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APPLICATION OF WAVELET TRANSFORM IN LONGITUDINAL ROAD CURVE RECOGNITION TECHNOLOGY

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Abstract. *The variable of road's slope could be online calculated by vehicle's NED velocity obtained from one GPS based vehicle attitude measure system. In order to wipe off measured noise and to identify the longitudinal road curve parameters more exactly, the wavelet analysis method was applied in the data processing. Using Symlets wavelet function, the row gradient data were divided into one approximate signal and ten level details signals which present the road's slope characteristics and the measured noise respectively. The design parameters of longitudinal road curve were obtained from approximate signal by using least square curve fitting method. The analysis results of survey data of ring road in Xi'an show that it is efficient to eliminate the measured noise by wavelet tools and the characteristic parameters of longitudinal road curve can quickly and accurately be identified.*
Keywords: GPS, Wavelet, Longitudinal road curve, Vehicle attitude

1. **Preface.** The longitudinal line designed in road profile consists of many straight lines (having a certain slope) and their intersection points (also known as turning point), which is shown in Figure 1. In practical engineering, setting up transition curve (known as vertical curve) in the road turning point is needed to ensure the driving safety and good appearance of road alignment. Circular vertical curve is generally adopted in China. The longitudinal road alignment and control points after introducing the vertical curve are shown in Figure 2. It can be seen in Figure 2 that the longitudinal road curve can be simplified to a sinusoidal function along the road ideally. The intersection points of the function and the datum plane are the grade change points and peak of the road, namely the points whose third derivative equals zero (known as inflection point). Taking the grade change point and inflection point as the starting points, the road slope i can be determined by least squares fitting method. For example, i_1 can be fitted according to the data in grade change point S_i and inflection point P_i.

2. **Principle of Vehicular GPS Slope Angle Measurement.** The vehicle speed, travel track, pitch angle, heading angle, etc., can be obtained fast and accurately using the vehicle attitude measurement system based on GPS real-time kinematics theory. According to GPS measurement principle, the road slope angle (called gradient) at any time can be calculated from the measured NED velocity of vehicle [1]. Figure 3 shows the

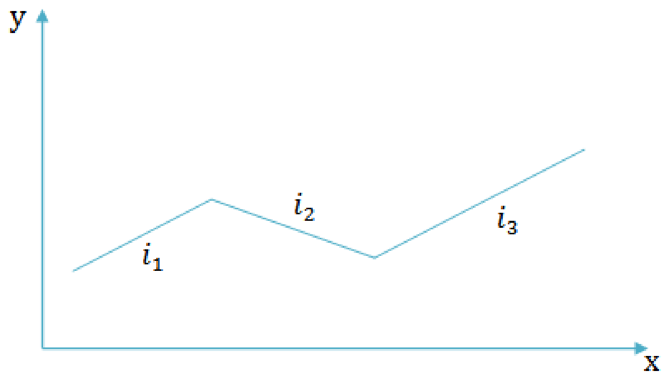


FIGURE 1. Longitudinal road curve composition

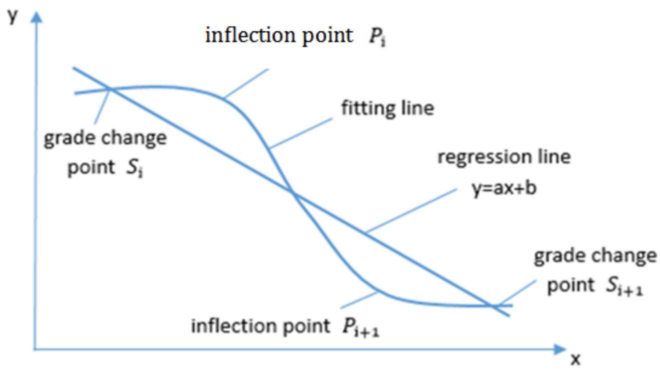


FIGURE 2. Simplified view of actual road longitudinal composition diagram

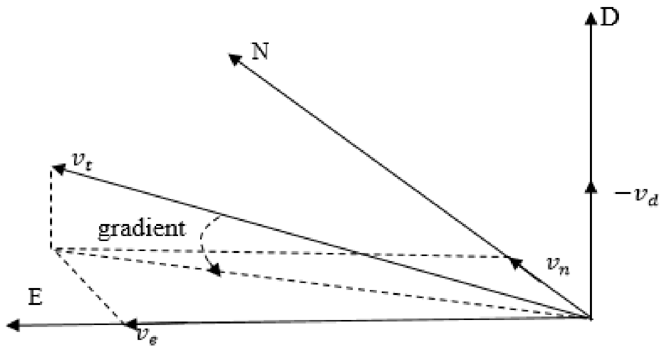


FIGURE 3. Gradient in NED coordinate system

relationship between NED velocity of vehicle and gradient of road when driving up and down along a ramp. Let the vehicle NED velocity be:

$$v_t = [v_d, v_e, v_n]^{\mathrm{T}} \tag{1}$$

where v_t is the vehicle velocity vector, v_d is the vertical velocity which is perpendicular and pointing to the earth surface. v_e is the horizontal velocity component pointing to east, v_n is the horizontal velocity component pointing to north.

The gradient of road can be got from Figure 3:

$$\vartheta = \arctan\left(\frac{v_d}{\sqrt{v_e^2 + v_n^2}}\right) \tag{2}$$

In this equation, ϑ is the gradient of road.

3. **Wavelet Transform.** When a vehicle travels on the ideal, smooth road with constant speed, the on board GPS measurement system will not be affected by the vibration coming from road excitation and the vehicle travel path in the profile coincides with the longitudinal road curve. Then the road slope angle can be calculated by Equations (1) and (2). However, on the one hand the road has roughness, potholes, convex hull, rut and on the other hand a constant speed is hard to maintain, so the on board GPS measurement system will contain vibration response which pollutes the gradient signal. The damage in road and roughness especially superimposed lots of high frequency noise onto the original signal. So how to remove interference and effectively propose the road profile information is the key to identify the longitudinal road curve (gradient, length of slope and so on) [2].

Normally, the noise signal measured can be effectively removed by low-pass filter. However, for the gradient signal measured by on board GPS measurement system under road excitation, adopting the traditional filter method will cause some problems:

1) The vibration response of on board GPS system is affected by both the road characteristics and the vehicle running condition, so the frequency components in response (which is noise to gradient signal) have the non-stationary random characteristics. As for lower grade road and those segments with large damage, the gradient signal is drowned in the noise, which makes it hard to extract the useful information.
2) Because of the damage type, space wavelength of the road and the vehicle speed are uncertain; it is difficult to accurately determine the low-pass filter's cut-off frequency which is the key factor to remove noise effectively.

To solve these problems, wavelet analysis technique is adopted in this paper to denoise and restructure the original signal aiming to get the accurate longitudinal curve.

Let $\varphi(t) \in L^2(R)$, where $L^2(R)$ represents the square integrable real space; its Fourier transform is

$$C_R = \int_R \frac{|\hat{\varphi}(\omega)|^2}{|\omega|} d\omega < \infty \tag{3}$$

When meeting the admissible condition, $\varphi(t)$ is called the mother wavelet or basic wavelet. Introduce the scaling factor a (represent the stretch related to frequency) and shift factor b under the requirements: a, $b \in R$ and $a \neq 0$. A family of function got through stretching the $\varphi(t)$ by a or translating it by b is called a wavelet sequence.

In continuous case, the wavelet sequence is

$$\varphi_{a,b}(t) = |a|^{-1/2} \varphi\left(\frac{t-b}{a}\right) \tag{4}$$

where $\varphi_{a,b}(t)$ is the analysis wavelet. The coefficient $1/\sqrt{a}$ is a normalization constant which makes the following equation right with a and b of any size.

$$\|\varphi_{a,b}\|^2 = \int_R |\varphi_{a,b}|^2 dt = \int_R |\varphi(t)|^2 dt \tag{5}$$

Normally, let $\int_R |\varphi(t)|^2 dt = 1$, which means $\varphi(t)$ possesses a unit of energy. The following equation can be got by continuous wavelet transform on any signal $f(t) \in L^2(R)$.

$$CWT_f(a,b) = |a|^{-1/2} \int_{-\infty}^{+\infty} f(t)\varphi^*\left(\frac{t-b}{a}\right) dt = \left\langle f(t), \varphi\left(\frac{t-b}{a}\right)\right\rangle \tag{6}$$

In this equation, $\varphi(t)^*$ is the conjugate function of $\varphi(t)$ and they are equal if $\varphi(t)$ is a real function.

If the basic wavelet $\varphi(t)$ satisfies the following condition,

$$\int_R \frac{|\varphi(\omega)|}{|\omega|} < \infty \tag{7}$$

the continuous wavelet transform can be inverse transformed and its reconstruction formula (inverse transformation) is:

$$f(t) = \frac{1}{C_\varphi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} CWT_f(a,b)\varphi\left(\frac{t-b}{a}\right) dadb \tag{8}$$

Wavelet transform discomposes the analysis single into a combination of multilayer high-frequency detail signal and low-frequency approximate signal in space. As for actual road gradient signal, it means that the road longitudinal profile curve (approximate signal) and high-frequency detail signal which reflects the road roughness, damage, rut, etc., can be got by wavelet decomposing.

4. **Engineering Example.**

4.1. **Test equipment.**

The vehicle attitude and driving track data acquisition system used in this paper is a GPS measurement system based on RTK technology [3]. It consists of GPS antenna, data acquisition and display instrumentation (Figure 4). After installing the instruments, the data can be collected and stored in the data acquisition instrument while the vehicle is running along the road.

FIGURE 4. Vehicle attitude testing system

4.2. **Experimental analysis and results.**

Figure 5 shows the road gradient curve measured in Xiajiadian segment of Xi'an Ring Road. After decomposing this signal into 10 layers by using wavelet function Symlet, the approximate signal and the first three layers of detail signal are shown in Figure 6 and the comparison of the approximate signal with original road gradient curve is shown in Figure 7. The partial enlargement is shown in Figure 7(b) at the same time, where it is clear that wavelet decomposition can effectively remove the noise in original signal and the longitudinal road curve is very smooth.

Figure 8 compares the road alignment curve after filtering the original signal by Butterworth low-pass filter (whose cut-off frequency is set by repeated trial and error) and the approximate signal by wavelet analysis. It can be seen in Figure 8(b) that using wavelet analysis can quickly and accurately remove both high and low frequency noises. This is beneficial to the least square identification of inflection points and then improves identification accuracy.

As for approximate signal (shown in Figure 9) after wavelet decomposing, the road gradient angle can be obtained by the following procedures.

Firstly, identify the zero point in the gradient angle curve to get the grade change points of longitudinal road curve.

Secondly, segment the gradient angle curve by the grade change points.

Thirdly, identify the slope change point (inflection point in longitudinal road curve) in the segments of gradient angle curve.

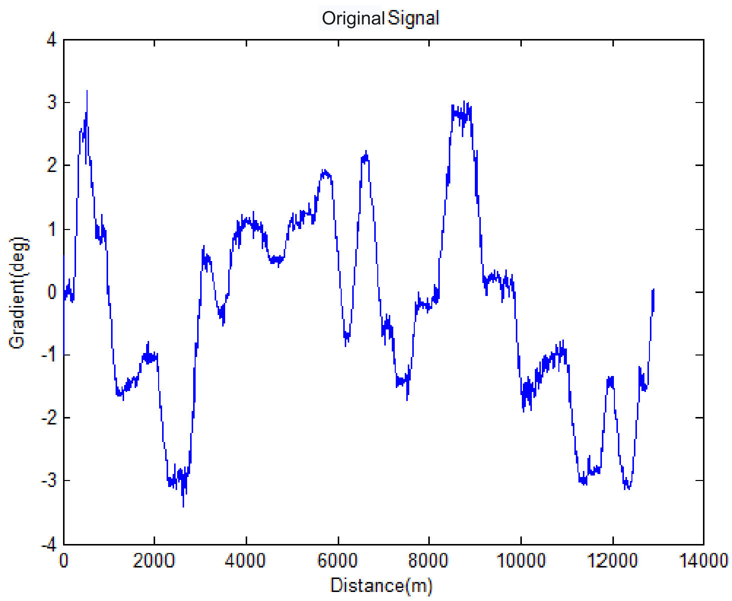


FIGURE 5. The original gradient signal

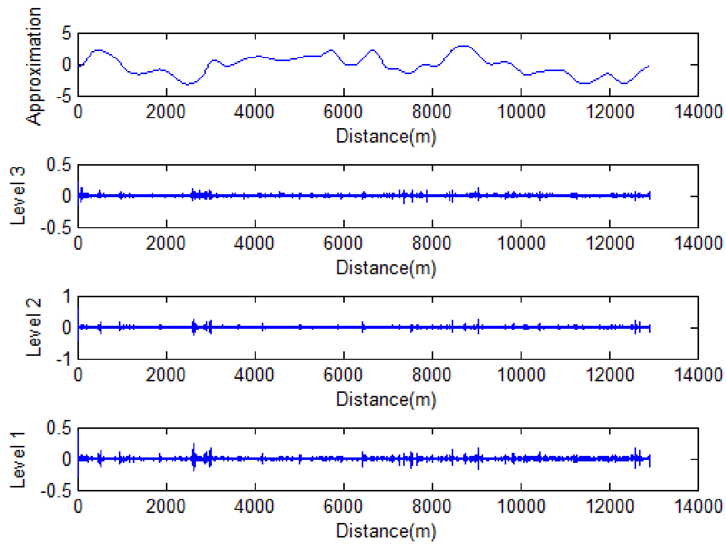
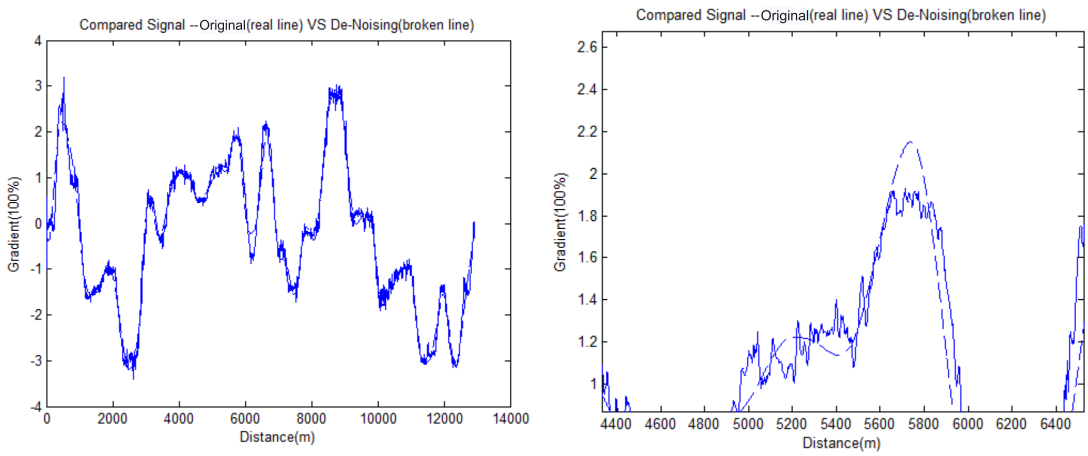


FIGURE 6. Approximate signal and detail signals after decomposing

Fourthly, segment the curve according to the identified zero point and slope change point. If the absolute value of the slope is less than the threshold value, set this segment as ramp segment, calculate the length and take the maximum value of the gradient angle as longitudinal gradient; on the contrary, set this segment as vertical segment, calculate the length and take the average value of the gradient angle as longitudinal gradient [4,5].

Fifthly, the threshold is determined by highway subgrade design specification (JTD D30-2004) and repeatedly test data analysis.

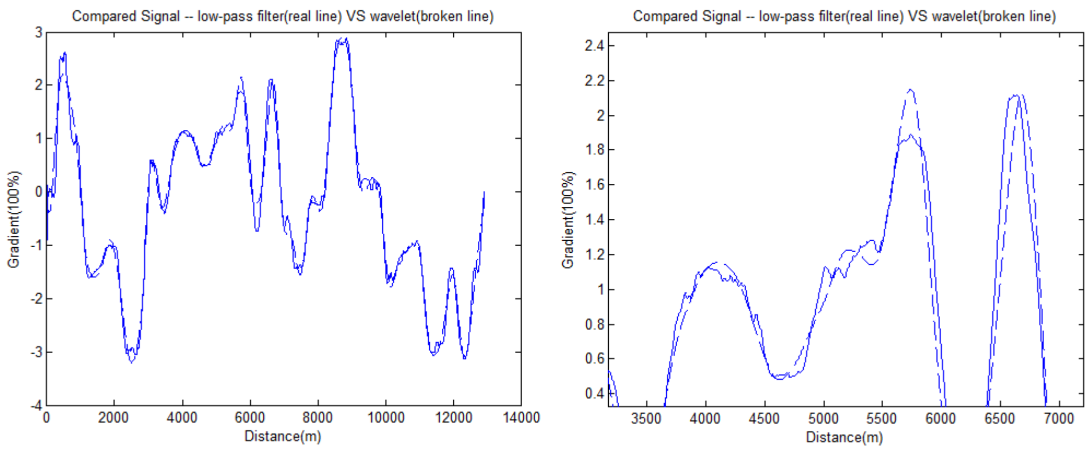
The results are shown in Table 1. It has to be illustrated here that the vehicle accident reconstruction does not have much to do with the vertical curve parameters. So in this paper, the arc length of vertical curve is divided by inflection point into the line segments in two sides, while the gradient equals each line segment.



(a) Comparison curve (b) Partial enlargement

Broken line: approximate signal after wavelet analysis; Real line: original signal

FIGURE 7. Comparison between approximate signal and original signal



(a) Comparison curve (b) Partial enlargement

Broken line: approximate signal after wavelet analysis; Real line: signal after low-pass filter

FIGURE 8. Comparison between low-pass filter and wavelet analysis

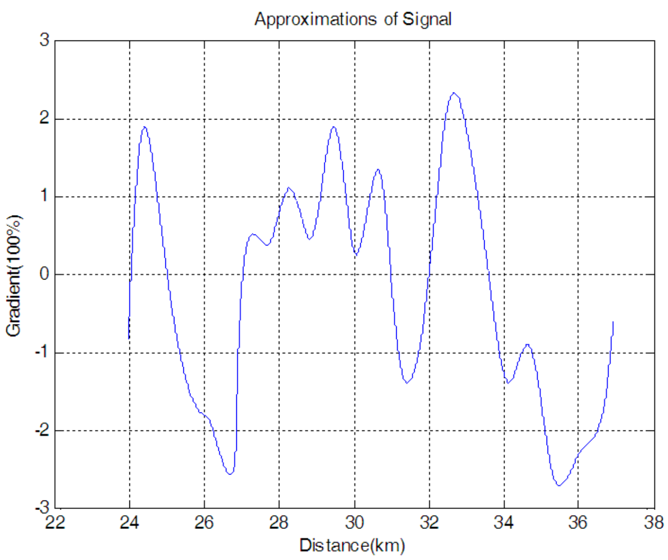


FIGURE 9. Approximate signal after wavelet decomposing

TABLE 1. Relationship between vehicle travel direction and GPS heading

Number	1	2	3	4	5	6	7	8	9
Length (m)	594	373	1186	623	186	2459	449	1012	324
Slope (%)	1.86	0.93	−1.23	−2.38	−1.13	0.70	1.84	0.78	−0.54
Number	10	11	12	13	14	15	16	17	18
Length (m)	386	543	269	553	821	1343	1376	377	
Slope (%)	−1.41	−0.31	0.89	2.31	1.15	−1.21	−2.99	−1.17	

5. Conclusions.

1) In comparison to using elevation to get the alignment parameters of the longitudinal road curve, it has the advantages of no coordinate conversion, faster and more accurate to calculate the gradient angle by the vehicle space velocity vector.

2) Wavelet transform can effectively eliminate the high-frequency interference caused by road roughness, potholes, rut, convex hull, etc., and accurately isolate the change in longitudinal road curve.

3) Compared to traditional filter technology, wavelet analysis can effectively remove the high and low frequency noise in signal by adjusting the bandwidth "automatically" according to the frequency components in signal. And the longitudinal road curve alignment is more accurately, which raises the parameter identification precision.

4) It is proved by accident reconstruction analysis software system that the gradient of longitudinal road curve can be identified faster and is more accurate by wavelet analysis.

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