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Identification of winter tires using vibration signals generated on the road surface

Tetsuya Tanizaki [a,*], Koji Ueda [b], Toshihiko Murabe [c], Hideyuki Nomura [d], Tomoo Kamakura [d]

[a] Nagoya Electric Works Co., LTD., Aichi, Japan
[b] Daido University, Aichi, Japan
[c] Central Nippon Highway Engineering Nagoya Co., LTD., Aichi, Japan
[d] The University of Electro-Communications, Tokyo, Japan

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A B S T R A C T

During the winter, traffic regulations state that automobile drivers must use winter tires on unsafe roads such as snowy expressways. The present report is concerned with the development of an automatic tire identification system that can discriminate winter tires from summer tires with high accuracy. The system detects the impact vibration signal that is specifically generated by winter tires when tread blocks with wide grooves strike the road surface during rolling. The signal is picked up by a commercially available vibration sensor. If the signal contains specified impact frequency components, the tire is judged to be a winter tire. Compared with the previous identification system, which used airborne tire/road noise, the proposed system has two advantages. First, it is unaffected by meteorological factors such as wind noise. Second, the proposed system performs well even when the target vehicle is traveling at low speed. We evaluate the performance of the system outdoors using a number of vehicles with various tires and demonstrate an overall improvement in identification accuracy for vehicles traveling at low or moderate speeds.

1. Introduction

Road administrators support and manage expressways with the goal of improving the effectiveness and efficiency of a variety of safety and security aspects. During winter, traffic regulations state that drivers must use winter tires, which improve safety and traffic flow on unsafe roads such as snowy expressways. However, not all automobiles are equipped with winter tires, so administrators visually inspect the suitability of the tires of each automobile considering the current state of the road surface [1]. This occasionally results in heavy traffic jams on access roads to expressways. In the worst case, unsuitable tires are overlooked due to severe work environments and physical fatigue due to bad weather conditions. An automatic tire examination system with high discrimination accuracy is, therefore, highly desirable.

Considerable attention has been given to numerical models and computer simulations of tire/road interface noise generation mechanisms to facilitate the design of quieter cars. For example, Biermann et al. developed a computational model that consists of several analyses, including a nonlinear tire rolling process [2]. They validated the accuracy of the computational model through comparison with data for a tire rolling on a drum. Other aspects of theoretical prediction were treated by Kim et al. [3]. In order to estimate the noise produced by the air displacement around a rolling tire, they used a hybrid technique that combines a computational fluid dynamics technique with the Kirchhoff integral method. Interestingly, they pointed out that the nonlinearity of the air-pumping noise generation mechanism affects the character of the frequency spectrum as well as the directivity of the patterns. Additionally, several investigations have been made into tire/road noises and vibration signals on roads in order to identify the type of automobile. Wu et al. investigated the recognition of sound signatures by principal component analysis [4]. Using the eigenface method, which is used in the vision community to recognize human faces, they attempted to characterize sound noise patterns and classified running automobiles as sedans, heavy trucks, or motorcycles. Krylov et al. presented analytical techniques for ground vibration spectra generated by heavy military vehicles, such as tanks and armed personnel carriers [5]. They considered a simple quarter-vehicle model in identifying the dynamic forces from ground vibrations, which generally behaved as Rayleigh surface waves. To the best of our knowledge, however, there have

* Corresponding author. Present address: 29-1, Mentoku, Shinoda, Ama-shi, Aichi 490-1294, Japan. Tel.: +81 524433981.
E-mail address: tani@nagoya-denki.co.jp (T. Tanizaki).

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been few studies that describe the discrimination and examination of summer and winter tires theoretically and/or experimentally. Seki et al. proposed a wavelet signal analysis method to discriminate summer and studless tires [6]. Although their method is promising, it has not been experimentally validated in an outdoor setting, in which operational efficiency is significantly affected by various factors, such as engine noise and meteorological conditions. There is also a technical report on software development for the discrimination of tire information of tread patterns using an image processing method [7]. Unfortunately, there are still problems that must be overcome for the development of such systems to progress. For example, muddy substances stuck on tires can reduce the discrimination rate considerably.

Under these circumstances, we previously proposed an automatic tire identification system using airborne sound signals that are generated at the interface between the tires and the road surface when a vehicle is moving. This system focuses specifically on the tread impact sound generated when the tire grooves strike the road surface. Generally, the impact sound of winter tires is of relatively high volume. The results of several field tests confirmed that the previously proposed system works well, with a 75% discrimination accuracy. However, the system has two primary drawbacks. First, the performance is affected by various sources of background noise, such as engine noise, wind, and rain. Second, the slower the target vehicle is moving, the smaller the tire/road noise signal that is generated. Hence, extracting information from the received signal with a reliable signal-to-noise ratio (SNR) becomes difficult.

In order to overcome such challenges, in the present paper, we use vibration signals from the road surface that are generated simultaneously with airborne sounds when the tread patterns of the tires strike the road surface through rolling. Using such vibration signals, the proposed discrimination system is expected to be robust and unaffected by meteorological factors such as wind noise.

The remainder of the present study is organized as follows. First, the main differences between summer and winter tires are summarized from a structural viewpoint and the general mechanisms of tire/road airborne sound generation are considered. In addition, a simple and comprehensible discrimination method is proposed that uses the tread impact signal. Typical measured spectral patterns of tire/road noise for summer and winter tires are then presented for comparison. Next, several problems involved in discriminating tire types are discussed. Furthermore, the report elucidates significant differences in performance on an actual access road to an expressway through comparison with the airborne sound discrimination method.

2. Principle of discrimination

In this section, the previously proposed discrimination principle using airborne tire/road noise is described [8]. In addition, some remaining problems with this system are discussed. Since most trucks and buses are equipped with nonskid tires during the winter, the target automobiles used in the present investigation are limited to compact cars.

2.1. Tread pattern and tire/road noise

Fig. 1 shows the structural differences between summer and winter tires. Summer tires usually have fine grooves for dry and wet roads. This tread structure is referred to as the rib pattern and is based on circumferential grooves running around the tire. In contrast, winter tires generally have very open and aggressive tread patterns with wide grooves for winter weather conditions. This tread pattern is referred to as the block pattern and has grooves running in both circumferential and perpendicular directions, thus forming separate tread blocks. Road traffic noise produced by the flow of cars can be classified into two categories, car noise and tire/road noise. The former comes from the engine and turbulent wind flow, and the latter is emitted from the interaction of the tires and the road as the tires roll over the road surface. When a car is traveling at more than 40 km/h, the tire/road noise dominates other noise sources, such as power unit noise, in the total road traffic noise [9]. In general, tire/road noise consists of the following three generation mechanisms [10,11]: pipe resonance sound, tread impact sound, and other sources.

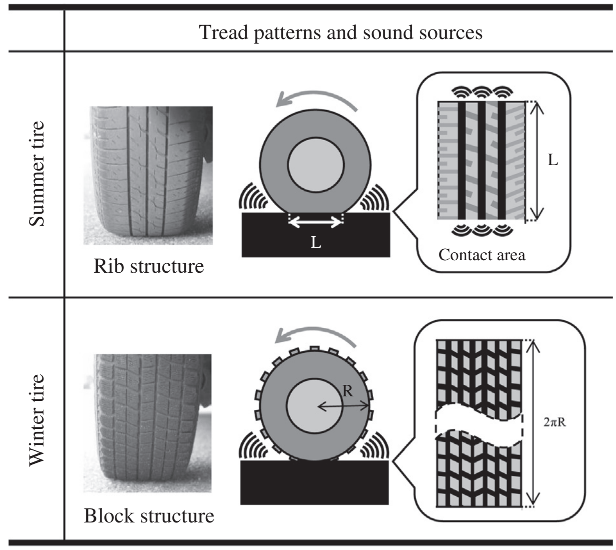

Fig. 1. Structural differences between summer and winter tires.

2.1.1. Pipe resonance sound

The source of this sound originates from the rib pattern of the tire. When the pattern is in contact with the road surface, sound is generated by the pipe resonance effect. The resonant frequency f (Hz) of which is given by

$$f = \frac{c}{2(L + 2\Delta L)}, \tag{1}$$

where c (m/s) is the speed of sound, L (m) is the groove length formed in the tire footprint, and ΔL (m) is the open-end correction. Note that the frequency basically depends on the groove length. Moreover, tire/road noise due to the pipe resonance mechanism generally has a peak frequency of approximately 1 kHz, being almost independent of the speed of the vehicle.

2.1.2. Tread impact sound

When tire tread blocks with wide grooves strike the road surface, an impact vibration propagates along the sidewall of the tire and is then emitted as an airborne sound. Normally, this is not the prominent sound generated by a pure rib pattern tire. The frequency of this sound f (Hz) is as follows [5]:

$$f = \frac{v}{a}, \tag{2}$$

where v (m/s) is the speed of the car, and a (m) is the block pitch around the tire. Using the tire radius R (m) and the number of blocks n (pieces), the pitch a is replaced by $a = 2\pi R/n$. The speed v is expressed in km/h by the variable V (km/h). Then, Eq. (2) can be rewritten as follows:

$$f = \frac{V\ n}{3.6 \times 2\pi R} \tag{3}$$