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CIVIL ENGINEERING

Automatic pavement macrotexture depth calculation using a statistical approach based on the tire/road noise signal by directional microphones

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Abstract. This paper develops an automatic method to calculate the macrotexture depth of pavement roads, using the tire/road noise data collected by the two directional microphones mounted underneath a moving test vehicle. The directional microphones collect valid tire/road noise signal at the travel speed of 10–110 km/h, and the sampling frequency is 50 kHz. The tire/road noise signal carries significant amount of road surface information, such as macrotexture depth. Using bandpass filter, principal component analysis, speed effect elimination, Gaussian mixture model, and reversible jump Markov Chain Monte Carlo, the macrotexture depth of pavement roads can be calculated from the tire/road noise data, automatically and efficiently. Compared to the macrotexture depth results by the sand-patch method and laser profiler, the acoustic method has been successfully demonstrated in engineering applications for the accurate results of macrotexture depth with excellent repeatability, at the test vehicle's travel speed of 10-110 km/h.

Key words: statistical approach; directional microphone; pavement; macrotexture depth; automation.

1. INTRODUCTION

The texture of pavement is "the deviation of a pavement surface from a true planar surface" within a specific wavelength range [1], and the macrotexture of pavement is one type of the pavement textures in the same order of size as coarse aggregate or tire tread element, with the spatial wavelength from 0.5–50 mm [1, 2]. The macrotexture depth (MTD) of pavement roads is important and necessary to the roadway health monitoring, which reflects the severity of segregation, road surface roughness, pavement wearing, and pavement skidding resistance [3–9]. Therefore, the MTD is an important parameter of roadway performance assessment standards and has significant effect on the traffic safety.

Currently, the MTD measurement methods are divided into two types – manual and automatic measurements. The manual measurement methods mainly include sand-patch method [10], the outflow meter, and the circular texture meter [11]. For example, in sand-patch method, the dry and clean sand with the grain size between 0.15–0.3 mm is spread on the dry surface of the pavement roads, shown in Fig. 1 [12]. If the volume of the sand is divided by the area of the sand on the road surface, the result will be the MTD value. The manual methods are straightforward, but labor intensive, inefficient, time-consuming, must close the traffic, and the results may have human error. On the other hand, the vehicle-mounted laser profiler is an automatic measurement method shown in Fig. 1, which can work well at driving speed without closing the traffic and get accurate MTD results with excellent repeatability [5, 6]. However, the equipment is expensive and has to be operated by professionals, which may prevent its widespread use in industry. Since the current manual and automatic methods both have their limitations, a new test principle and a cost-effective and fast test methods are needed to evaluate the MTD of the asphalt pavement roads. Also, an accurate and automatic data analysis algorithm has to be developed and validated by field tests.

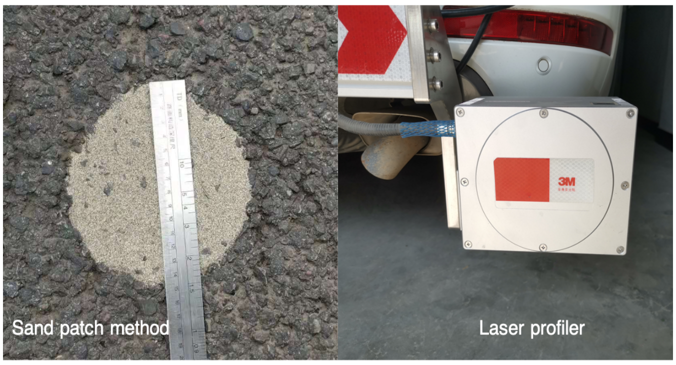

Fig. 1. Sand-patch method and laser profiler

Therefore, in this paper, the tire/road noise signal is used as a new test method for calculating the MTD. The tire/road noise is generated by the interaction between tire and road dur-

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ing driving. Directional microphone, an acoustic sensor, is used for the tire/road noise data acquisition. In the field tests, two directional microphones are mounted underneath the test vehicle and close to the rear tires, one is on the driver's side and the other is on the passenger's side. The directional microphone has several advantages over the current test methods described above. It is less expensive and of compacted size, collects small datasets, does not have to close the traffic, and can work well at the travel speed of 10-110 km/h, which is good for the applications on both highways and urban roads. From the acoustic theory and previous research, the tire/road noise signal is able to reflect the MTD.

Hence, this paper summarizes the research work conducted from July 2018 to June 2020 and focuses on developing an automatic and accurate method to calculate the MTD of pavement roads from the tire/road noise signal collected at normal travel speed. This algorithm is a statistical method. Bandpass filter is used for extracting the certain frequency range of the noise signal, which can reflect the macrotexture condition. After that, principal component analysis (PCA) is used for reducing the dimensionality of the noise signal datasets containing the sound from different sources and keeping the first component for further analysis. Then, the speed effect on the sound pressure level (SPL) of the tire/road noise signal is eliminated by an empirical equation and validated by field tests. The recommended test speeds are 40–50 km/h and 60–80 km/h for urban roads and highways, respectively. At last, a Gaussian mixture model is created to estimate the model parameters, such that the relationship between the tire/road noise signal and the corresponding known MTD in the training database can be established. Using the model parameters and the tire/noise signal from the tests, the MTD can be calculated and compared to the results from either sand-patch method or laser profiler. The field test results indicate that the proposed statistical algorithm works well for the acoustic data processing and is good for engineering applications.

The structure of this paper is as following. First, the theoretical background of the tire/road noise and MTD is introduced. Then, the unsupervised algorithm of the MTD calculation from the tire/road noise signal is presented. The authors eliminate the speed effect on the noise signal, use PCA, Gaussian mixture model and reversible jump Markov Chain Monte Carlo (RJMCMC) to calculate the MTD. The algorithm is validated by the field test results on highway and urban roads. Finally, the major findings are summarized, and the future work is discussed.

2. THE THEORY ABOUT USING THE TIRE/ROAD NOISE TO CALCULATE THE MTD

2.1. The generation of the tire/road noise

The tire/road noise during traveling is generated by tire-road interaction and is collected by the two directional microphones mounted underneath the test vehicle. The generation of the tire/road noise can be expressed by either vibratory mechanism or aerodynamics [13–15]. In general, the sources of the tire/road noise include the following: a) tire/road collision, b) deformation of the tire, c) stick slip, d) air pump principle, and e) aerodynamics. The directional microphones are installed close to the rear wheels, shown in Fig. 2.

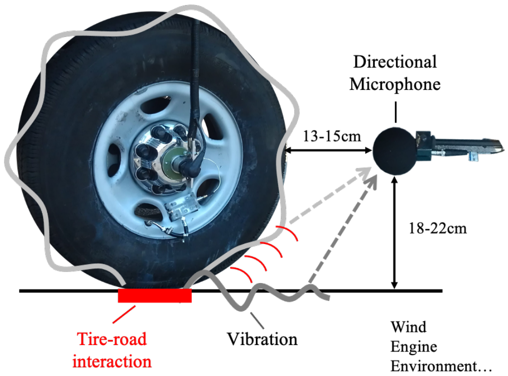

Fig. 2. The installation of the directional microphone on driver's or passenger's side

The pattern of the tire, the properties of pavement surface, and the travel speed of the test vehicle have significant influences on the tire/road noise during driving. First, the travel speed of the test vehicle influences the SPL – the higher the travel speed is, the higher the SPL will be, assuming that the other conditions are all the same. Since the driving speed during the road tests is not a constant, the speed effect has to be eliminated. Secondly, it is complicated to figure out the tire patterns influences on the tire/road noise, such that the authors have to fix the pattern of the tire used for field tests in this paper.

2.2. The relationship between MTD and the tire/road noise

As stated above, the tire/road noise signal carries significant amount of information about the pavement road surface conditions, such as MTD, defects, friction, elastic modulus, and so on. In this paper, the authors focus on developing a statistical algorithm to calculate the MTD from the tire/road noise. Previous research on the tire/road noise indicates that dynamic interactions between the tire and the road surface produce the noise signal, whose frequency dependence is related to the macrotexture during driving [16–18]. Therefore, the tire/road noise signal has potential for MTD measurement.

In fact, the acoustic signal collected by the directional microphones includes the sound from different sources besides the tire/road noise, such as the sound from wind, engine, horns, traffic and so on. Thus, the frequency band of the acoustic signal corresponding with the tire/road noise and the MTD has to be identified in the first step and extracted for further data analysis.

Previous research results have shown that the different sources of the sound correspond with different frequency bands. For instance, the noise of the frequency above 1000 Hz is mainly from tire-road collision [19]. In addition, the acoustic signal sources of the tire deformation and stick slip correspond with the frequency bands of 100–1000 Hz and 1000–2000 Hz, respectively [20]. Also, the maximum sound pressure value of the tire/road noise shows up in the frequency band of 700–1300 Hz [18]. Hence, the tire/road noise data can be extracted from the raw data by the directional microphones.

To identify the frequency band corresponding with the MTD in the acoustic signal, the authors collect acoustic data using the directional microphone from several different field testbeds at normal driving speed, such as the acoustic data collected from G15 Chinese Highway (Wenzhou section), Chongqing Inner Ring Express Road, several urban roads in Chongqing city, and the test roads at Chongqing Vehicle Test & Research Institute (CVTRI). The acoustic data is collected on more than 1000 lane kilometers roadways. From the large amount of the acoustic datasets and careful analysis, it is concluded that the frequency band 40–700 Hz of the acoustic data has strong correlations with the MTD of the pavement.

3. THE ALGORITHM OF THE MTD CALCULATION BASED ON THE TIRE/ROAD NOISE

The flowchart of the algorithm is shown in Fig. 3. First, the speed effect on the tire/road noise is eliminated through a preprocessing procedure, including Fast Fourier transform (FFT), bandpass filter, principal component analysis (PCA), and an empirical equation. Then, the authors create a training database from the field test results, which contains the MTD results from the sand-patch method and laser profiler, and the corresponding acoustic signal from the same road sections. A Gaussian Mixture Model is created to estimate the model parameters using RJMCMC. Finally, the acoustic MTD is calculated from the model parameters and the tire/road noise data. The details of each step are to be discussed below.

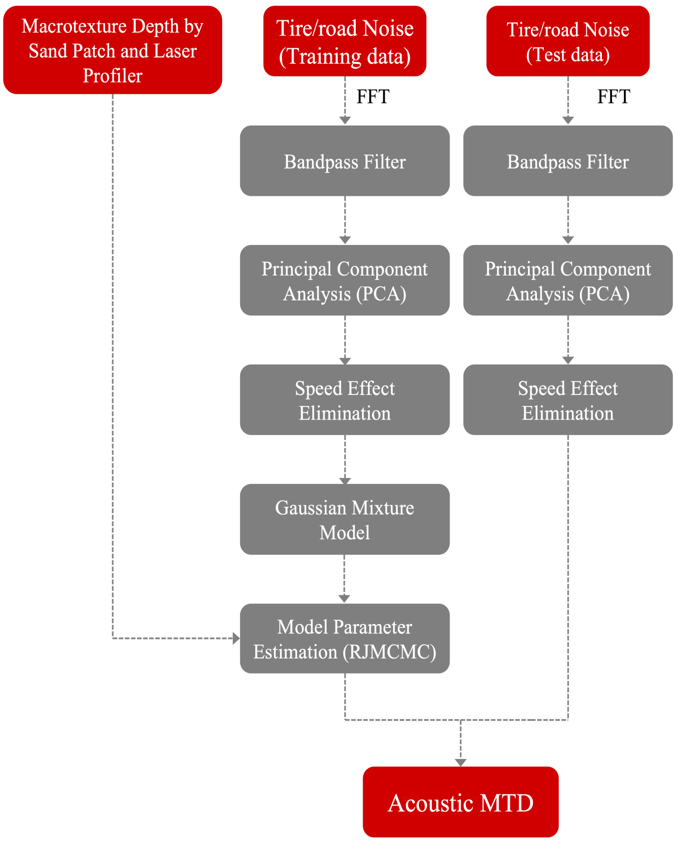

Fig. 3. The flowchart of the MTD calculation

3.1. Principal component analysis (PCA) and speed effect elimination PCA

In this paper, PCA is used for filtering the background noise. PCA is a well-known statistical method for feature extraction from the original datasets and shown in equation (1) [21], where $A_{m\times n}$ is the matrix containing the principal component vectors, $Q_{m\times m}$ is the weighting coefficients matrix, $B_{m\times n}$ is the original data, m is the number of variables in original matrix, and n is number of experiments/observations. As stated above, the acoustic signal collected by the directional microphones includes the tire/road noise, as well as the sound of wind, engine, and the surrounding environment. The objective of PCA is to reduce the dimensionality of the acoustic signal datasets containing the sound from different sources, and to extract the components representing the tire/road noise for further analysis.

$$A_{m\times n} = Q_{m\times m} \times B_{m\times n}. \tag{1}$$

As it is known, the tire/road noise is mainly influenced by the pavement road surface conditions, which are different from one road section to another, and different from the flat road surfaces to the defects, such that it carries much information about the pavement surface conditions. The sound from the other sources, is either random with an impulse sound (e.g., horn), or white background noise (e.g., the engine of the test vehicle, wind), which is expected to have relatively smaller standard deviation. Figure 4 shows the comparison between the first component and the other components, which represents the tire/road noise and the sound from the other sources, respectively. It is found that the first component of the acoustic signal collected by the directional microphones contains the tire/road noise, since it has a higher standard deviation, and the other components contain the acoustic signal from the other sources. Therefore, the authors keep the first component of the acoustic signal after PCA for MTD calculation, since it has the potential to be used for analyzing the pavement road conditions.

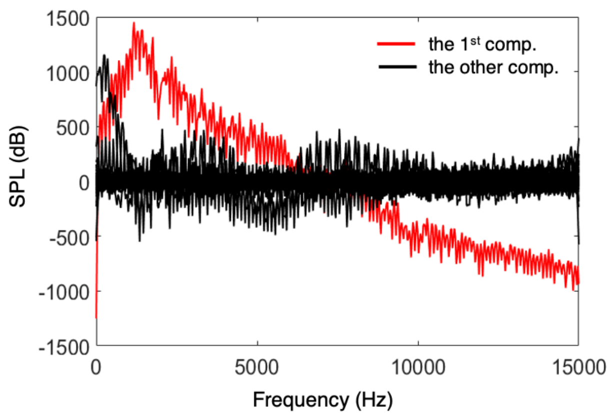

Fig. 4. The comparison of the first component and the other components

Speed effect elimination

After extracting the first component, the speed effect of the tire/road noise has to be eliminated. The travel speed of the test vehicle has significant influences on the SPL of the tire/road noise signal. Assuming that the road surface and other conditions are all the same, the higher the travel speed is, the higher the SPL will be. In the field tests, the driving speed of the test vehicle changes due to traffic, speed limit and other factors, which is not a constant. Thus, it is necessary to eliminate the speed effect, such that the SPL at different travel speeds could be normalized.

The speed effect of the tire/road noise is eliminated by an empirical equation and verified by field tests. The empirical equation is shown in (2), where L_c is the SPL corresponding with the travel speed of V_c, L_n is the normalized SPL at a fix speed of V_n, and m is the speed coefficient.

$$L_n = L_c + m \lg\left(\frac{V_c}{V_n}\right). \tag{2}$$

1. Field tests at CVTRI
The test road at the CVTRI field is considered as a highway road, since the road surface is flat and there is no traffic or speed limit, shown in Fig. 5. The driving speed range during test is 10 km/h to 100 km/hr. In each test, the travel speed is a constant (e.g., 10 km/h or 80 km/h), which is not difficult to control due to no traffic. Also, at each travel speed, the test is repeated for three times to check out the repeatability.

Fig. 5. The test road at CVTRI field

The results of speed effect elimination are shown in Fig. 6. It indicates that the PCA method and the empirical equation work effectively on eliminating the speed effect of the tire/road noise signal, at the travel speed under 40 km/h. Also, there is almost no speed effect at the driving speed above 50 km/h. Since the speed limit on highway is no lower than 60 km/h in most cases, the method could satisfy the use of the directional microphone on highway tests. Thus, in highway test, the normalized speed V_n of 60–80 km/h is optimal.

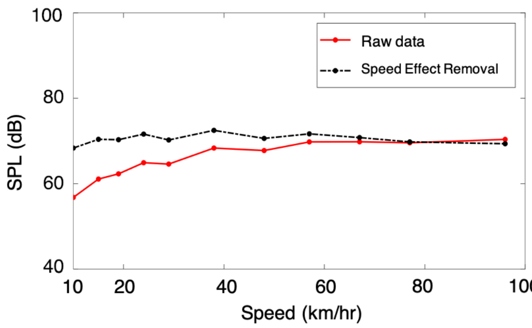

Fig. 6. Speed effect elimination results – the test field at CVTRI

2. Field tests on urban roads
Several urban roads with little traffic are selected to verify the effectiveness of the PCA method and the empirical equation. Similarly, the driving speed range at urban roads during test is 10 km/h to 80 km/h and the travel speed in each test is a constant (e.g., 20 km/h or 50 km/h).

Figures 7 and 8 are the speed effect elimination results from Jiangying Road and Qiangwei Road, respectively. These two urban roads are in Nan'an District of Chongqing city. From Figs. 7 and 8, the SPL increases with the speed. However, the speed effect is not obvious at the speed above 50 km/h. Also, the speed effect elimination method works well for the tire/road noise data collected from urban roads. Thus, in urban road tests, the normalized speed V_n of 50 km/h is optimal. In case that the travel speed is lower than 40 km/h due to speed limit or the traffic, the PCA and speed effect elimination method described above is able to work effectively.

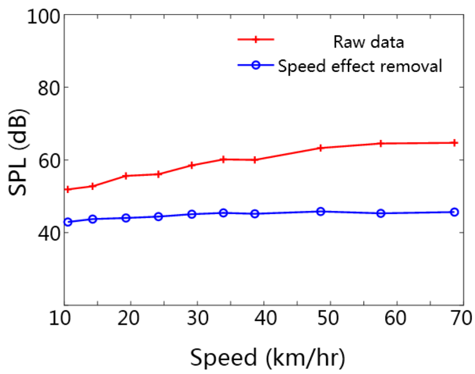

Fig. 7. Speed effect elimination results – Jiangying Road

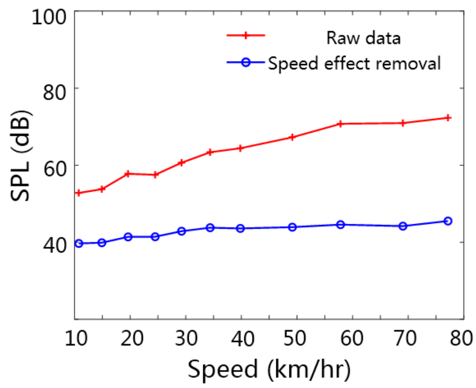

Fig. 8. Speed effect elimination results – Qiangwei Road

In summary, the practical test results verify that the speed effect elimination method works well for the tire/road noise data collected from both highway and urban roads. Also, the optimal driving speeds during the road test are selected, which are 80 km/h and 50 km/h for highway and urban roads, respectively. After this step, the SPL of the tire/road noise at any travel speed could be normalized to a reference speed and for further analysis.

3.2. The creation of Gaussian mixture model

The training database, including the known results of the MTD by the sand-patch method and laser profiler as well as the corresponding tire/road noise data after preprocessing, is created to study Gaussian mixture model. The sand-patch or laser MTD is considered as a reference. The objective of Gaussian mixture model is to create the relationship between the known MTD values and the tire/road noise signal, through the model parameters.

As stated above, the original tire/road noise data is preprocessed by bandpass filter, PCA and speed effect elimination. The first component is obtained and used as the input for creating the Gaussian mixture model. Since the tire/road noise is random and its first component is not subjected to a certain type of distribution, the authors create a Gaussian mixture model, which contains a series of Gaussian basis functions. Assuming that the number of the Gaussian basis functions is k, it is shown in equation (3) [22], where $y_{mtd,t}$ is the t-th MTD value by either sand-patch method or laser profiler, μ_j is the clustering center of the j^{th} Gaussian basis function, a_j is the weight of the j-th Gaussian basis function, b and β are the regression coefficients, and x_t is the corresponding tire/noise data.

$$M_k : y_{mtd,t} = \sum_{j=1}^{k} a_j \emptyset(\|x_t - \mu_j\|) + b + \beta x_t \,. \tag{3}$$

From equation (3), it is found that the parameters k, $[\mu_{1:k}]$ and $[b, \beta, a_{1:k}]^T$ are the unknows to be estimated, through the known results of the MTD and their corresponding tire/road noise data, which is to be discussed.

3.3. The estimation of the model parameters and the calculation of the MTD

According to the previous research and experimental tests, the prior probability of the parameters in Gaussian mixture model is subjected to the assumption, that the clustering center μ is obtained in the input x_t by random walk [22]. Also, it is assumed that the prior probability of k, the number of the Gaussian basis functions, is subjected to a Poisson distribution, shown in equation (4), where λ is the expected value.

$$P(k) = \frac{\lambda^k}{k!} e^{-\lambda}. \tag{4}$$

The model parameters, k, $[\mu_{1:k}]$ and $[b, \beta, a_{1:k}]^T$, are estimated through maximum a posteriori probability by RJMCMC method. There are five steps on a Markov chain:

1) create a new basis function;
2) delete a basis function randomly;
3) divide a random basis function into two functions;
4) select a random basis function, combine with its nearest basis function, and get a new basis function;
5) update the basis functions.

The automatic iteration is ended when the model converges. Also, the model parameters, k, $[\mu_{1:k}]$ and $[b, \beta, a_{1:k}]^T$, are obtained at the maximum a posteriori probability, from the training database. Finally, the MTD is calculated by equation (5), where $y_{\text{mtd\_acoustic}}$ is the MTD from the tire/road noise data, x_{acoustic} is the input, which is the first component of the tire/road noise data after preprocessing by speed effect elimination.

$$y_{\text{mtd\_acoustic}} = \sum_{j=1}^{k} a_j \emptyset(\|x_{\text{acoustic}} - \mu_j\|) + b + \beta x_{\text{acoustic}} \,. \tag{5}$$

4. TEST RESULTS

The developed algorithm is validated by the field tests on urban roads and highway to verify its effectiveness and accuracy for large dataset processing. The test vehicle of China Merchants Roadway Information (Chongqing) Co., Ltd. (CMRI) is used for the tire/road noise data acquisition on both urban roads and highway. The test vehicle and the directional microphone on the passenger's side are shown in Fig. 9. Global positioning system (GPS) is also installed on the test vehicle, to collect the travel speed data at any time stamp for speed effect elimination. At the same time, the laser profiler is installed on the test vehicle to measure the MTD value on highway for training and comparison. Also, the sand-patch MTD is measured on urban roads.

Fig. 9. The test vehicle and the microphone on the passenger's side

Urban Road 1 – Shengbao Road

The urban roads with less traffic are selected for field tests. The test vehicle travels at a constant speed on this urban road in each test. The section of Shengbao Road for test is about 1 km long. The range of the travel speed in the field tests is from 10 to 110 km/h to evaluate the speed effect elimination and the repeatability. After the acoustic tests, the traffic is closed to measure the MTD with the sand-patch method for comparison.

Figure 10 shows the speed elimination results on Shengbao Road. The SPL of the raw acoustic data increases with the travel speed. After the speed effect elimination, the SPL is normalized

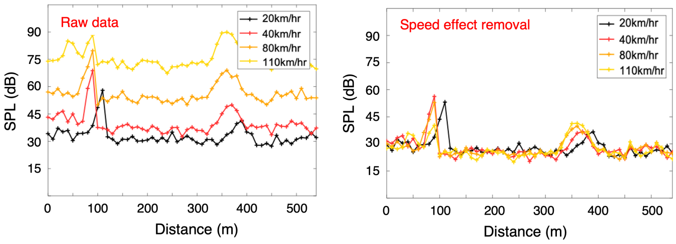

Fig. 10. Speed elimination results – Shengbao Road

to a reference speed, and the tire/road noise at any speed can be used for MTD calculation.

Figure 11 shows the results of the MTD from the tire/road noise data at different travel speeds of the test vehicle, compared to the sand-patch MTD. It indicates that the acoustic MTD at different test speeds is close to each other, and the proposed algorithm works well on this urban road at the travel speed as low as 20 km/h. Also, the acoustic MTD is accurate and close to the sand-patch MTD, which is considered as ground truth.

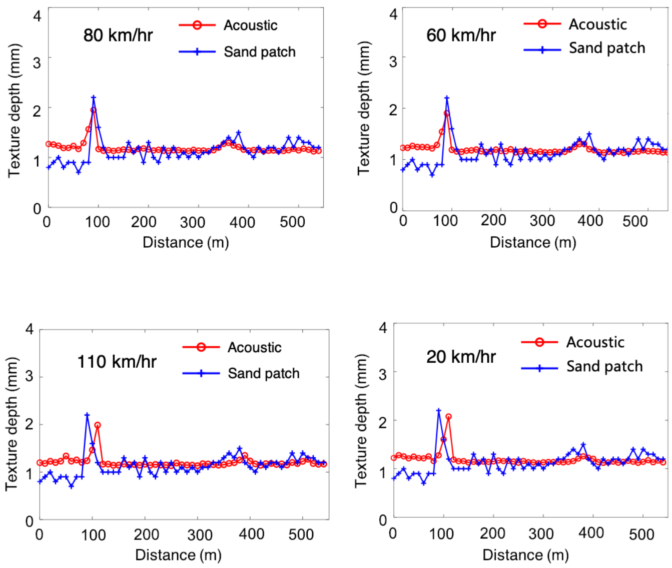

Fig. 11. Acoustic MTD at different speeds and sand-patch MTD – Shengbao Road

Urban Road 2 – Jiangying Road

Similarly, as the tests above, the test vehicle travels at a constant speed on this urban road for each test, with the range of the travel speed from 10 to 80 km/h. The section of Jiangying Road for test is 0.8 km long. The acoustic and sand-patch MTD are also compared to each other.

Figure 12 shows the MTD results from the tire/road noise at different travel speeds and the sand-patch method. It indicates that the MTD values from the acoustic method and the proposed algorithm are accurate with excellent repeatability. If the sand-patch MTD results are used as reference, the largest difference between the two test methods is less than 0.15 mm.

Equation (6) is used for evaluating the accuracy of the acoustic MTD, and its histogram distribution is shown in Fig. 13. It is found that the accumulative probability of the accuracy higher than 80% is 0.852, which has good correlation with the sand-patch MTD.

$$\text{accuracy} = \frac{\text{macrotexture depth}_{\text{acoustic}}}{\text{macrotexture depth}_{\text{sand patch}}} \times 100\%. \tag{6}$$

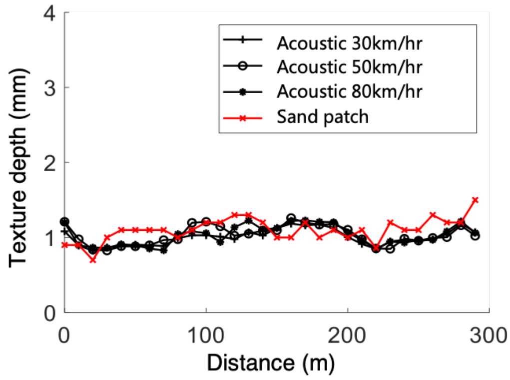

Fig. 12. The comparison of MTD results on at different travel speeds – Jiangying Road

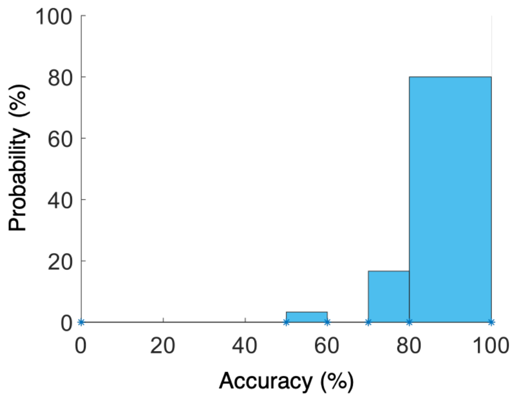

Fig. 13. The histogram of the accuracy – Jiangying Road

Highway 1 – Chongqing Inner Ring Express Way

Chongqing Inner Ring Express Way is one of the highways, which is selected to perform acoustic tests. This highway is 72 km long, and the driving speed is in the range of 20 to 100 km/h due to the traffic conditions in the test. The acoustic MTD is calculated by the proposed algorithm stated above, and the processing time is only a few hours with no supervision. Since it is not cost-effective to close the traffic on this highway and the sand-patch method is inefficient and labor intensive, the laser profiler is also installed on the test vehicle to measure the MTD, such that the results from the two methods can be compared. If the laser MTD is considered as the reference, and the MTD difference between the laser profiler and the acoustic method are shown in Fig. 14. The probability of the absolute value of the difference under 0.1 mm is 90.6%, which indicates that the algorithm works well on highway MTD measurement from the tire/road noise data.

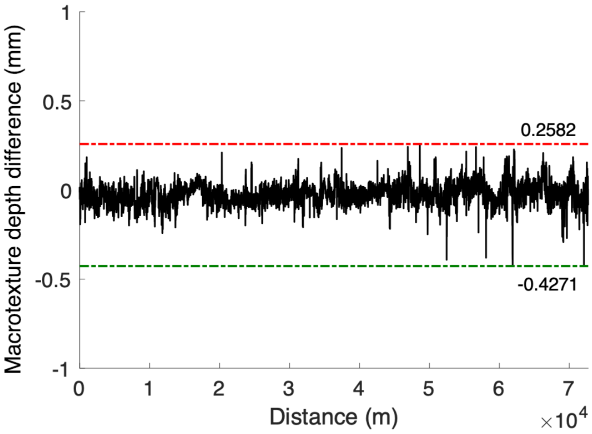

Fig. 14. The difference of the MTD results between the acoustic method and laser profiler – Chongqing Inner Ring Express Way

Figure 15 is the histogram of the distribution of the MTD accuracy. Since the accumulative probability of the accuracy higher than 80% is 0.974, it is found that the accuracy of the MTD on highway is higher than that from urban roads. The reason is that the laser MTD can provide a much larger training database, such that the accuracy can be significantly improved.

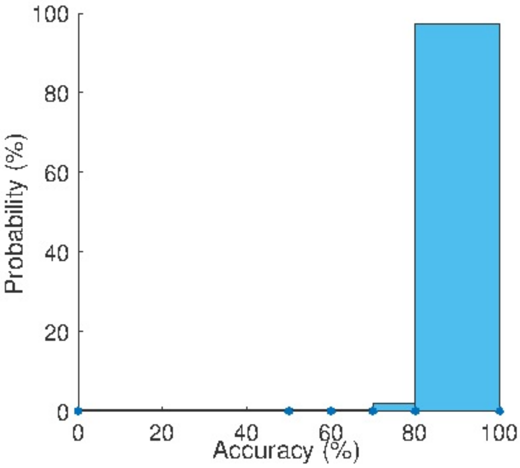

Fig. 15. The histogram of the accuracy on Chongqing Inner Ring Express Way

To visualize the MTD data from the acoustic method in a user-friendly way and make it easy to understand, a roadway pavement management system is developed based on a geographical map. This roadway pavement management system is a web-based system, which consists of a geographical module for data visualization and spatial analysis of the pavement information for the maintenance decision making. The results of the acoustic MTD are color coded and displayed as a polyline in this pavement management system. By clicking one specific point on the polyline, the results of the acoustic and laser texture depth can be shown in a popup window. The screenshot of the acoustic MTD accuracy is shown in Fig. 16. It is clear that the acoustic MTD by the proposed algorithm is accurate on highway.

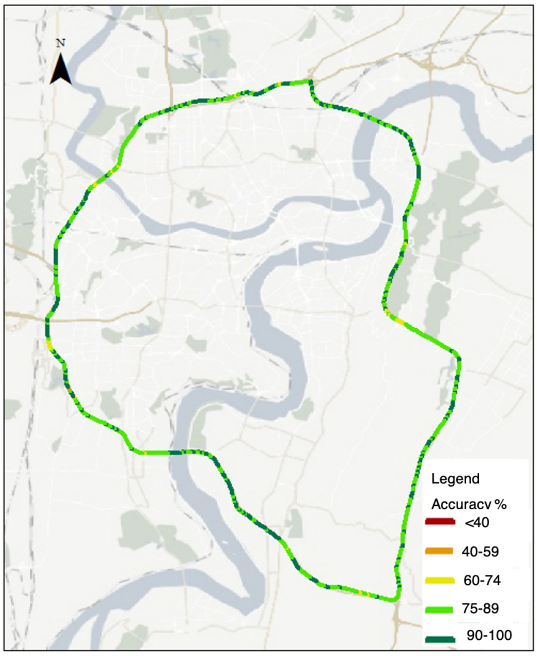

Fig. 16. The MTD accuracy on a geographical map – Chongqing Inner Ring Express Way

Highway 2 – G210 Provincial Highway

A section of G210 Provincial Highway is also selected for field tests. The section is 3.74 km long, and the driving speed is in the range of 20 to 70 km/h. Since the travel speed is not a constant during the test, it is necessary to eliminate the speed effect. The MTD is calculated by the proposed algorithm from the tire/road noise data and compared to that from the laser profiler, which is considered as the reference.

The MTD difference between the acoustic and laser methods is calculated, which is shown in Fig. 17. The probability of the absolute value of the difference under 0.1 mm is 96.27%, which is similar as the results from Chongqing Inner Ring Express Way.

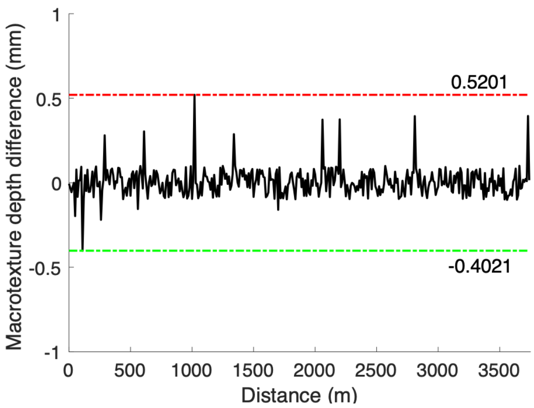

Fig. 17. The difference of the macrotexture depth results between the acoustic method and laser profiler – G210

Using (6), the accuracy of the acoustic MTD is also calculated, and its distribution is shown in Fig. 18. The accumulative probability of the accuracy above 80% is 0.893. Since the test section of the G210 is shorter, it is found that the accuracy is lower than that from Chongqing Inner Ring Express Way due to smaller training database.

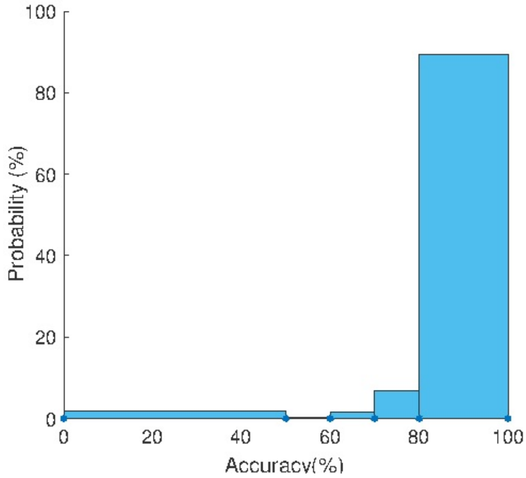

Fig. 18. The histogram of the accuracy on the test section of G210

Highway 3 – G75 National Highway

The acoustic test is also performed on a section of G75 National Highway, which is 9.8 km long. Since this is a section of a national highway and there is not much traffic, the travel speed during the field test is almost constant. Similarly, the MTD is calculated by the proposed algorithm from the tire/road noise data and compared to that from the laser profiler, which is considered as the reference. From Fig. 19, it is found that the MTD difference between the two methods has lower standard deviation due to the stable travel speed.

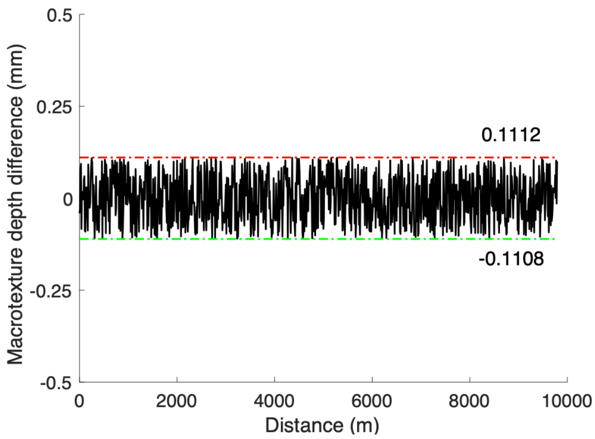

Fig. 19. The difference of the MTD results between the acoustic method and laser profiler – G75

The accuracy of the acoustic MTD is also calculated by equation (6), and its distribution is shown in Fig. 20. The accumulative probability of the accuracy above 80% is 0.881. Similarly, as the test section of G210, the accuracy from the test section of G75 is also lower than that from Chongqing Inner Ring Express Way due to smaller training database.

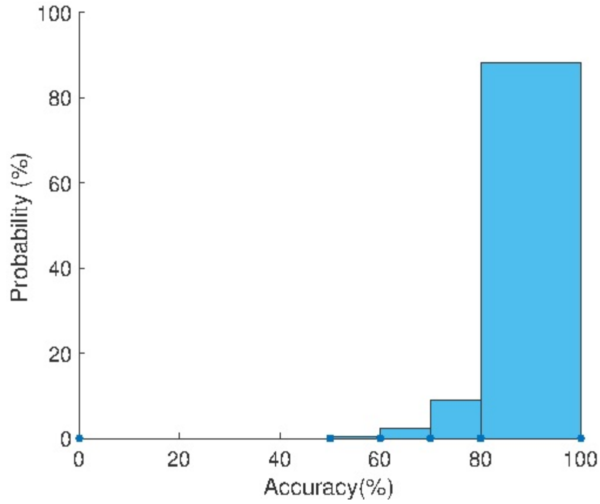

Fig. 20. The histogram of the accuracy on the test section of G75

5. CONCLUSIONS AND FUTURE WORK

In this paper, an automatic algorithm is developed, validated, and applied in engineering work to calculate the MTD from the tire/road noise data collected at traffic speed. The original data is collected by the two directional microphones mounted underneath a test vehicle, one is on the passenger's side, and the other is on the driver's side. The field tests are performed on multiple urban roads and highways. Several conclusions can be drawn from the field test results.

1. The proposed algorithm is automatic, accurate and efficient to calculate the MTD of the pavement from the tire/road noise data collected at traffic speed.
2. The MTD results from the tire/road noise data are validated by cross checking the results from the sand-patch method on urban roads and the laser profiler on highways.
3. The speed effect on the SPL of the tire/road noise data during driving is effectively eliminated by PCA and the empirical equation described in this paper, on both urban roads and highway.
4. The repeatability of the MTD results through the tire/road noise data is also verified.
5. A training database is necessary to the proposed algorithm, and the size of the database also has significant influences on the accuracy of the acoustic MTD – the bigger the training database is, the more accurate the result will be.

The future research work is in two respects. First, the algorithm without creating a training database will be developed, such that the directional microphone can work independently to measure the MTD. Second, the acoustic sensor can be used for detecting the surface distresses and evaluating the riding comfortability of pavement surfaces, through the tire/road noise data. To accomplish the missions, further analysis of the tire/road noise data is needed. For instance, to detect the surface distresses, an automatic algorithm is to be developed, such as energy spectrum method. On the other hand, to evaluate the riding comfortability of the pavement surface, the other sensors have to be involved in the field tests, such as the dynamic tire pressure sensor, which is used for evaluating the surface roughness.

The future research work will significantly improve the pavement surface condition assessment technology.

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