Analysis and Simulation of Road Profiles

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(Reviewed by the Highway Division)

Abstract: The power spectral density (PSD) estimate is a parameter commonly used to characterize the acceleration of vehicles and, in conjunction with closed-loop random vibration controllers, to simulate the transport environment. The vertical acceleration experienced by the loading tray of road transport vehicles is mainly a function of the type of suspension, load, vehicle speed, and road surface characteristics. While the first three parameters may vary considerably between and during journeys, the statistical parameters used to describe road surface profiles are much less susceptible to change with respect to time. This paper presents a brief analysis and discussion of the spectral and statistical characteristics of actual road surface elevation records. The deviation of the road profile distribution from the Gaussian distribution is revealed, and it is shown that roads of different roughness seem to retain their spectral shape. In addition, a range of statistical parameters are introduced and recommended for use in the classification of road profiles. A technique in which a random vibration controller is used to simulate road profile spectra by controlling the displacement instead of the acceleration of a shaker table is demonstrated. The technique uses a physical model of a vehicle suspension to account for the dynamic characteristics of the vehicle. Finally, the use of digital signal processors (DSP) together with a time domain adaptive filter control technique for the accurate reproduction of synthesized demand signals is presented.

INTRODUCTION

The most fundamental excitation variable in the road transport process is the road profile. In the absense of surface defects, any vertical acceleration experienced by a road vehicle would emanate from engine vibrations, wheel imbalance and other deterministic sources of excitation. Therefore, it makes sense to attempt to characterize road profiles and classify them in relevant categories. Dodds and Robson (1973) laid the foundations to the description of road surface roughness and showed that typical road surfaces with large irregularities may be considered a realization of the homogeneous and isotropic two-dimensional Gaussian random process. They proposed a road classification method based on spatial power spectral density (PSD).

Lack of a consistent and universal practical method for quantifying roughness led to the international road roughness experiment (IRRE) (Sayers et al. 1986; Gillespie 1986) sponsored by The World Bank. Several methods and "roadmeters" were compared, including the Transport and Road Research Laboratory, (TRRL) bump integrator meter and a National Association of Australian State Roading Authorities (NAASRA) meter. The referenced average rectified slope (RARS) method, which is based on accumulating the displacement of the suspension motion in a host vehicle was recommended as the international roughness index (IRI). It was also found that numerically different values of road roughness may be obtained due to variations in the dynamic characteristics of the host vehicle. All paved roads investigated in the IRRE had the RARS index below 10 m/km. The IRI is based on the response of a simple linear "quarter car" model. De Pont (1994) compared a NAASRA index and IRI based on heavy vehicle response in New Zealand, concluding that IRI provided a reasonably good predictor for such vehicles.

However, it can be argued that it is more convenient to consider the vertical vibrations of a vehicle loading tray as the immediate source of mechanical excitation to transported goods. Therefore, it is understandable that there had been extensive work on the measurement, analysis, and simulation of vibrations produced by road vehicles. It is common practice to evaluate the performance of package systems by simulating the vibrational parameters of vehicles by means of a shaker table and a random vibration controller. The now well-accepted procedure consists of synthesizing a random signal from a PSD function by means of the inverse fast fourier transform (FFT). This technique assumes that the phase component of a signal is random and uniformly distributed, that the process has a Gaussian distribution, and that it is stationary (i.e., devoid of transients). These are of course convenient assumptions, but these tend to oversimplify the characteristics of the process. The PSD functions are usually obtained from measurements of accelerations of a vehicle loading tray during transit. However, due to the large number of uncontrolled parameters such as vehicle suspension characteristics, payload, and road roughness. The process of measuring and analyzing acceleration records must be undertaken and repeated for any combination of the aforementioned parameters. Further, this procedure does not take into account the variations of parameters such as vehicle velocity and transient accelerations, which occur during a single journey. In addition, the use of shaker tables to simulate vehicle loading tray vibrations does raise questions about compliance during impact. In cases where relatively large masses are tested, the cushioning effects offered by the compliance of a vehicle suspension system may not be reproducible with a shaker table, which would be far less compliant.

This paper proposes to review and examine both the advantages and disadvantages of physically simulating road surface elevations in the laboratory for package performance evaluation purposes.

CHARACTERISTICS OF MEASURED ROAD PROFILES

Approximately 2.35 km of typical road surface elevation data was obtained from the Australian Road Research Board

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(ARRB) Limited, which used a laser profilometer with a verticle accuracy of 0.2 mm. The data, measured on the driver's side (left-hand drive) on bitumen roads in suburban Melbourne, were classified by the ARRB into three sections of equal lengths: smooth, moderate, and rough. The horizontal spatial sampling frequency, λ_s, was 20.75 samples/m (or a sampling length, δ_l, of 0.0482 m). The road surfaces measured were free of major defects such as potholes and are therefore considered steady-state processes.

Spectral Characteristics

The spectral characteristics of the road surface elevation record were evaluated by means of the FFT and are displayed in Fig. 1. It shows the PSD estimates for the smooth, moderate, and rough portions of the record as well as the PSD estimates for the whole record (thick line). All three road types as well as the whole record have very similar spectral characteristics, and only the root-mean square RMS value (proportional to the area under the PSD curve) seems to change in proportion to road roughness.

Statistical Characteristics

While it is quite common to use the RMS value of a random signal as an indication of power, it was considered pertinent to evaluate the trends and variations in the RMS road surface elevation record as a function of horizontal distance. This was achieved by extracting overlapping sections of the record sequentially and computing their respective RMS values, as shown in Fig. 2. The selection of the window size is critical in achieving sensible results. Although it is desirable to use small window sizes to detect rapid fluctuations in RMS, these also contain variations that are random in nature. Therefore, care must be taken when selecting the window size and when analyzing the results.

The crest factor of any random process is an indication of the severity of any localized or transient component within that signal. In the road transport environment, these are usually represented by sharp road surface defects such as potholes. Since damage to the vehicle or the goods within may be initiated and/or exacerbated by large transients, it is important to include the crest factor in any analysis of transport-related data. The crest factor of a sample is the ratio of the highest peak (or trough) to the RMS value of the sample. However, the crest factor is not an indication of the number of large peaks within the sample. To illustrate this point, three processes were considered: The entire original road profile record was seeded with a single large peak in the first instance and, in the second instance, seeded evenly throughout with some 66 large peaks and valleys of varying amplitudes. The introduction of these large transients into the original signal has little effect on the RMS value of the signal. However, when the crest factor of these signals is computed as a function of distance, the localized variations and trends in the crest factor are revealed. Fig. 3 shows that, for the original road surface evaluation record, there is little variation in the crest factor as a function of the horizontal distance. However, the crest-factor curve for the signal doped with a single large peak displays a single fluctuation while the signal doped with multiple large peaks and valleys displays a decreasing trend in the crest factor. The overall crest factor of both seeded signals are practically the same. The illustration demonstrates the importance of evaluating crest-factor variations when analyzing random processes that contain large peaks or transients. Fig. 4 shows the probability density estimates of all three road sections individually [Fig. 4(a–c)] and combined [Fig. 4(d)], together with a plot of the best-fitting Gaussian distribution (Charles 1993; Hasegawa 1989). It is interesting to observe how the

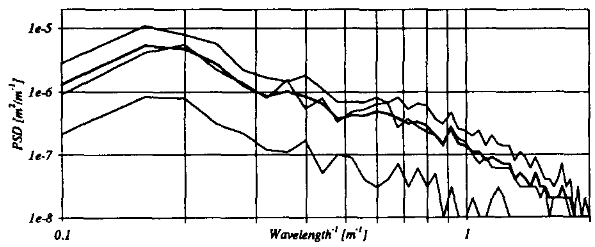

FIG. 1. PSD Estimates for Smooth, Moderate and Rough Road Sections (N_d = 16, δl = 0.02026 m^{-1}) [Thick Line: PSD Estimates for Whole Record (N_d = 48, δl = 0.02026 m^{-1})]

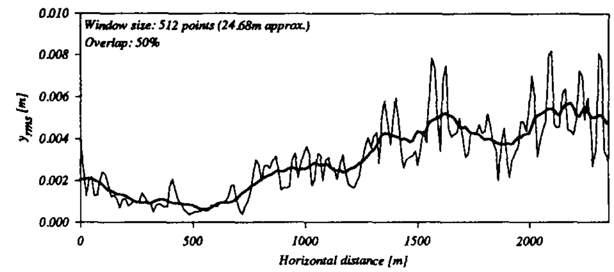

FIG. 2. Road Profile RMS Variations (Thick Line: 15 Point Rectangular Window Moving Average)

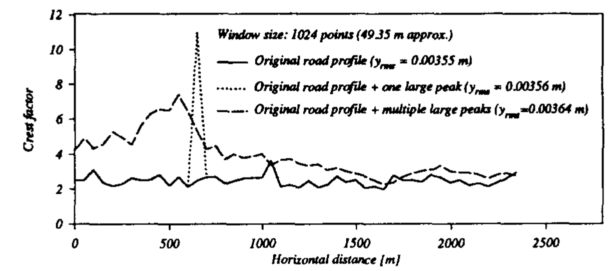

FIG. 3. Crest-Factor Variations for Original and Modified Road Profiles

deviation of the road surface distribution from the normal increases as the RMS value decrease. The kurtosis statistic (three for a truly Gaussian record) was computed to give an indication of the sharpness of the probability density estimates.

It can be shown that for a normally distributed narrow band process the distribution of the fluctuations amplitudes (the verticle distance between each peak and the mean) follows the Rayleigh distribution. This assumes that for narrow band records, there are no secondary maximums or minimums i.e., all peaks occur above the mean and all valleys occur below the mean. However, for broader band processes, such as road surface elevation, the presence of secondary maximums and minimums is evident. Rice (1944, 1955) and Cartwright and Longuet-Higgins (1956) have derived an expression for the distribution of fluctuation amplitudes for broad band signals as applicable to noise in electrical signals and the study of ocean waves. Unlike the Raleigh distribution, the expression is not only a function of the main variable (road surface elevation), but also of a spectral width parameter, ε, which represents the RMS width of the PSD (Rouillard and Lleonart 1994). The spectral width parameter can be computed from the zeroth, second, and fourth moments of the PSD or from the ratio of the number of secondary and primary peaks. When the process is truly narrow-banded, ε approaches 0 and distribution of the fluctuation amplitudes tends to a Gaussian distribution. Cartwright and Longuet-Higgins (1956) show that as ε increases from 0 to 1, the mean of the fluctuation amplitudes gradually decreases, the variance increases, the skewness decreases, and the proportion of secondary peaks and valleys

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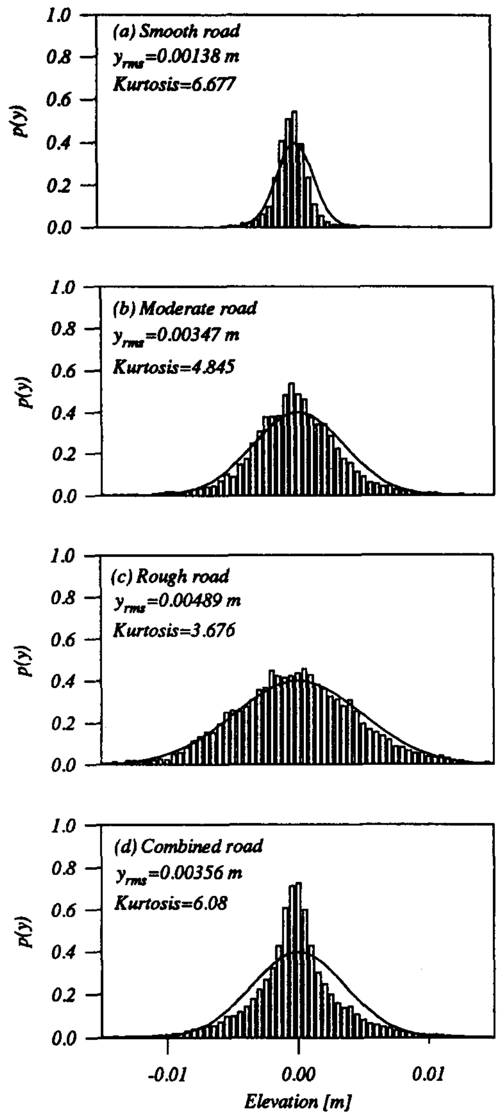

FIG. 4. Probability Distribution of Road Profiles Together with Gaussian Distributions

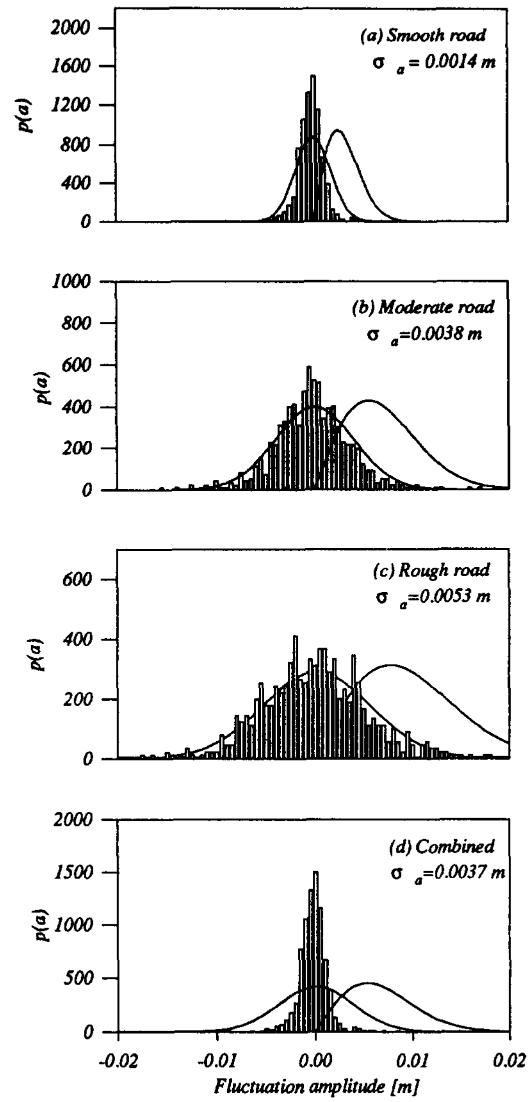

FIG. 5. Distribution of Fluctuation Amplitudes Together with Rayleigh and Gaussian Distributions

increases. It was thought relevant to compute and plot the distribution of fluctuation amplitudes for all three road sections individually [Fig. 5(a–c)] and combined [Fig. 5(d)], together with the best-fitting Rayleigh and normal distributions. As the road gets rougher (RMS increases), the distribution of the fluctuation amplitudes approaches the normal distribution and the standard deviation of the fluctuation amplitudes increases. Despite the fact that the analyses presented here have been performed on limited road surface elevation data, some important comments can be made:

1. The PSDs of road surface elevation records seem to retain their shape regardless of the road roughness.
2. The trends in road surface elevation RMS variations as a function of distance are important indicators of road roughness characteristics.
3. Trends in crest-factor variations must be taken into consideration when analyzing and simulating road profiles that contain large peaks or transients.
4. Any large transients present in the signal may be isolated and analyzed separately.
5. Due to obvious variations in road surface elevation RMS during one journey, the process should not be treated as stationary. However, for simulation purposes, the process may be treated as weakly nonstationary, whereby statistical parameters such as RMS are made to vary (slowly) according to the history of road roughness.
6. Individual sections of roads display different probability density characteristics and should be treated separately. Except for small portions of the road surface elevation record (rough in this case), the process may not be treated as Gaussian or narrow band.
7. Rigorous analysis of more representative road surface elevation records should be used in an attempt to classify road surfaces using the following parameters:
   - Moving RMS road surface elevation
   - Moving crest factor
   - Spectral characteristics
   - Road surface elevation probability distribution characteristics (kurtosis statistics)
   - Fluctuation amplitudes distribution characteristics (standard deviation of fluctuation amplitudes)
   - Characteristics of transients (joint distribution of amplitude and duration)

SIMULATION OF ROAD SURFACE ELEVATION

This paper proposes that the road transport environment may be more accurately simulated if the shaker table is made to emulate road surface elevations while the effects due to the dynamic characteristics of the transport vehicle can be accounted for with actual suspension systems or other physical devices with similar dynamic characteristics. This technique also ensures that the true compliance of the vehicle suspension system is represented during the simulation. To that effect a simple experiment, illustrated in Fig. 6, was devised to evaluate the effectiveness of such a technique. A verticle electrohydraulic shaker table was connected to a Schlumberger 1209 random vibration controller (RVC). The shaker table displacement signal, monitored by a Schlumberger linear variable displacement transducer (LVDT), was fed back into the RVC as the control variable. Since the random signal synthesized by most RVCs (including the one used here) is Gaussian, the PSD of the rough section of the road profile (as described earlier) was programmed into the RVC together with the corresponding RMS value. A single-axis loading tray, complete with tyres, leaf springs, shock absorbers, and payload of 100 kg (10% capacity), was placed onto the vibration table. In addition to the table displacement, the table acceleration and loading tray acceleration were also monitored. Fig. 7 shows the results of a 21 simulation in the frequency domain for a constant vehicle speed of 30 m/s. As can be seen, the results indicate good agreement between the programmed road surface elevation PSD and the PSD estimate of the table displacement. It is believed that the following are the main advantages of this technique:

- Once a wide range of road profiles have been analyzed and universally classified, only these road categories and the suspension characteristics of particular road vehicles will be required to physically simulate the complete process in the laboratory.

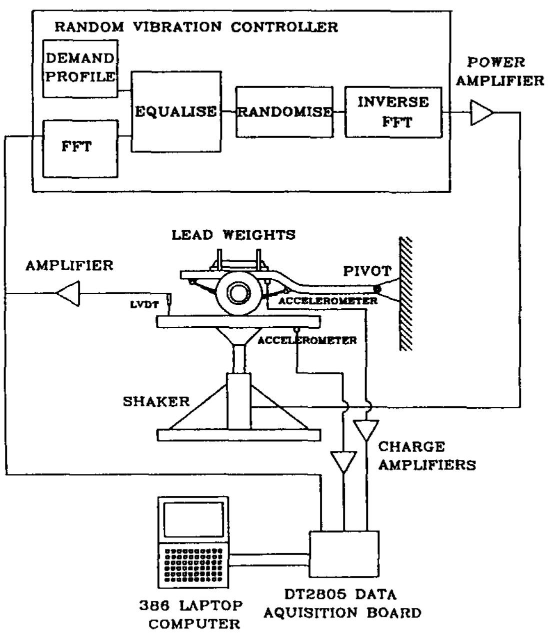

FIG. 6. Schematic of Experimental Arrangement

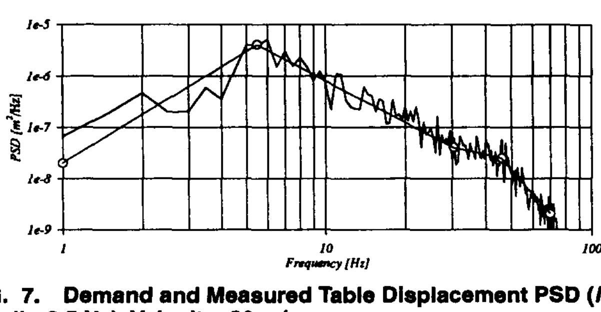

FIG. 7. Demand and Measured Table Displacement PSD (N_d = 21, df = 0.5 Hz), Velocity: 30 m/s

- Suitable adjustable mechanical devices may be easily designed and built to represent the dynamic behavior of a wide range of road transport vehicles as well as provide the necessary compliance during impact between a test package and the shaker table.
- Mean vehicle speed may be taken into consideration by simply shifting the PSD along the frequency axis.

The technique can be further improved by systems that will enable the generation of non-Gaussian random signals and allow the spectral characteristics, both shape and RMS, to be (slowly and incrementally) varied as a function of time. This is to account for variations in road surface characteristics and vehicle velocity, which occur during a single journey. Further, the presence of spurious and transient phenomena such as potholes and other major road surface defects can be taken into account by superposition of the actual dimensions of the "defects" onto steady-state signals.

PROPOSED TECHNIQUES FOR IMPROVEMENTS IN SIMULATION OF ROAD PROFILES

The spectral and statistical parameters suggested for the characterization and classification of road profiles may also be used to generate synthetic signals for reproduction under controlled, laboratory conditions. The following are areas being explored and developed to improve the simulation of road profiles.

Random processes with a known arbitrary distribution other than Gaussian can be numerically generated by the transformation method or the rejection methods (Press et al. 1993).

The generation of weakly nonstationary random processes may be achieved by concatenating sections of stationary signals defined by and synthesized from relevant statistical and spectral parameters. This technique allows parameters such as RMS, crest factor, kurtosis, etc. to be modulated as a function of time or distance. Fluctuations in vehicle speed, which occur during a journey, can be modeled by shifting the PSD functions of these individual sections along the frequency axis. Alternatively, it may be easier to vary the rate of digital to analog conversion during the simulation. The major advantage of this technique is that, prior to the experiment, the test sequence can be defined and numerically generated given the statistical and spectral parameters of individual sections of road classes to be combined. Furthermore, this technique allows transient phenomena to be numerically superimposed onto the synthesized steady-state signal.

However, the accurate conversion of these demand signals into real mechanical vibrations is difficult to achieve with conventional control systems. The dynamic response characteristics of vibration generators must be taken into account if the nature of the command signal is to remain unaffected. The adoption of recent developments in digital signal processing hardware enables the implementation of fast time-domain con-

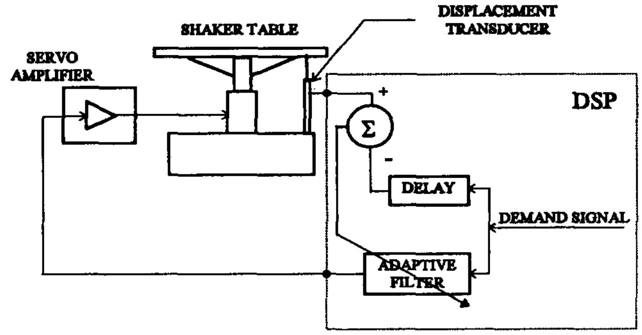

FIG. 8. Schematic of Adaptive Control System

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trol systems for random vibration generation, as shown in Fig. 8. During the process, the dynamic characteristics of the vibration-generating system is evaluated by means of the impulse response function. The coefficients of the adaptive filter are continually convolved with the demand signal and updated in real time in order to minimize the difference (error) between the demand and actual position of the shaker table. This method can be used to effectively compensate for the (variable) dynamic characteristics of electromechanical shaker systems, and to accurately control a wide range of stationary and nonstationary demand signals, including transients.

CONCLUSIONS

Simulation of the road transport process can be better achieved by synthesizing road profiles instead of accelerating vehicle loading trays.

The spectral shape of a section of road profile was found to be independent of road roughness, and the distribution of the process was found to deviate from the Gaussian distribution.

A range of spectral and statistical parameters were considered for the universal classification of road profiles. Subsequently, only the parameters describing these road categories and the vehicle suspension characteristics are required to simulate the transportation process.

The compliance of the loading tray can be modeled with a physical device to more accurately simulate the package-loading tray interaction, especially during impacts.

The use of digital signal processors (DSPs) together with a time-domain adaptive filter-control technique was recommended for the accurate reproduction of stationary and nonstationary demand signals.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

N_d = number of spectral averages;
$p(a)$ = distribution of fluctuation amplitudes;
$p(y)$ = distribution of road surface elevation;
δl = sampling length (in m);
$\delta\lambda$ = spatial frequency resolution (in m^{-1});
ε = spectral width parameter;
λ_s = spatial sampling frequency (in samples/m); and
σ_a = standard deviation of fluctuation amplitudes.

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