Response type roughness measurement and cracking detection method by using smartphone

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As for pavement maintenance management, cracking, rut and roughness are important issues. In recent years, with the spread of smartphones, the new response type of the measurement method has been developed, and it has been adopted as actual evaluation by local governments. In this paper, at first, response type roughness measurement technology and measurement repeatability will be discussed. In detail, by using developed IRI class 2 method named "BumpRecorder" longitudinal profile first, then IRI by quarter car simulation can be calculated. Calculated data about road roughness all over Japan has been recorded since 2011 until now, that is more than 1.8 million km long as of Sep. 2016. Especially road cracking is more significant issue than roughness. However, previously, it was difficult to detect by the conventional method of the response type. In this paper, the response type cracking detection method will be proposed. It only needs a smartphone, not requiring any other devices. The detection principle and results will be reported. In addition, as for roughness and cracking evaluation, section determination is important. Traditionally, a kilo post marker has been used for section determination. But it requires long time and much cost to make kilo post data. To solve such problems in this paper, "Square Mesh Section" will be proposed. It is determined by latitude and longitude. Using this section, only by collecting GPS data, it will be determined the same section under repeated measurement. Response type roughness measurement and cracking detection and Square Mesh Section will reduce data collection and analysis costs for pavement maintenance management.

Keywords: response type measurement, roughness measurement, cracking detection, smartphone

1 Response type roughness measurement

For roughness measurement, the smartphone measurement technology has been developed. It measures vehicle vibration by using smartphone built-in accelerometer and GPS. Then road roughness e.g. IRI can be calculated. This convenient method brings routinely inspection and screening. "BumpRecorder" is one of the applications. In this paper, measurement principle is explained as follows.

A smartphone is placed on the vehicle dashboard which is located over the vehicle suspension. In the case of this response type measurement, because a vehicle has suspensions, recording acceleration is easily influenced by a vehicle model and its driving speed. As the result, measurement results are not stable. To improve this problem, calibration driving has been applied for each vehicle before measurement driving. The biggest expectancy of the response type measurement is its convenience. However, calibration driving decreases its advantage. And traditional response type measurement needs correlation formula which is determined experimentally during calibration driving. It means that traditional response type IRI measurement is IRI class 3. This method is not only inconvenient but also inaccurate in actual road conditions where are not including situations at calibration driving roads.

"BumpRecorder" is not requiring calibration driving. It is IRI class 2,which is increasing measurement convenience and measurement repeatability. In order to get these features, vibration frequency analysis is applied. Figure 1 is drawing the calculation steps.

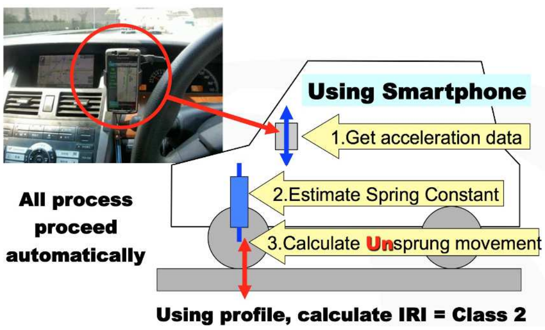

Figure 1. Roughness calculation steps

At first, by using FFT, vehicle suspensions resonant frequency and damping ratio are estimated. Even if recorded acceleration is including several resonant frequencies, suspensions movement is a main vibration, so its resonant frequency can be found around 1.5[Hz] easily.

Next, by using this spring parameters, the equation of motion of the one mass spring model is calculated. This model is drawn in Figure 2. An equation (1) is an equation of motion for this model. In this equation, *Lz* is a sprung vertical movement, *"u"* is an unsprung vertical movement, *"ω"* is an angular frequency, *"h"* is a damping ratio. *"ω"* is defined by equation (2). In this equation, *"f"* is a resonant frequency. Here, previous FFT result is using for *"h"* and *"f"*.

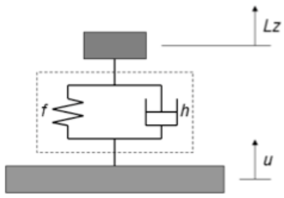

Figure 2. One mass spring model

$$\ddot{L}z + 2h\omega(\dot{L}z - \dot{u}) + \omega^2(Lz - u) = 0 \tag{1}$$

$$\omega = 2\pi f \tag{2}$$

And finally, an unsprung movement *"u"* is assumed that it is equal to road longitudinal profile, and it is calculating the Quarter Car simulation, then IRI will be calculated.

2 Experimental results

Figure 3 shows the sprung elevation of each position calculated by double integral of sprung vertical acceleration. In this experiment, TOYOTA PRIUS is used, which has 2,700 [mm] wheelbase and 1,400 [kg] weight, driven at several speed from 20[km/h] to 55[km/h]. Look at the period from latitude 36.1095 to 36.1096, and the period from latitude 36.1098 to 36.1099, the sprung elevation profile of each speed is different. Figure 4 shows unsprung elevation of each position calculated by equation (1). Look at the two periods above. Difference of unsprung elevation for each speed is smaller than sprung elevation. It means that unsprung elevation estimation is effective to get good repeatability. And unsprung elevation can reproduce more pointed profile than sprung elevation profile. It means that unsprung elevation estimation provides higher response, and a vehicle can be driven at faster speed with higher accuracy. This result says this method could reduce time and costs for the roughness measurement.

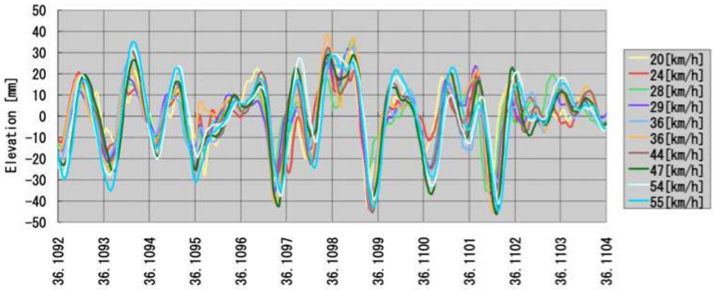

Figure 3. Sprung elevation profile.

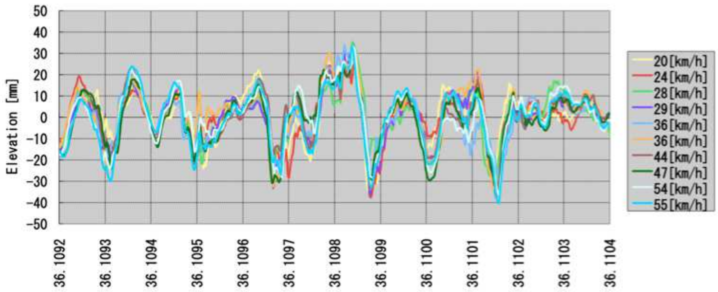

Figure 4. Unsprung elevation profile.

To compare dispersion of the measurement sprung elevation with the estimated unsprung elevation, elevation standard deviations of each speed are calculated at each position. This value is drawn in Figure 5. It clearly shows unsprung standard deviation is smaller than sprung standard deviation. Look at position around latitude 36.11017. The standard deviation of sprung elevation is 15[mm], and unsprung elevation is 6[mm]. Unsprung elevation dispersion is reduced to 40% variability.

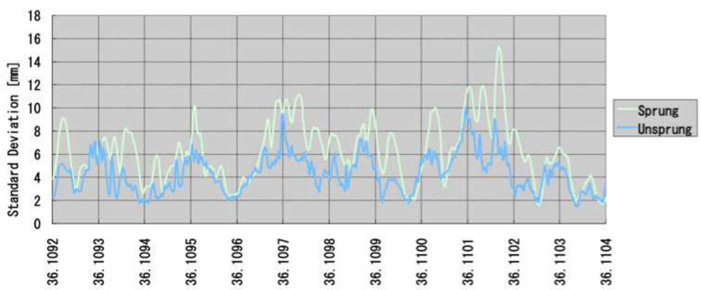

Figure 5. Elevation standard deviation.

3 Response type cracking detection

Response type cracking detection method is described. Target cracking is an alligator cracking like Figure 6. An alligator pattern size is about 20~40 [cm]. To detect this cracking, smartphone built-in accelerometer and GPS are only used, any other sensors not required. The smartphone is placed on the vehicle dashboard. These measurement conditions are the same as the response type roughness measurement. It means that roughness measurement and cracking detection can be done by the same smartphone at the same time.

Figure 6. Target cracking of alligator cracking

When the vehicle is passing over road cracking, the vehicle will vibrate. For example, a vehicle speed is 36 [km/h] or 10 [m/s], and an accelerometer sampling cycle is 100 [Hz], the vehicle is driven 10 [cm] in one sampling cycle. It means that the size of each cracking is about few sampling cycles. An expecting acceleration frequency is approximately 30 [Hz] to 50 [Hz]. This frequency is higher than vehicle natural frequency of the suspension’s 1.5 [Hz] and tire’s 15 [Hz].

To detect amplitudes of each frequency, FFT calculation is used. This time, the data size of FFT is using about 1 cycle of suspension’s natural frequency, which is about 0.7 [s]. For FFT, the number of samples must be power of 2. So, the number of data sample is selected by the biggest number of power of 2 less than the sampling cycle number. For example, when the sampling cycle is 100 [Hz], the number of FFT sample is 64.

4 Basic experimental results

For the test drive, TOYOTA PRIUS was used. And 3 models of smartphone were used. One is Sony Xperia Z1 which has 200 [Hz] sampling cycle, another one is Sharp AQUOS Phone SH-12C which has 100 [Hz], and the other is HTC EVO 4G which has 50 [Hz]. This experimental driving was done in Tokyo, Japan. Figure 7 shows IRI conditions in this road. Line colour indicates IRI value. Light blue is indicating smooth road, blue, green, brown are rougher road, and red is the roughest road. In this experiment, the start point is light blue circle position, and the end point is orange circle position in Figure 7.

FFT result is drawn in Figure 8. The horizontal axis is the longitude [deg.] of driving path. The starting point shows located at right hand side. The vertical axis shows FFT frequency [Hz]. And the circle diameter indicates the wave strength for each frequency of each position. In Figure 8, for example, the longitude around 139.71702 has cracking. In this point, FFT frequency around 50[Hz] has the large strength. As above paragraph of this paper indicates, cracking features are expecting around 30~50[Hz]. The result of Figure 8 is matched with this expecting.

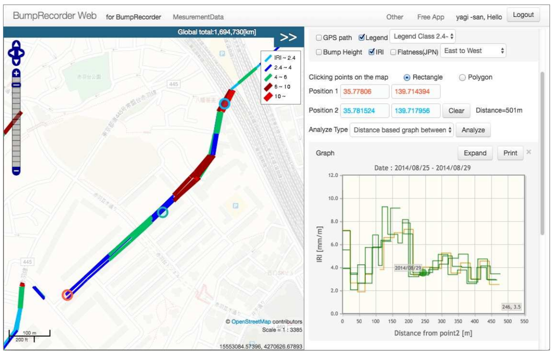

Figure 7. IRI conditions

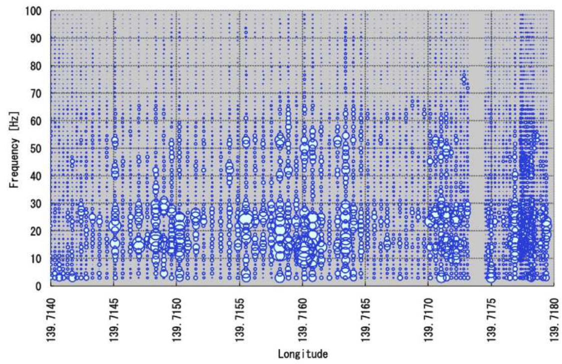

Figure 8. FFT result

5 Cracking detecting logic and experiment on actual road conditions

As above experiment, the cracking detection logic is designed as follows. For FFT analysis data, frequency is defined $f(i)$, and amplitude is defined $a(i)$. The weighted average of frequency f_{ave} is defined by equation (3). And mean amplitude is defined a_{ave}. Here, the cracking index CI is defined by equation (4). When there is cracking, CI is expected to become large value.

$$f_{ave} = \frac{\sum_i f(i) \times a(i)}{\sum_i a(i)} \tag{3}$$

$$CI = f_{ave} \times a_{ave} \tag{4}$$

Figure 9 shows cracking index *CI* recorded by Sony Xperia Z1, which has 200[Hz] sampling cycle. In this figure, the horizontal axis is longitude, the vertical axis is latitude, and the circle diameter indicates *CI* value. Especially, the red circle indicates the large *CI* point that is estimated cracking point. Position 1 has cracking and *CI* becomes large. It means cracking is detected successfully. Position 2 is *CI* becomes large. But here has no cracking. This road is paved by concrete. Figure 10 shows picture of this road. Aggregate is seen on the concrete surface., therefore road surface is uneven. As the result, cracking index *CI* is reflecting this concrete road.

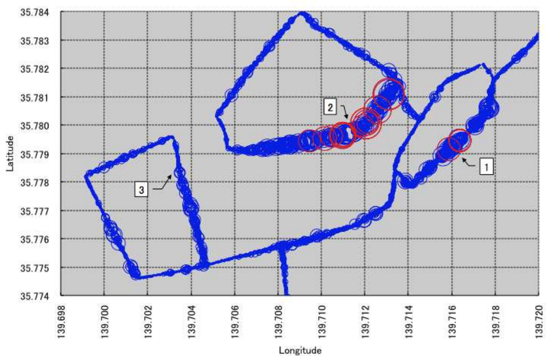

Figure 9. CI by 200 [Hz] sampling cycle

Figure 10. Concrete road at position 2

Figure 11 shows IRI conditions of experimental road. An orange circle position of Figure 11 is the point 3 of Figure 9. Look at Figure 11, this position's roughness is serious. But there is no cracking. Look at Figure 9, *CI* is not large. According to this result, *CI* is reflecting cracking, not reflecting roughness. That is good characteristic.

Figure 12 shows the cracking index *CI* which is recorded by Sharp AQUOS Phone SH-12C, which has 100 [Hz] sampling cycle. Figure 13 is recorded by HTC EVO 4G which has 50 [Hz]. These figures clearly show the detecting trend is same. According to this result, cracking index *CI* can be used for cracking detections for several types of smartphones.

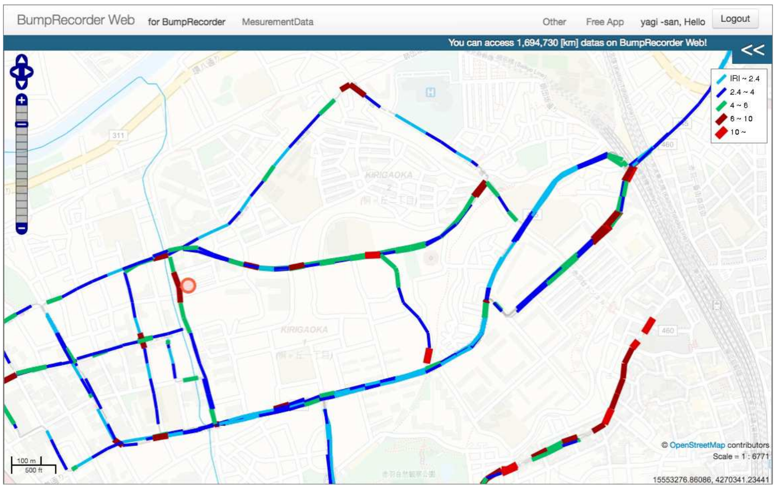

Figure 11. IRI conditions

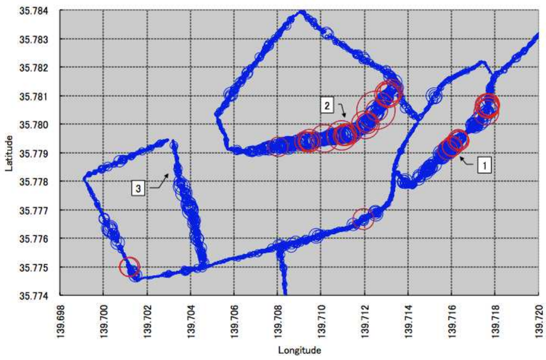

Figure 12. *CI* by 100 [Hz] sampling cycle

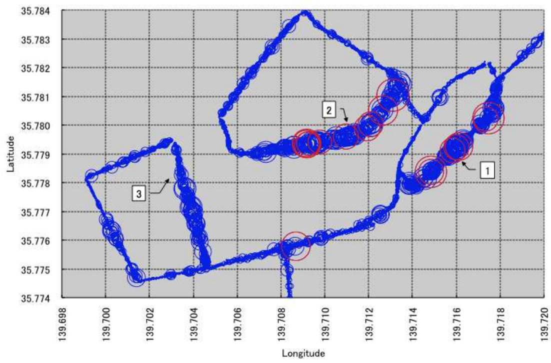

Figure 13. *CI* by 50 [Hz] sampling cycle

6 "Square Mesh Section" for section determination

To calculate IRI, a calculating section is an important factor. Traditionally, this section has been defined by road location markers e.g. kilo-post data. Kilo-post data is prepared for main roads, but not for community roads. For this reason, the data has not been easily defined on the community road, which makes roughness measurement difficult. It means that kilo-post data was not easily defined on the community road, which makes roughness measurement difficult. When kilo-post data is not used, GPS data is separated in a certain distance, for example each 100[m]. This calculation is easy. But unfortunately GPS data has an error. So, even if origin position is adjusted, a section separating point could be deviated, and this deviation is increase, depending on the length of measurement distance. In this situation, when needed the comparison of the current IRI with the previous one, because IRI section is not same, a comparison check becomes difficult.

To improve this situation, "Square Mesh Section" is proposed. It can pick up the same section at anytime, anywhere, only by using GPS data. Square shape mesh is defined by the longitude and the latitude on the earth. When the driving path is crossing over this mesh, IRI section is determined from an entry point to an exit point. Figure 14 shows "Square Mesh Section".

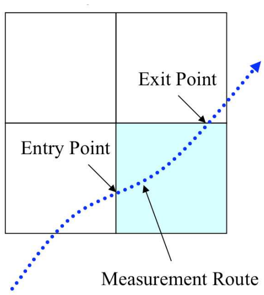

Figure 14. "Square Mesh Section" for IRI calculation section

In detail, for this Square Mesh, East West width is defined by $1/8192=2^{-13}$ length for each 1 degree of the longitude. It is about 10[m] around Japan located at latitude 35 degrees. And North South width is defined by the same length of East West width. For this square shape mesh, "Square Mesh Code" is defined by a pair code for the longitude and the latitude. An equation (5) defines *LonCode* for the longitude code, and an equation (6) defines *LatCode* for latitude code. *LonCode* and *LatCode* are integer.

$$LonCode = \mathrm{int}(\frac{longitude}{2^{13}}) \tag{5}$$

$$LatCode = \mathrm{int}(\int \frac{1}{\cos(latitude)} \times \alpha) = \mathrm{int}(\log \frac{1+\sin(latitude)}{1-\sin(latitude)} \times \frac{\alpha}{2}) \tag{6}$$

Here, "α" is defined by *LatCode* is 1 when *LonCode* is 1. That is as follows.

$$\alpha = 469{,}367.1234 \tag{7}$$

In addition, a magnification mesh is defined to use longer section for IRI calculation. A magnification mesh is defined by 2 times, 4 times, 8 times, and 16 times width of original mesh width. As the result, "Square Mesh code" is defined by array of (*MeshSize*, *LatCode*, *LonCode*). It shows in Figure 15.

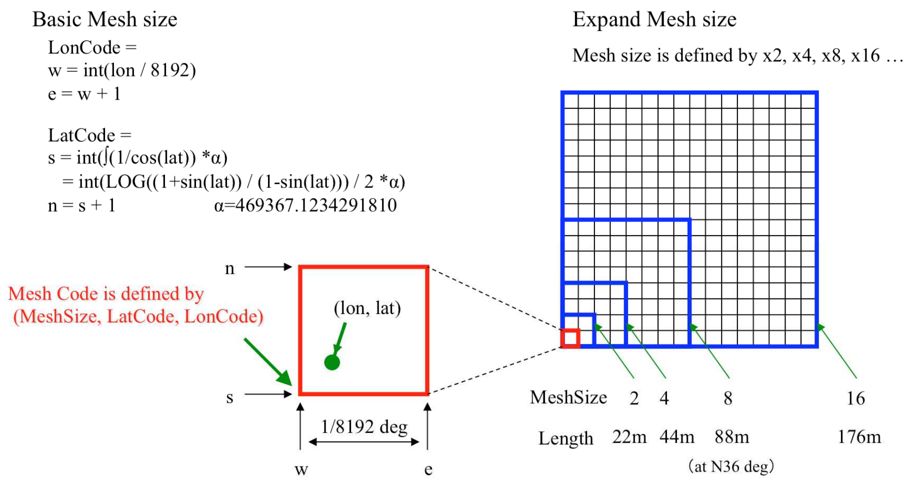

Figure 15. Definition of the "Square Mesh Code"

6 Conclusions

In this paper, the response type roughness measurement method and the cracking detection method are proposed. Both of them are using the same acceleration data and GPS data which are recorded at same time by same device. And the proposed roughness measurement "BumpRecorder" is calculating longitudinal profile first and then IRI is calculated by Quarter Car Simulation. That is IRI class 2. In Addition, "Square Mesh Section" is proposed for IRI calculation section. It is defined by latitude and longitude. It is not requiring kilo-post data. "BumpRecorder" and "Square Mesh Section" is reducing measurement costs and lead-time. For these reasons, the methods enable users to operate routine measurement. Routine measurement is available with these methods, and it will bring an increase in level of pavement maintenance management.

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