Available online at www.sciencedirect.com

SCIENCE DIRECT®

Sensors and Actuators A 126 (2006) 277–286

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Passive wireless strain monitoring of actual tire using capacitance–resistance change and multiple spectral features

Ryosuke Matsuzaki *, Akira Todoroki

Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, 2-12-1-I1-58 O-okayama, Meguro-ku, Tokyo 152-8552, Japan

Received 29 June 2005; accepted 18 October 2005
Available online 1 December 2005

Abstract

To improve reliability of automobile tires and anti-lock braking system (ABS), intelligent tires that measure strain of tires are increasingly demanded. The high stiffness of an embedded sensor like a strain gage, however, causes debonding of a sensor from tire rubber. In a previous study, the authors proposed a wireless strain monitoring method that adopts a rectangular tire specimen as a sensor with a tuning circuit. Compared to the tire specimen, an actual tire has a large hysteresis between the measured strain of the inner tire surface and the capacitance in a tire belt. The large hysteresis in the actual tire makes it difficult to measure a tire strain precisely. In the present study, to measure the strain precisely, multiple power spectrum features of the sensor output are used to estimate the strain with a statistical method. As the spectral features, a peak power spectrum and a sharpness of the resonance in addition to a tuning frequency are used for the estimating. As a result the experiments demonstrate that the method is effective for the passive wireless strain monitoring of actual radial tires.

Keywords: Wireless sensor; Strain monitoring; Tire; Tuning circuit; Power spectrum; Quality factor

1. Introduction

As a result of the recall of Firestone Co. tires in 2000, U.S. Transportation Recall Enhancement, Accountability and Documentation (TREAD) legislation has mandated the installation of Tire Pressure Monitoring Systems (TPMSs) [1–10]. A simple method for TPMS is based on indirect measurement using wheel speed sensors and electronic control unit (ECU) of anti-lock braking system (ABS) [1,2]. The indirect measurement, however, depends on the type of the tire and needs calibration, which causes low reliability. Direct measurement of TPMS has been developed using clamp-on-rim sensors by SmarTire System Inc. in Canada or valve-attached sensors by Schrader Electronics Ltd. in UK. Although these methods have high accuracy and reliability for the pressure monitoring, they need battery to activate the sensors. For a battery-less TPMS, Snyder [3] proposed piezoelectric reed included in a tire sensor unit. The wheel movements cause the piezoelectric reed to bend and generate electricity.

Advanced tire sensor system is under developing as “intelligent tire” which is equipped with a sensor to monitor strain, air pressure, temperature, etc., of a tire to improve automobile safely [11–23]. In Europe, a EU-project named APOLLO (2002–2005) [4] was started to develop intelligent tires. A tire strain monitoring system that has sensors transmitting the tire strain to ABS or electronic stabilization program (ESP) systems is demanded to enhance security of tires. Contrary to the indirect measurement of friction between a tire and a load surface based on the wheel slip [24,25], the direct monitoring of tire strain allows precise measurement of friction, and hence it increases the efficiency of ABS. As a direct method for tire strain monitoring, Pohl et al. [11] proposed surface acoustic wave sensors, and Palmer et al. [12] proposed optical fiber sensors to monitor strain of the tire. Intelligent tires also offer beneficial effects for the other advanced active safely systems such as traction control systems (TCSs) and vehicle stability assist (VSA), early detection of tire separation [13] and tire-burst prevention [14].

The key technology for the intelligent tire sensor is direct measurement, wireless data transmission, battery-less power supply and low stiffness sensor. The stiffness of the integrated or attached sensors is usually much higher than

* Corresponding author. Tel.: +81 3 5734 3178; fax: +81 3 5734 3178.
E-mail address: rmatsuza@ginza.mes.titech.ac.jp (R. Matsuzaki).

0924-4247/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2005.10.029

that of tire rubber. The large difference in stiffness may disturb deformation and stress of tires; it may also cause the debonding of sensors and rubber over a long period use. The attached sensors are also easily damaged by fatigue of 10^6 cycles during tire lifetime or abrupt large deformation. A wireless monitoring is indispensable because a tire usually rotates.

In the previous study [15–20], we have demonstrated dynamic strain monitoring of tires using a change in capacitance of a tire itself. The proposed sensor module using tuning circuit is passive type and does not need any power supply [20]. In this method, the capacitance change between two adjacent steel wires in an actual tire belt is adopted as a strain sensor. Since the tire itself performs as a sensor, the sensor does not cause the debonding from the tire surface. The proposed system was applied to a tire specimen. The specimen is a rectangle belt part cut from a commercially available radial tire in size of 270 mm in length and 20 mm in width. The deformation of the steel wire in the specimen is limited in the in-plane direction. As a result, the output of the tuning frequency changes linearly to the applied tensile strain to the tire specimen. This linear change in the tuning frequency enables us to measure the applied strain precisely.

The structure of an actual tire is, however, three-dimensionally layered with a carcass, a belt and a tread. Moreover, in the actual tire, a compressive load is applied to a tire due to contacting a road surface. It causes a bending load to an actual tire surface unlike the tensile test using a tire specimen. Compared to the tire specimen, the actual tire has a large hysteresis between a strain of the inner tire surface measured by means of an attached strain gage and the capacitance in the tire belt. The hysteresis is caused by following reasons: the deformation paths in loading and unloading are different from each other due to the complexity of the actual tire structure; the viscoelastic belt in the actual tire deforms delaying against the deformation of an elastic strain gage, while the deformation of the thin tire specimen does not delay because it behaves like an elastic material due to the adhesion of a strain gage. The large hysteresis in the actual tire makes it difficult to measure a tire strain precisely because the each capacitance value corresponds to two different strain values.

Since the tire rubber is not pure dielectric material and acts also as an electrical resistor [21], it can be assumed as a capacitance–resistance parallel model. To measure a tire strain precisely, we utilize multiple kinds of variables: the electric resistance and the capacitance of an actual tire. The values of the multiple variables enable us to know whether the condition is loading or unloading, and it is possible to measure the strain precisely.

In the present paper, the effects of the deformation of the tire belt on the electric resistance and the capacitance are experimentally investigated. The tuning circuit is employed here to transmit the electric resistance and the capacitance data wirelessly to an external receiver. To measure the tire strain precisely and wirelessly, multiple spectral features of the sensor output instead of the electric resistance and the capacitance are used for estimating the strain with a statistical method. As the spectral features, a peak power spectrum and a sharpness of the resonance in addition to the tuning frequency are used for the estimating. The tuning frequency and the peak power spectrum reflect the capacitance and the electric resistance, respectively, the sharpness of the resonance reflects both the electric resistance and the capacitance. Although the resonance point features like the tuning frequency and the peak power spectrum are easily affected by an environmental noise, the sharpness of the resonance is not affected because it is measured using whole power spectrum shape. Using these multiple spectral features and a statistical method, the proposed sensor system is applied to a commercially available tire, and the applicability of the proposed sensor is examined.

2. Wireless strain monitoring system

2.1. Structure of tire belt

The passive wireless strain measurement system employs a tire itself as a sensor. Fig. 1 shows a typical radial tire's inner structure. Carcass fibers are perpendicular to the beads wire on radial tires as shown in Fig. 1. The carcass's function is to maintain the shape of the tire. Usually the carcass fiber is an organic fiber such as polyester. On the carcass fiber layer, steel wire layers are mounted similarly to cross-ply laminates of composite materials. These fibers are coated with rubber, and the tread rubber layer is mounted on the steel wire layers, as shown in Fig. 1. Tread deformation is transferred to the steel wire layers. This transferral implies that measurement of the steel wire layer strain indicates the tire tread deformation.

In the steel wire layer, the steel wire is a straight electrically conductive material; the rubber is a dielectric and electrically resistive material. Fig. 2 shows a couple of adjacent steel wires. In this figure, the steel wires are placed face-to-face; the dielectric rubber is inserted between the two steel wires. Electric voltage is charged between the steel wires. This structure thereby represents a parallel circuit of an electric resistor and a condenser. The adjacent steel wires are electrodes of these electric resistor and the condenser.

Let us consider the adjacent steel wires are given electric charges per unit length, q, $-q$, respectively. From Gauss' law, the electric field on the line through centers of the adjacent steel

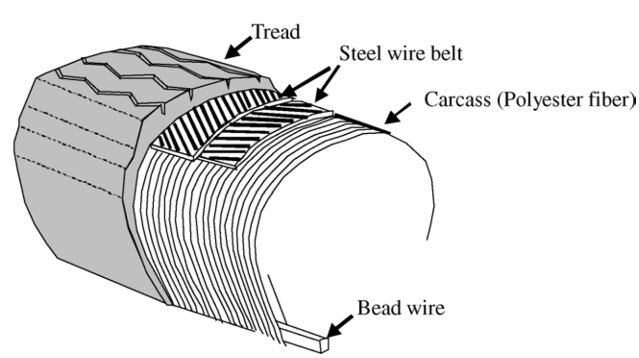

Fig. 1. Inner structure of a steel wire-reinforced radial tire.