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Wireless strain monitoring using electrical capacitance change of tire: part I—with oscillating circuit

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Abstract
Strain monitoring of tires of automobiles in service is quite effective to improve the reliability of tires and design tools. Since conventional strain gages have high stiffness and require lead wires, the conventional strain gages are cumbersome for the strain measurement of tires. Sensors of micro-electro-mechanical systems are also usually of high stiffness themselves, and those are not applied to tires. The background requires a new low cost wireless sensor for tires. In the present study, a new strain measurement system utilizing the electric capacitance change of steel wire reinforced tires is proposed and experimentally investigated. A small oscillating circuit is embedded in the tire; deformation of the tire induces a capacitance change of the tire comprising steel wire and rubber; the change of the capacitance makes a change in oscillating frequency of the oscillating circuit. Measurement of the frequency of the oscillating circuit enables us to measure the strain of the tire wirelessly. A rectangular specimen cut from a commercially available tire is adopted as a specimen. A tension test is performed and the frequency of the oscillating circuit is measured during the test. As a result, the method is experimentally proved to be effective for the wireless strain monitoring of tires.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, the safety of automobiles is increasingly being demanded. To prevent the bursting of tires, smart tires are currently under development [1–7]. Most smart tires have integrated or attached sensors to measure the deformation or internal pressure of tires during a long period of service. For example, Pohl *et al* [2] have revealed a smart tire that has an embedded pin connected to a surface acoustic wave (SAW) sensor to measure the deformation of the rubber of the tire tread. The embedded sensor enables highly precise measurement of road surface friction, and the precise friction make a more efficient anti-lock braking system (ABS). This information also enables the early detection of separation of the tire tread that is a significant threat to automobile safety, as is well known [7].

To install the smart tires, there are several required specifications for the sensors for tires. First, wireless monitoring is indispensable because a tire usually rotates and it is difficult to use wired sensors. Second, since the rubber in the tires has low stiffness, embedding or attaching the sensors easily disturbs the stress or deformation of the tires: sensors should not cause such disturbance. Third, the large difference in stiffness of the sensors from the rubber may cause debonding between the sensors and the rubber after a long period of running time: the stiffness difference should be small. Fourth, since the tire itself is not an expensive product, the sensor must be low price.

Most of the sensors employed for smart tires sacrifice one or two of these required specifications. For example, the

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SAW sensors are usually made from piezoelectric ceramics, and the sensor requires a special tool like a pin to reduce the deformation of tires and to enhance the force owing to deformation. This implies that the implementation of the SAW sensors causes a disturbance of the tire deformation or stress.

Micro-electro-mechanical systems (MEMS) for wireless strain measurement have been embedded for smart composite structures [8, 9]. The wireless MEMS includes a sensor, a signal processing unit and an antenna. The wireless MEMS strain sensor is an attractive product, but to embed the MEMS sensor into a tire is not recommended. This is because of the large difference of stiffness between the sensor and the rubber tire. The large difference in the stiffness may cause a disturbance of the deformation and stress; it also may cause debonding between the sensors and the rubber over a long period of service.

Conventional strain gages also have similar problems to that of the wireless MEMS. A small wireless data transfer tip can be applied to the conventional strain gages to transfer the data wirelessly. Even for the strain gage, however, the large stiffness difference and weak bonding between the strain gage and the rubber may cause debonding over a long period of service. A novel sensor, therefore, is demanded for the true 'smart tire'.

Tires comprise rubber with carbon black, steel wire and organic fiber. Under the tread rubber, steel wire belts are inserted. As is well known, the steel wire itself is an electrically conductive material and the rubber is a dielectric material. This structure of the tire is quite similar to a well known electrical condenser comprising a couple of electrodes and inserted dielectric material: the tire deformation causes changes of the spacing between the steel wires, and this change implies a change of the capacitance of that part of the tire. Measurement of the capacitance change of the tire enables us to know the strain or deformation of the tire without embedding or attaching additional sensors.

In the present study, therefore, a novel strain measurement method is proposed. The method measures the change of electrical capacitance during deformation of a tire wirelessly. The method employs an oscillator circuit to transfer the capacitance change data wirelessly. The steel wire usually used for tires is adopted as an electrode of an electrical condenser. The condenser made from the tire is connected to the oscillator circuit as the condenser of an inductance–capacitance (LC) oscillator circuit. The tire deformation causes the electrical capacitance change of the circuit, and that leads to the change of oscillating frequency. Measurement of the change of frequency of the oscillator circuit enables us to know the strain of the deformed tire wirelessly. The present paper proposes this novel system and shows the result of a basic demonstration using a small simple specimen. The system is applied to a rectangular specimen made from a commercially available steel radial tire, and static tension tests are performed here to confirm the system. The novel wireless strain measurement system adopts the tire itself as a sensor. The system, therefore, does not cause any of the problems mentioned earlier.

2. Theory and system

A novel wireless strain measurement system in the present study employs the tire itself as a sensor. The internal structure

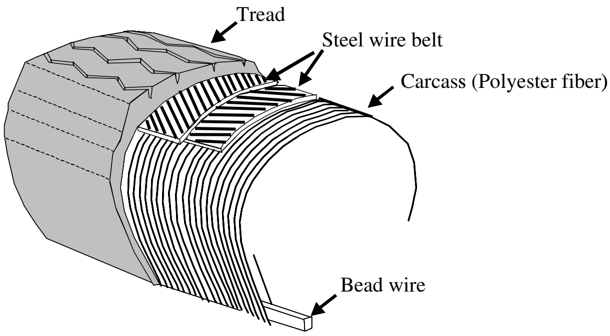

Figure 1. Inner structure of steel wire reinforced radial tire.

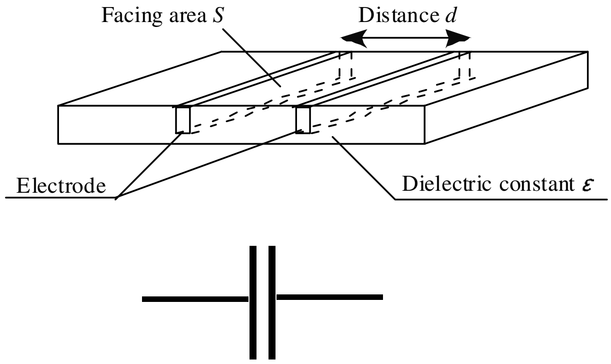

Figure 2. Condenser model of a steel wire belt of a tire.

of a tire is shown in figure 1. This figure shows the inner structure of a typical radial tire. For the radial tire, the direction of the carcass fiber is in radial direction of the tire. Usually the carcass fiber is made from organic fibers like polyester fibers. On the carcass fiber layer, steel wire layers are mounted like cross-ply laminates of composite materials. These fibers are covered with rubber and the tread rubber layer is mounted on the steel wire layers as shown in figure 1. The deformation of the tread is transferred to the steel wire layers. This means the measurement of the strain of the steel wire layer reveals the deformation of the tread of the tire itself.

In the steel wire layer, the steel wire is a straight electrically conductive wire. Rubber is an electrical insulator although the rubber includes carbon black particulates. Let us consider a couple of adjacent steel wires as shown in figure 2. In this figure, the couple of steel wires are placed face-to-face and the dielectric rubber is inserted between the two steel wires. Let us consider that an electric voltage is charged between the steel wires. This structure is modeled like an electrical condenser as shown in figure 2. The adjacent steel wires are the electrodes of an electric condenser. The electrical capacitance of the condenser is calculated as follows:

$$C = \varepsilon \frac{S}{d} \tag{1}$$

where ε is the dielectric constant of the rubber, S is the area of the electrodes and the d is the spacing between the adjacent steel wires. For an actual tire, the diameter of the steel wire is approximately 0.7 mm and the spacing is 1.4 mm. The steel wire layers are placed like angle plies. An electric current flow between these layers also exists. This is, therefore, a simple

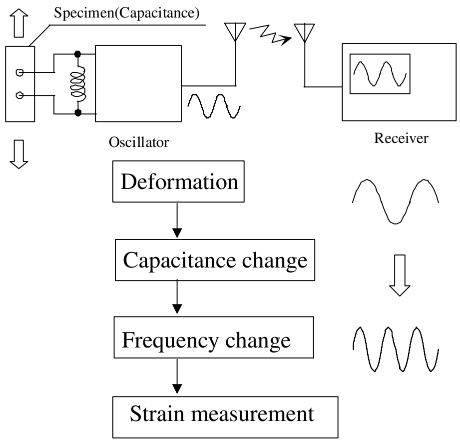

Figure 3. Schematic image of the wireless strain measurement system.

model to explain the mechanism of capacitance change, but this is not a precise model. To predict the precise change of capacitance of a tire, a more complicated model is required. When the steel wire layer is elongated, the spacing d is enlarged: this means that the capacitance is reduced from equation (1). When the steel wire layer is shrunk, an increase of capacitance is observed. The tire deformation causes the change of the electrical capacitance of the tire.

Let us consider a typical LC-type oscillator circuit that creates high-frequency electromagnetic waves like radio waves. The circuit usually emits constant frequency waves when the inductance L and capacitance C are fixed. The frequency of the typical oscillator circuit is as follows:

$$f = \frac{1}{2\pi\sqrt{LC}}. \qquad (2)$$

This means that a decrease of the capacitance C causes an increase of the oscillating frequency when the inductance L is fixed.

The schematic representation of the novel wireless strain measurement system is shown in figure 3. In this figure, a specimen means a part of the tire. Inside the tire, the oscillator circuit is installed and electric power can be supplied by means of a battery or using high frequency electromagnetic waves. The receiver is installed inside a car body. Instead of a condenser, a small part of a tire is connected to the oscillator circuit. When the tire deforms, the electrical capacitance of the tire changes; the capacitance change causes a change of the oscillating frequency. Setting the frequency of the oscillator circuit to the appropriate high frequency to send the oscillating waves wirelessly, the oscillating waves can be measured with a receiver. The received oscillating waves are stored in the memory of the digital oscilloscope and the data are sent to a signal-processing unit. Using FFT, the frequency of the transmitted waves is obtained wirelessly. Measurement of the change of the frequency enables us to know the change of the capacitance of the tire, which means the deformation of the tire.

The oscillator circuit employed here is a typical Hartley type as shown in figure 4. Details of the Hartley-type oscillator circuit are described in the literature (for example, see [10]). Of course, another kind of oscillator circuit can be used in this system. For example, a crystal oscillator is one of the candidates to miniaturize the circuit, although a lot of trial and error will be required to find a stable oscillation circuit. A capacitance–resistance (CR) type oscillator circuit is also available. The CR oscillator can prove to be more sensitive to the change in capacitance. However, it also requires more trials to obtain a stable oscillator circuit. This is our future target.

The advantage of this system is that the tire itself is adopted as a sensor. This does not cause debonding of the sensor over a long period of service and this system does not cause disturbance of the stress and deformation field of the tire.

The system can be applied as an attached or embeddable patch, like a strain gage, instead of using the actual steel wires of a tire. The patch type system is similar to a conventional strain gage. When strain measurements in two directions are required, at least two systems are necessary to be installed.

3. Experimental process

The specimen employed in the present study is shown in figure 5. A rectangular specimen is cut from a commercially available radial tire. The specimen length, width and thickness are 250, 30 and 5 mm, respectively. The longitudinal direction of the specimen is the circumferential direction of the tire. The carcass is made from two polyester-fiber reinforced layers as shown in figure 5. Over the carcass, steel wire layers are placed like the angle plies of composite laminates. The fiber angle is approximately $\pm 20°$ to the specimen longitudinal direction. On the specimen surface near the steel wire layer, surface rubber is removed with a normal grinder. Since the surface of the steel wire is covered with a special surface treatment to improve the bonding between steel and rubber, the wire is polished with a sheet of sandpaper to remove this surface treatment. After polishing, two lead wires are soldered to the steel wires to make a couple of electrodes. The spacing between the electrodes is approximately 50 mm. A conventional strain gage designed for rubber is attached to the specimen surface between the two electrodes to measure the applied strain.

Three types of tests are performed here. First, a static tension test is performed to measure the capacitance change of the specimen during tensile loading. Second, the wired measurement system is conducted to check the frequency change during loading and unloading, as shown in figure 6(a). Third, a wireless strain measurement system is performed to check the feasibility of the system, as shown in figure 6(b). In figure 6, a resonance circuit is added to measure oscillating waves for the digital oscilloscope.

For the first test, the electrical capacitance is measured with a LCR meter (LCR meter no 3522) produced by Hioki Electric Co. Ltd. For the measurement, the charged alternating current is 100 kHz and the charged voltage is 1.0 V. The applied strain is also measured with the conventional strain gage attached to the surface. The test is performed with a static material-testing machine produced by Shimazu Co. Ltd. Loading speed is 0.5 mm min^{-1}. The tensile test is performed up to 2 mm of displacement, and after that, unloading is performed. The electric capacitance is measured without

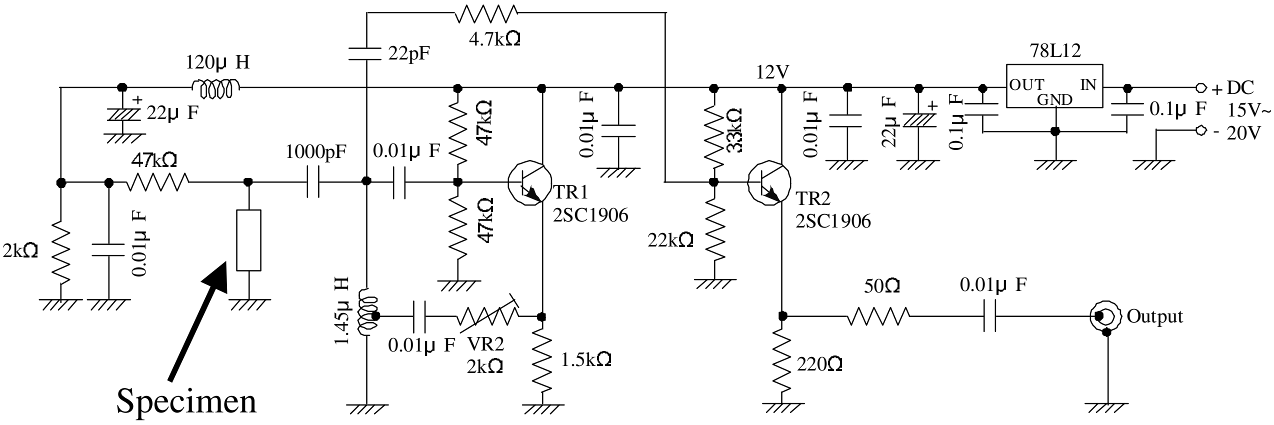

Figure 4. Typical Hartley-type LC oscillator circuit.

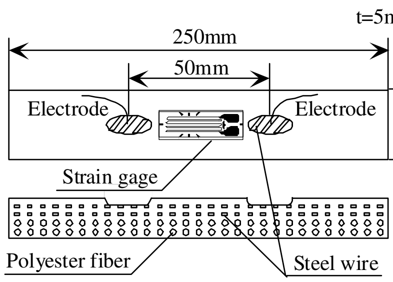

Figure 5. Specimen configuration.

stopping the loading. To prevent electrical shorts between the specimen and the jigs of the testing machine, a silicon rubber sheet is inserted between the jig and the specimen.

For the second and third tests, a Hartley-type oscillator circuit is connected to the specimen. The oscillator circuit is shown in figure 4. In this oscillator circuit, a condenser, which is one of the two key parts needed to calculate the oscillating frequency is replaced with the tire specimen. For tuning the oscillating frequency, a condenser of 1000 pF is connected in series to the tire specimen. This circuit has the ability to emit oscillating waves from 20 to 30 MHz with tuning of the coil inductance and a variable resistance of 2 kΩ. The oscillating waves are measured with a digital oscilloscope (Lecroy Waverunner LT224). The sampling frequency of the digital oscilloscope is 400 MS s^{-1}; the limit of resolution is set to 10 kHz and the measurement area is set to from 0 to 50 MHz. The frequency of the oscillating waves is measured with FFT analysis by averaging 500 analytical results. Tensile tests are similar to the first test. The oscillating frequency measurements, however, are performed after stopping the loading at every 0.5 mm elongation.

4. Experimental results and discussion

4.1. Measurement of electrical capacitance change

Figure 7 shows the results of the first test for measurements of the capacitance change with tensile loading. The abscissa is the applied strain measured with the attached strain gage and the ordinate is the measured electrical capacitance. This figure reveals that the capacitance increases with the increase of tensile loading from approximately 3.7 to 5 pF. From equation (1), the increase of the capacitance means the decrease of the spacing distance between the steel wires during tensile loading. This decrease of the distance can be explained using figure 8. Since the steel fiber angle is approximately 20°, the tensile loading causes the rotation of the wire, as shown in figure 8, and this rotation decreases the wire angle; the transverse compressive strain causes the decrease of the width of the specimen. These causes lead to the decrease of the spacing distance during tensile loading.

The results show that there is only a small difference of capacitances during loading and unloading. As is generally known, rubber is a highly viscoelastic material. For the static tensile test, this viscoelastic effect affects the specimen deformation. The strain gage measures deformation in the middle of the specimen. At the free edges of the specimen, severe shear stress is applied and the deformation is different from that of the middle of the specimen. The effect of the viscoelastic behavior at the specimen edges is different from that of the middle of the specimen. This causes the hysteresis of the capacitance to change. The hysteresis may be improved for dynamic deformation. This is also for future work.

As shown in figure 7, the change of the electrical capacitance has an upper limit at the strain region over 3000 μ. This upper limit is created by the slight change of capacitance over the region, and this slight change of capacitance is caused by the slight change in the wire spacing distance over the high tensile strain region. This slight change of the distance over the region is caused by the high stiffness of rubber in the high strain region, which is the typical nonlinear stress–strain relationship of the normal rubber: low stiffness in the small strain region and high stiffness in the high strain region. For an actual tire, the maximum deformation stress is approximately 2000 or 3000 μ. This upper limit, therefore, is not a serious problem for actual measurements.

4.2. Oscillating frequency change of wired system

Figure 9 shows the results of frequency change of the oscillating waves under the loading and unloading condition of the wired system. The abscissa is the applied strain measured with the attached conventional strain gage. The ordinate is the

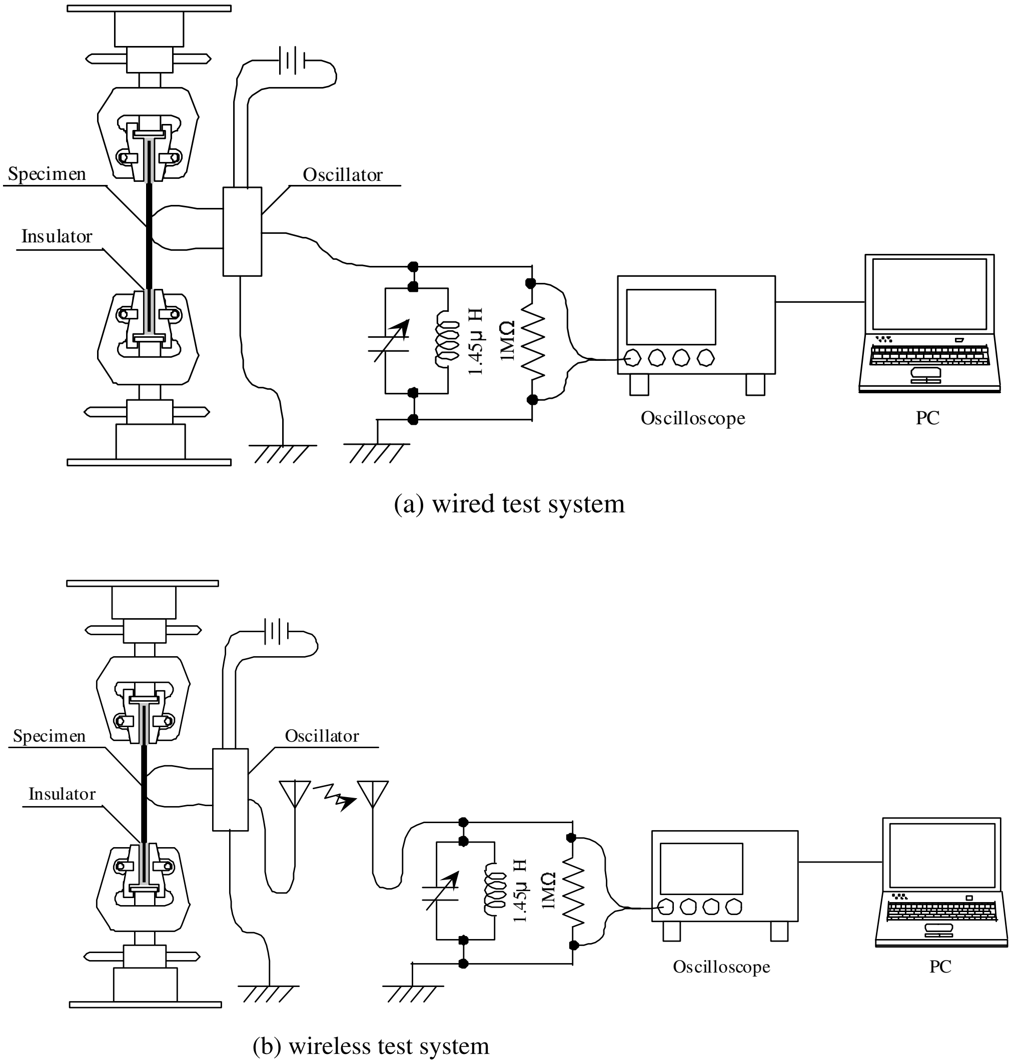

Figure 6. Experimental set-up.

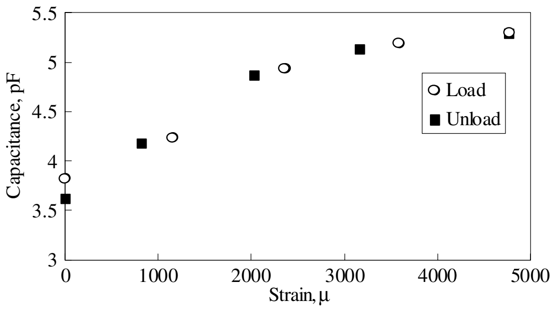

Figure 7. Measured capacitance change during loading–unloading.

frequency of the measured alternating electric voltage of the wired system circuit.

Since the inductance of the connected coil is fixed to 1.45 μH and the capacitance of the specimen is from 3.7 to 5 pF, the frequency of the oscillating waves of the circuit is approximately calculated to be 20 MHz from equation (2). The measured frequency is from 26.5 to 26.2 MHz. The difference comes from the serially connected condenser included in the oscillating circuit.

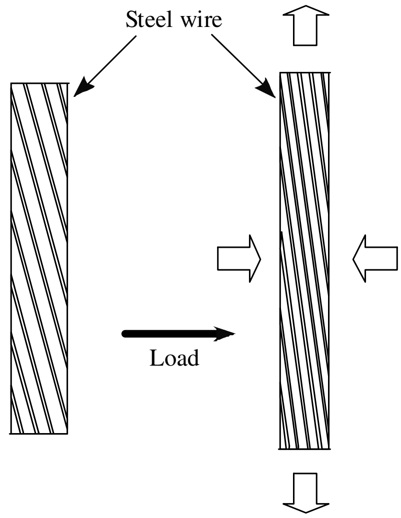

Figure 8. Spacing decrease with the increase of tensile load.

Corresponding to the capacitance increase with the increase in tensile strain, as shown in figure 7, the measured

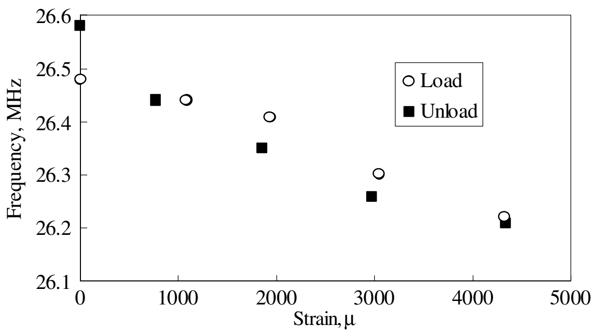

Figure 9. Measured frequency change of the wired system.

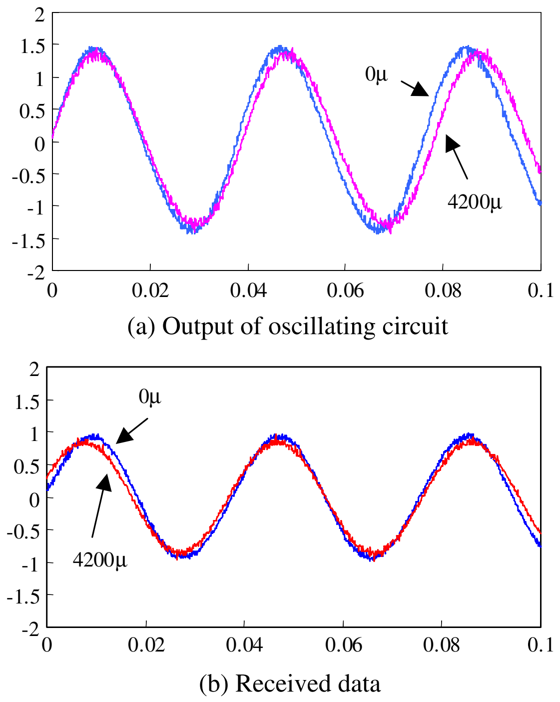

Figure 10. Measured oscillation data of the wireless system.

frequency decreases with the increase in the applied strain, as shown in figure 9. Although the change of frequency due to loading is small, the frequency change is detectable. From this figure, we can conclude that the strain of the tire can be measured with the frequency change of the oscillating electric voltage waves of the oscillator circuit.

4.3. Oscillating frequency change of wireless system

Figure 10 shows the results of the measured oscillating waves of the wireless system. In each figure, the abscissa is the time and the ordinate is the measured voltage. Figure 10(a) is the output signal of the oscillator circuit and figure 10(b) is the result of the measured signal of the wireless receiver. In these figures, the results of the completely unloaded case and the results of the applied load of 4200 μ are shown. From figure 10(b), we can conclude that the oscillating wave signal is transmitted wirelessly although the amplitude of the signal is reduced compared to the output signal.

Figure 11 shows the results of the power spectrum of five cases of applied load. The abscissa is the frequency and the

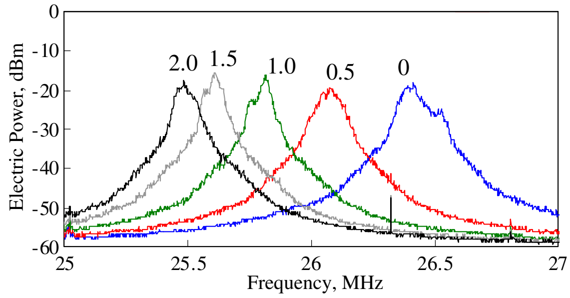

Figure 11. Measured power spectrum of the wireless system of various deformations from 0 to 2.0 mm.

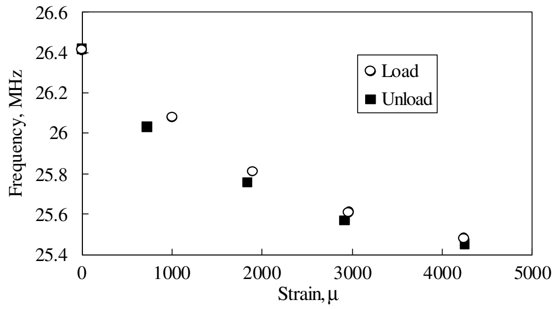

Figure 12. Measured relationship between strain and frequency of the wireless system.

ordinate is the electrical power. The five measurements were performed at each loading condition. As the tensile loading increases, the frequency of the waves shifts to a lower region. As shown in this figure, the frequency of the oscillator circuit is easily determined from the maximum point of the power spectrum obtained with FFT.

Figure 12 shows the results of the frequency change of the oscillating waves under the loading and unloading condition of the wireless system. The abscissa and the ordinate are the same as those of figure 9. As shown in this figure, the frequency of the oscillating waves decreases with the increase in applied strain, the same as the wired system. The relationship between the frequency change and the strain is almost the same as that of the wired system. From this figure, we can conclude that the strain of the tire can be measured using the oscillator circuit as the frequency change of the oscillating waves. Although the transmitted signal power of the wireless system is reduced owing to wireless data sending, these results clearly mean that the proposed method is applicable for wireless strain measurement of tires without using additional sensors.

5. Concluding remarks

In the present study, a novel method to measure the strain of a tire wirelessly is proposed. The method does not use additional sensors, but it employs the tire itself as a sensor. Steel wires of the tire are adopted as electrodes to charge high-frequency alternating current. Deformation of the tire causes a change of the electrical capacitance of the tire. The tire is connected to an oscillator circuit as a condenser. The capacitance change of the tire is converted to a frequency change of the oscillating waves using the oscillator circuit. Since this method does not use additional sensors, it does not disturb the stress and deformation field of the tire and it does not cause debonding of the sensor. The method is applied to a rectangular specimen cut from a commercially available tire and is experimentally investigated. The results obtained are as follows.

(1) The electrical capacitance of the tire increases with the increase of tensile loading. This increase in capacitance is caused by the decrease of the spacing of the wires under tension loading.
(2) The tire is connected to the oscillator circuit as a condenser, and the frequency of the oscillator circuit is changed owing to the change of the capacitance of the tire.
(3) The frequency change of the oscillator circuit is measured wirelessly, although the signal power is reduced compared to the signal of the wired system.

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