance purposes including joint blow-ups, pot holed 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 computed.

Summary

The General Motors Rapid Travel Profilometer (RTP) 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 since 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.