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Continuous wavelet analysis of pavement profiles

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ABSTRACT

Pavement roughness can be quantified by analyzing the response of vehicle suspensions to road geometry or by analyzing basic geometric measurements (e.g., crack width and depth). These analyses can be either summative or pointwise. In recent studies, wavelet transform has been used to quantify road roughness by correlating the energies of wavebands to summative IRI values rather than identifying localized features and their effect on vehicle suspension response (SR) using quarter-car (QC) simulations. Because pointwise SR analysis can identify localized features, the objective of this study is to investigate the applicability and advantages of analyzing asphaltic and Portland cement pavements with QC simulation and continuous wavelet transform (CWT). This approach provides spatial assessment of roughness as a function of both frequency band and position and allows statistical comparisons of SR at different frequency bands. An advantage of this method is analyzing relatively short segments which can support near real-time assessment.

1. Introduction

Pavement surface roughness increases vehicle operation and travel delay costs [13,28]; reduces vehicle durability [4,27]; and reduces ride quality and structural performance [1]. Structural performance diminishes faster on rough roads because roughness features increase dynamic stresses that accelerate pavement deterioration [20]. Accurate evaluation of pavement roughness levels and modes is a key factor in optimizing maintenance decisions [10,18,19].

Roughness can be quantified by analyzing the response of vehicle suspensions to road geometry, using, for example, the quarter- or half-car models or actual vehicle responses, or by analyzing basic geometric measurements (e.g., crack and pothole width and depth). These analyses can be either summative (i.e., results in summary indices) or pointwise (i.e., results in a response profile or map). The most widely used summative method, the international roughness index (IRI), calculates the average rectified slope (i.e., vehicle suspension rate) of a pavement elevation profile, but does not provide sufficient detail to indicate the roughness mode or describe localized features [16,26,40].

Pointwise analysis of vehicle responses can identify localized features, but this approach is still open for research and technology development. Studies of geometry-based pointwise quantification have classified pavement features by size and extent [8,9,15,21]. Tsai et al. [39] developed a crack fundamental element model to extract, cluster, and classify pavement cracks. Gavilán et al. [14] proposed a seed-based linear support vector machine approach to develop a fully automated distress classifier that uses textural properties as inputs. Radopoulou and Brilakis [32] developed an automated system to detect road patches from video data based on the surface elevation and texture. Zalama et al. [42] used Gabor filters and a statistical learning system that had been trained from a large database to detect longitudinal and transverse cracks. Other studies [23,25] have demonstrated the advantages of using wavelet analysis as inputs to neural network schemes in classifying pavement distresses. Bosché and Guenet [5] investigated the use of continuous wavelet transform in evaluating surface flatness based on terrestrial laser scanning data [6].

Several response-based studies have used signal processing techniques, such as power spectral density (PSD) and discrete wavelet transform (DWT), to quantify pavement roughness. DWT outperformed PSD analysis in verifying road roughness features and detecting localized defects such as cracks and potholes [17,36]. Wei et al. [41] calculated energies of wavebands and correlated these energies to IRI values. Sen et al. [35] used wavelet analysis to assess changes in pavement elevation profile characteristics over time and linked the changes to traffic loading, climate conditions, pavement composition, and subgrade soil type.

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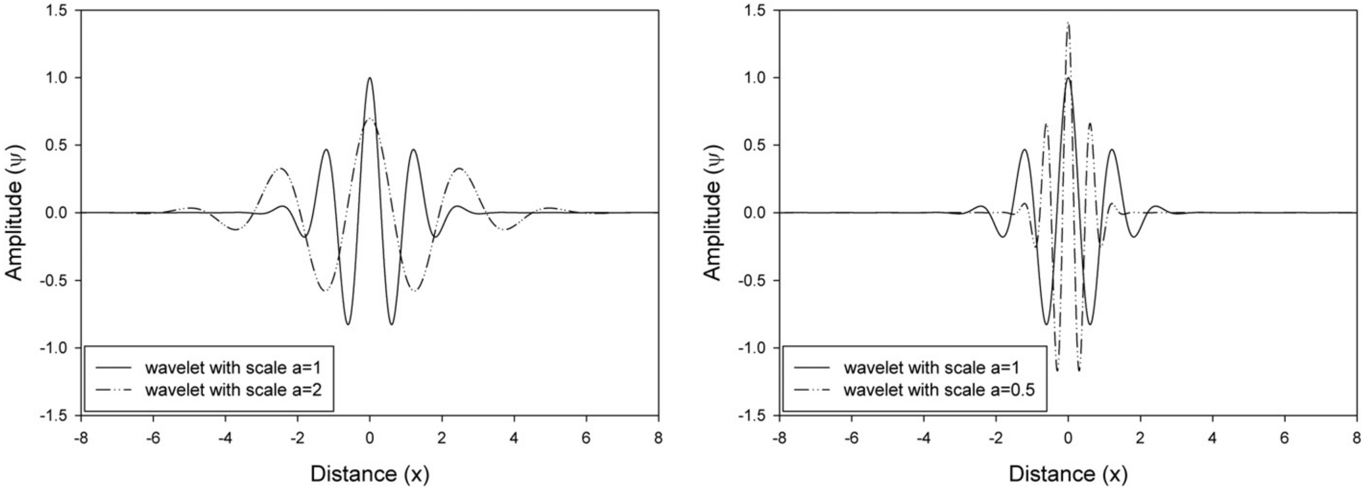

Fig. 1. The Morlet wavelet comparisons for different scale factors: (left) a = 1 and 2, and (right) a = 1 and 0.5.

Taken together these studies suggest that wavelet analysis is a promising technique for pavement roughness assessment, for locating problematic segments of any road, and for identifying possible causes of deterioration. Most previous wavelet analysis studies have used pointwise analysis (i.e., decomposing profiles into wavebands) but have correlated the energies of the wavebands to summative IRI values rather than identifying localized features.

Papagiannakis et al. [30] used DWT to analyze the suspension responses obtained from a 5-axle semi-trailer truck equipped with an air suspension on the driver axle and a rubber suspension on the trailer axles. Total energies of 11 wavebands were calculated and compared with dynamic loads. Dynamic loads correlated best with sub-bands with pseudo-frequencies between 0.65 and 3.76 cycle/m. Tomiyama et al. [38] analyzed the data collected with a response-type profiler that used a lifting wavelet transform to detect and quantify pavement distresses that identified target distresses with an average accuracy of 78%.

In this paper, 30 elevation profiles of both asphalt concrete (AC) and Portland cement concrete pavements (PCC) sections obtained from the Long Term Pavement Performance (LTPP) database [12] were analyzed with quarter-car simulations and continuous wavelet transform (CWT). The simulation results are reported as suspension rate profiles. The variance of suspension rate profiles has been used as a summary index because variance is a more common statistical parameter. The advantage of this approach is that CWT decomposes profiles in greater detail and provides spatial assessment of roughness as a function of both frequency band and position.

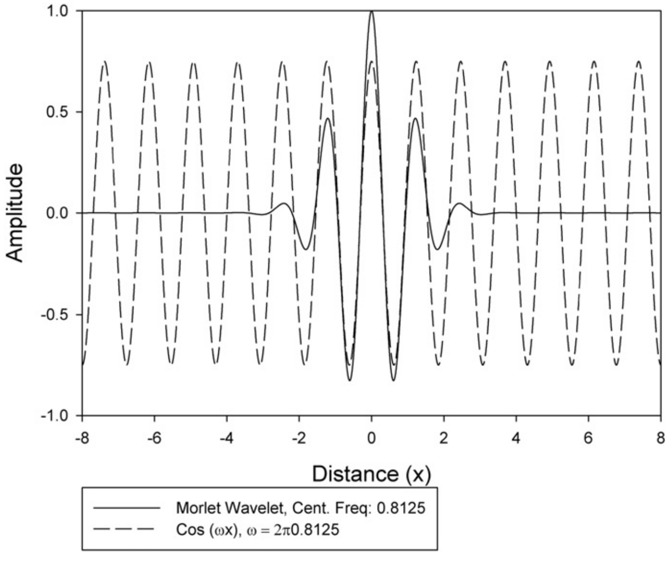

Fig. 2. The Morlet wavelet overlapped with the sinusoidal wave (frequency = 0. 8125).

2. Continuous wavelet transform

Wavelet analysis techniques were developed independently in different fields (i.e., pure mathematics, physics, and engineering) to overcome the time-frequency resolution issue in Fourier analysis [2,3,7,11,24]. This issue results from the assumption that sines and cosines, which are infinitely periodic functions, are the building blocks for any function. This assumption induces uncertainty in the analysis, where high resolution cannot be achieved simultaneously in both the frequency and the spatial domains. Pinsky [31] and Stein and Shakarchi [37] reported that as the dispersion of a function in the spatial domain about a fixed point x_0 decreases (i.e., higher resolution) the dispersion of the transformed function in the frequency domain about a fixed frequency ξ_0 increases to satisfy the inequality condition expressed in Eq. 1,

$$D_0(f)D_0(f) \geq \frac{1}{16\pi^2} \tag{1}$$

Table 1
LTPP profile information.

State code	SHRP code	Pavement type	IRI	State code	SHRP code	Pavement type	IRI
49	A351	AC	3.23	90	6420	AC	1.78
49	C331	AC	0.76	06	B441	PCC	7.95
90	B340	AC	3.11	48	C430	PCC	2.68
01	0101	AC	0.82	49	E458	PCC	2.31
04	1062	AC	0.32	06	3005	PCC	4.71
06	8535	AC	0.93	12	4138	PCC	5.21
12	4137	AC	0.36	19	0222	PCC	2.10
25	1002	AC	4.28	19	3055	PCC	0.40
34	0502	AC	1.24	21	3016	PCC	0.65
47	3075	AC	2.09	40	0160	PCC	1.27
48	1065	AC	4.96	42	1613	PCC	1.18
51	0120	AC	1.05	42	1617	PCC	0.99
81	0503	AC	2.51	46	0661	PCC	1.20
85	1801	AC	4.80	49	7083	PCC	1.26
90	6420	AC	6.05	89	3015	PCC	2.61