Detection of Tire Types Using Tire Noise from Passing Vehicles

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Abstract— **Winter tire is important and helpful for road users or automobile drivers to obviate serious traffic accidents. They also help road administrators to prevent many slip traffic accidents by such vehicles especially from the expressways, particularly in a snowy area. This paper is concerned with the reliable detection of tire types using only tire noise from passing vehicles. In practice, the tire noise emitted from moving vehicles varies momentarily depending on several mechanisms, such as road surface properties, tire tread patterns, and so on. As a result, it may be possible to passively and easily detect the tire type. For example, the least signal differences between winter and summer tires. To detect tire noise from running vehicles at 30, 40, 50 and 60 km/h on average, only when road surfaces were dry or wet state, we used a commercially available microphone as an acoustic sensor, which enabled us to easily reduce cost and size in a practical system for detecting tire types. We propose simple detection methods based on the cumulative distribution function of the power spectrum and the autocorrelation function of the tire noise signals to extract the signal features in the frequency domain and the time domain, respectively. Experimental results obtained from recorded signals in the snowy area demonstrated that the proposed method achieves high classification accuracy.**

Introduction

The discrimination of winter and summer tires is an important process for efficient road management. Particularly, in snowy areas, prior information about winter tires can help road users or automobile drivers to obviate serious traffic accidents and also help road administrators to prevent many slip traffic accidents by such vehicles, especially on the expressways. In practice, the types of tires have been monitored by visual inspection with human eyes. In a previous report [1], our research on the detection of winter and summer tires using road surface vibration caused by passing vehicles has been ongoing at Tokai-Hokuriku, Gifu-Kagamigahara IC. The signals from road surface vibration were recorded with a commercially available accelerometer as a sensor. We proposed a classification method based on the principal component analysis using only the road surface vibration from passing vehicles. A few signal features that are readily extracted in the frequency domain of the signals could be classified with a high-classification accuracy rate. However, all classifications of concern to us, suffered from systematic problems of high cost, complex method. To detect types of tires using a cheap and simple method, it therefore is necessary to continuously develop practical classification methods with the goal of remotely predicting types of tires as accurately as possible. In this paper, we recorded tire/road noise signals emitted from moving vehicles using a commercially available microphone as an acoustic sensor. To study the distribution of the power spectrum, we recorded a number of the tire noises at Gifu-Kagamigahara IC. The noise signals are processed through a high-pass filter with a low cut-off frequency of 100 Hz to remove wind noise and unnecessary signals [2], and then are converted into the power spectrum by Fast Fourier Transform (FFT). After that, we determine the frequency at which the power spectrum reaches its maximum. Additionally, our classifying approach relies on a slope value of the cumulative distribution curve of the power spectrum and signal features based on the autocorrelation function of the tire noises. The effectiveness of the feature indicators proposed is verified by noise data samples obtained at Gifu-Kagamigahara IC and are compared with visual inspections of actual road surface conditions.

Experimental Conditions

Tire noise signals from moving vehicles were recorded on the side of a two-lane road near Gifu-Kagamigahara IC, where the experimental field of the Central Nippon Expressway Company Limited Nagoya Branch is located. The road is paved with fine graded asphalt, as already shown in our previous article [1]. The hardware system of measurement is shown in Fig. 1. Tire/road noises emitted from moving vehicles on the road by various mechanisms, such as air pumping, were recorded with a microphone built-in a data recorder, which was set at a 1.5 m height from the road surface level to avoid the noise effect from the studs. It was directed towards passing vehicles at 45^{o} with respect to the road surface. The noise signals were recorded with a PCM recorder, which was set up on the side walk. Vehicles passed by at around 30, 40, 50 and 60 km/h on average. The recorder digitally sampled sound signals at a frequency of 44.10 kHz with 16 bit quantization. To discriminate between signal features, we used winter and summer tires of the same brand and size, as shown in Table 1. Generally, the structure of the winter tire and its tread pattern are designed to bite snow and keep grip on the winter road. The winter tires contain millions of uniformly distributed microscopic pores constantly being exposed as the tread surface wears and grips like suction cups.

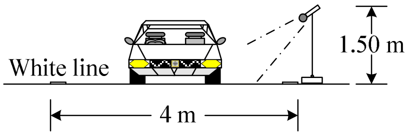

Fig. 1 Experimental setup for detecting tire noise from vehicles.

TABLE I
WINTER AND SUMMER TIRES USED FOR EXPERIMENTS
(SMALL CHARACTER AS IN FIGURE)

	Winter tire	Summer tire
Type		
Maker	GOOD YEAR (ICE NAVI ZEA)	GOOD YEAR (GT3)
Size	185/65R15	
Structure	Block structure (56 blocks)	Rib structure
Rubber	Soft	Hard

In addition, thousands of miniature biting edges provide a better adhesive to the surface increasing traction. To reduce power unit noise such as engine noise, we used two hybrid cars [Toyota Prius]: one mounted with winter tires and the other summer tires.

CLASSIFICATION METHODS

A. Peak Frequencies

Analog sound signals recorded continuously for more than one hour are extracted manually. The individual waveforms that last for 1.5 s are prepared for time history records observed using a free sound engine program. Noise signals fed to a high-pass filter with a low cut-off frequency of 100 Hz to remove unnecessary signals such as wind noises and complex vibrations caused by a collision between tread blocks and the road, the sidewall acts as a spring and tread band acts as a mass [2]. Then, FFT is applied to obtain a power spectrum $p(f)$, (f is frequency) for tire noise signal from each vehicle.

We usually observe that timbre of tire noise emitted from winter and summer tires are almost equal. However, winter and summer tires have differences in structure such as tread pattern, rubber block and groove. We first focus our attention on the frequency at which each noise signal attains a peak in its power spectrum. All spectra are obtained by executing FFT on the signal waveform that last for 1.5 s. Figure 2 shows the peak frequencies of about 60 vehicles that passed by the observation point when the road surface was dry. Two different types of the tires are the targets of classification. Actually, the frequency varies from waveform to waveform, probably because vehicle speeds were changed. Unfortunately, it seems difficult to obtain information about the types of tires from randomly scattered frequencies. The peak frequencies

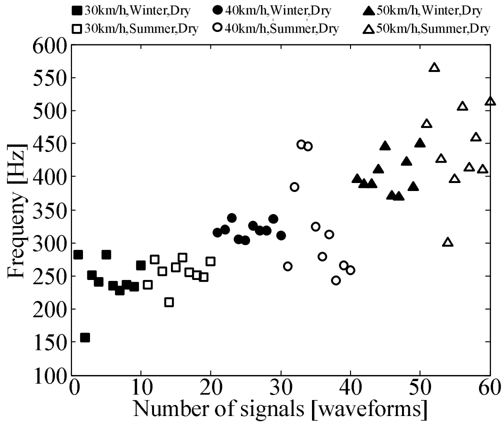

Fig. 2 Peak frequencies for all waveforms in the power spectra of tire noises.

are within the range of 155 to 450 Hz for the winter tire and indicate less scattering results than those for the summer tire. The magnitudes for the summer tire become extremely scattered with increasing vehicle speeds because of the structures of their patterns or rubber blocks. Apparently, almost the same patterns are obtained for the two types of tire. From these results in peak frequency, we cannot discriminate the winter and summer tires offhand using only the peak frequencies of tire noise. However, our main aim on the discrimination of winter and summer tires using noise data from passing vehicles is to extract the effective signal features based on signal processing techniques.

B. Cumulative Distribution Analysis

Since the peak frequencies depend greatly on vehicle speeds, it is not sufficiently stable for classifying the types of tire on the basis of only the magnitude of the spectrum. Prior to taking the next step, [3] we introduce the following function that can be defined as

$$\overline{P}(f) = \left(\int_{f_l}^{f} p(f')df' \right) \Bigg/ \left(\int_{f_l}^{f_h} p(f')df' \right) \qquad (1)$$

where f_l = 100 Hz is the low-cut frequency. Generally, the tire noise is generated as a result of complex interaction between the tread block of a rolling tire and the texture of the road's surface layer. Its spectrum frequency range is most dominant between 100-600 Hz [4, 5]. Then, the upper limit of integration with respect to frequency is determined to be f_h = 600 Hz. Hereafter, we refer to $\overline{P}(f)$ as the cumulative distribution of power spectrum. For example, the cumulative distribution curves recorded for 1.5 s at Gifu-Kagamigahara IC are shown in Fig. 3.

In all curves of the winter tires, the first increase in magnitude is relatively slow in frequency, and then the rate of increase becomes abrupt near 220 Hz, 280 Hz and 340 Hz according to vehicle speeds, respectively. After that, they slow down again near 400 or 500 Hz. Such monotonic

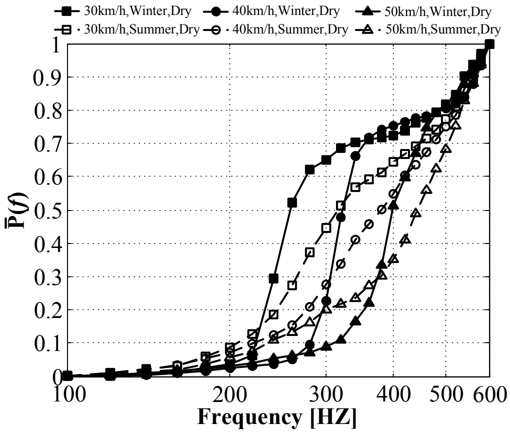

Fig. 3 Typical cumulative curves of the power spectrum of tire noise from passing vehicles for 1.5 s.

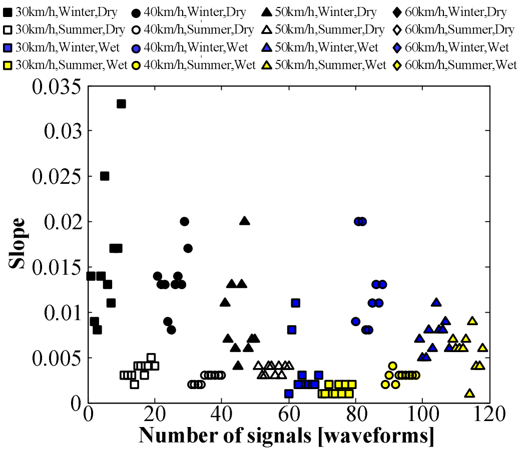

Fig. 4 Slope magnitudes of cumulative curves of power spectrum for passing vehicles in 1.5 s.

increment tendencies of $\overline{P}(f)$ resemble a Gaussian distribution function. The difference being that, the rates of increase for summer tires are all lower than those for the winter tires between 200-500 Hz. This means that the winter tires predominate over the summer tires in a higher slope.

From the cumulative distribution curves in Fig. 3, we propose a classification indicator in accordance with the fact that easy classification of the types of tire is feasible when there are difference of slope between the winter and summer tires. This indicator is the slope of $\overline{P}(f)$ at frequency 200-500 Hz. Hereafter, we refer to it as the slope.

To evaluate the effectiveness of the proposed classification method, we performed signal processing using the tire noise recorded at Gifu-Kagamigahara IC. Vehicles passed by at around 30, 40 and 50 km/h on average when the road surface was dry and wet. Figure 4 show the time history of the slope for two types of tires at vehicle speeds. It demonstrates that the slope exhibits differences in magnitudes for two types of tires, although the magnitude of the slope itself changes somewhat from location to location. For example, the magnitude remains within the range of 0.0025 to 0.005 for the

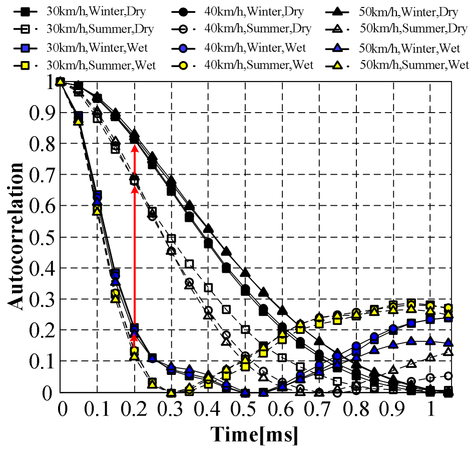

Fig. 5 Typical autocorrelation curves of the power spectrum of tire noises from passing vehicles for 1.5 s.

summer tire and within the range of 0.005 to 0.033 for the winter tire when the road surface is dry. Obviously, the magnitudes of the winter tire obtained indicate more scattering results than those of the summer tire. Even for wet and dry surfaces, the winter tires take the slope magnitudes of 0.013 and 0.008 on average, respectively. Likewise, both surfaces take the same magnitude of 0.003 for the summer tires. It seems to be feasible to discriminate the winter and summer tires using the slope magnitude at least for dry conditions. For wet condition, it appears difficult to classify the types of tires from only the slope magnitude.

C. Autocorrelation analysis

In general, a tire noise is a type of stochastic signal and can be considered to be a stationary signal or quasi-stationary process if the running conditions of a vehicle do not change often. The autocorrelation function (ACF) for a stationary signal is a measure of the time-related properties in the data that is delayed by a fixed time. ACF tells us more about the signal, such as whether significant correlation between the time series exists and whether the similarly tendency of the same type remains from one observation to another. We focus here on ACF that is readily calculated from the power spectrum using FFT to extract signal features in the recorded tire noise.

Autocorrelation curves of the power spectrum of tire noises from passing vehicles for 1.5 s when the road surface was dry and wet states are shown in Fig. 5. We restrict our attention to the first main lobe in each curve because important information about signal similarities generally appears here. Obviously, all curves decrease in magnitudes relatively abruptly with time lags. However, both road surfaces state a great difference in their shapes: the magnitude for the summer tire is entirely lower than those for the winter tire. This result is somewhat expected from the fact that the magnitude of the high-frequency components in the tire noise signal emitted from the summer tire of running vehicles is dominant in comparison with the magnitudes in the winter tire. Since the high frequencies are equivalent in short time periods, the correlation in the summer tire becomes as small as the time

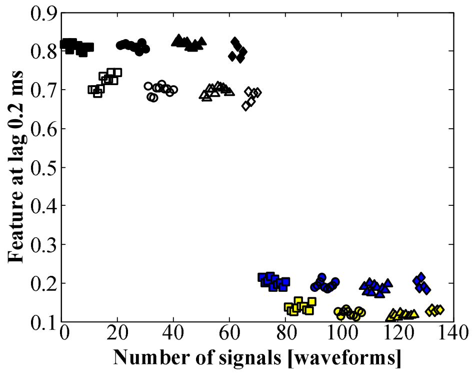

Fig. 6 Time lag of autocorrelation curves of power spectrum for passing vehicles in 1.5 s. (We use the same symbols in Fig. 4.)

lag is increased. On the other hand, low-frequency components in the tire noise emitted from the winter tire of running vehicles predominate a relatively strong correlation should remain at even short time lags.

We then propose a feature indicator that was used to detect road surface states from tire noise and was defined in our previous report [6]. This indicator is the magnitude of the autocorrelation at 0.2 ms or "feature at lag 0.2 ms", which its threshold value is $A_s = 0.41$ for classifying the wet and the dry states. In Fig. 5, the feature at lag 0.2 ms is determined to be $A_h = 0.76$ and $A_l = 0.16$ for classifying the winter and summer tires in dry and wet states, respectively.

D. One –hour classification

To clarify whether the proposed features of the ACFs can actually discriminate the winter and summer tires, we first examine typical one-hour tire noise data from recorded signals at Gifu-Kagamigahara IC. Figure 6 shows the time history of the feature at lag 0.2 ms. Interestingly, even if the vehicle speeds are changed, all sample data indicate relatively less scattered results than the data obtained using the slope magnitude. When the road surface was wet, the results of the two types of tires obtained using the feature at lag 0.2 ms are more be close at low vehicle speed. However, it seems easy to discriminate both the tires using the feature at lag 0.2 ms when the vehicle speeds are increased. Table 2 shows the experimental results based on the feature at lag 0.2 ms using a simple method, as shown in Fig. 7.

CONCLUTIONS

We presented a simple method based on autocorrelation function for classifying winter and summer tires using only tire/road noises emitted from moving vehicles. A feature indicator was proposed: the magnitude of the autocorrelation at 0.2 ms. From experimental results obtained in snowy area, the classification ability by using a feature of ACF shows high precision to be almost the same accuracy rate stated in our previous report [1]. This result implies that it is essential for reliable discrimination and accurate classification of the two types of tire. The present study leads us to believe that the feature offers great potential for the detection of winter and summer tires.

TABLE II

ONE-HOUR EXPERIMENTAL RESULTS OF DETECTING THE WINTER AND SUMMER TIRES USING 1.5 S SOUND SIGNALS

Method	Threshold values				Accuracy [%]
	Road surface states		Tire types		
			Winter	Summer	
Feature at lag 0.2 ms	Dry	>0.41	>0.76	<0.76	100
	Wet	<0.41	>0.16	<0.16	

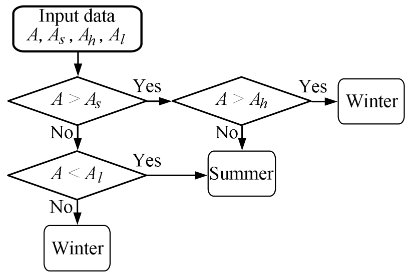

Fig. 7 Flowchart for a simple method of classifying the winter and summer tires using feature at lag 0.2 ms. A is feature at lag 0.2 ms. A_s is threshold value for classification of road surface states. A_h and A_l are thereshold values for classifying the types of tire.

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