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Wireless strain monitoring using electrical capacitance change of tire: part II—passive

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Abstract
In-service strain monitoring of tires of automobiles is quite effective for improving the reliability of tires and design tools. In a previous study, the authors proposed a new wireless strain monitoring method that adopts the tire itself as a sensor, with an oscillator circuit. In the method, steel wires are employed as electrodes to measure electrical capacitance changes of tires. A specimen cut from a commercial tire is connected to an oscillator circuit, and the oscillation frequency changes with the capacitance changes of the tire. This method is very simple and useful, but it requires a battery to activate the oscillator circuit. In the present study, a new passive strain measurement system utilizing electrical capacitance changes of steel-wire-reinforced tires is proposed and experimentally investigated. The passive wireless strain monitoring method makes use of the specimen cut from the tire as a condenser of a passive filter circuit. Deformation of the tire causes capacitance changes of the tire comprised of steel wire and rubber; the change of the capacitance causes a change of the filtering frequency of a radio wave. Measurement of the frequency of a radio wave passed through the filter 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. Tension testing is performed and the change of the filtering frequency is measured during the test. As a result, the method is experimentally proved to be effective for the passive wireless strain monitoring of tires.

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

1. Introduction

Safety of automobiles is increasingly important, and smart tires that contain sensors designed to prevent bursting of tires in service are currently under development [1–7]. Most of the smart tires have integral sensors for picking up information on tire deformation or internal pressure during a long period of service. 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 measurement makes for a more efficient anti-blocking system (ABS). This information also enables the early detection of separation of tire tread, which is a significant threat to automobile safety as is well known [7].

If one is to install smart tires, there are several specifications for the sensors for the tires. First, wireless monitoring is indispensable because a tire usually rotates and it is difficult to use wired sensors. Second, since the rubber of the tires has low stiffness, embedding or attaching stiff sensors can easily disturb the stress or deformation of the tires, but the sensors should not cause disturbance. Third, the large

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difference in stiffness between the sensors and the rubber may cause debonding between the sensors and the rubber for a long period of running time; the stiffness difference should be minimized. Fourth, since the tire itself is not an expensive product, the sensor must be inexpensive.

Most of the sensors employed in the smart tires fail to meet one or two of these specifications. For example, the SAW sensors are usually made from piezoelectric ceramics, and the sensor requires a special tool such as a pin to reduce the deformation of the tires and to enhance the force due to the deformation. This means that the use of SAW sensors causes disturbance of the tire deformation or stress.

Microelectromechanical systems (MEMS) for wireless strain measurement are embedded in 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 it is not recommended to embed a MEMS sensor into a tire. This is because of the large difference in stiffness between the sensor and the rubber tire. The large difference in stiffness may cause disturbance of the deformation and stress; it may also cause debonding between sensors and the rubber for a long period of service.

Conventional strain gages have similar problems to the wireless MEMS. A small wireless data transfer tip can be applied to 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 for a long period of service. A novel sensor, therefore, is required for a 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 that of a well known electrical condenser comprising a couple of electrodes and inserted dielectric material: the tire deformation causes change of the spacing between the steel wires, and this change means a change of the capacitance of that part of the tire. Measurement of the capacitance change of the tire enables us to establish the strain or deformation of the tire without embedding or attaching additional sensors.

In the previous study [10], therefore, a new strain measurement method was proposed. The previous method wirelessly measured the change of electrical capacitance during deformation of a tire. The previous method employed an oscillator circuit to wirelessly transfer the capacitance change information. The steel wire of the tires was adopted as an electrode of an electrical condenser. The condenser made from the tire was connected to the oscillator circuit as the condenser of an inductance–capacitance (L–C) oscillator circuit. The tire deformation caused electrical capacitance change of the circuit, and that caused a change of the oscillating frequency. Measurement of the change of the frequency of the oscillator circuit enabled us to establish the strain of the deformed tire wirelessly. The previous system was applied to a rectangular specimen made from a commercially available steel radial tire, and static tension tests were performed. The previous wireless strain measurement system adopted the tire itself as a sensor. The system, therefore, does not cause any of the problems mentioned before. The system, however, requires batteries to activate the oscillator circuit. This may cause trouble in long-term service.

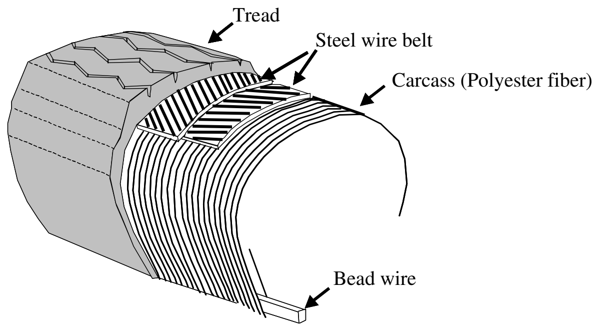

Figure 1. The inner structure of a steel-wire-reinforced radial tire.

Varadan *et al* [8] have proposed a passive wireless strain MEMS sensor, and Harpster *et al* [11] have proposed a passive wireless humidity sensor consisting of a capacitive humidity sensor chip and a hybrid coil. These passive sensors do not require batteries to activate the sensor circuit. In the present study, the previous method for wireless tire monitoring is improved to produce a passive wireless sensor. A specimen made from a commercially available tire is connected to a filter circuit comprising an inductance (L) and a capacitance (C) as a condenser. Two antennas are connected to the filter circuit. A high-frequency radio wave is emitted from one of the antennas of the filter circuit. At the other antenna, the filtered radio wave is picked up. When the specimen deforms, the capacitance of the specimen changes, and the capacitance change causes changes of the filtered radio wave frequency and amplitude. This change of the filtered radio wave enables us to measure the applied strain of the specimen wirelessly, without any power supply from outside. This new passive wireless method is applied to a specimen and the static applied strain is measured here.

2. Theory and system

The wireless strain measurement system in the previous study [10] employs the tire itself as a sensor. The internal structure of a tire is shown in figure 1. The figure shows the inner structure of a typical radial tire. For the radial tire, the direction of carcass fiber is the radial direction of the tire. Usually the carcass fiber is made from organic fibers such as polyester fibers. On the carcass fiber layer, steel wire layers are mounted like angle-ply laminates of fiber 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 that the measurement of the strain of the steel wire layer reveals the deformation of the tread of the tire.

In the steel wire layers, the steel wire is a straight electrical 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, a couple of the steel wires are placed face to face, and the dielectric rubber is inserted between the two steel wires. Let us consider the case where an electric voltage is induced between the steel wires. This structure is modeled like an electrical condenser, as shown in figure 2. The adjacent steel wires

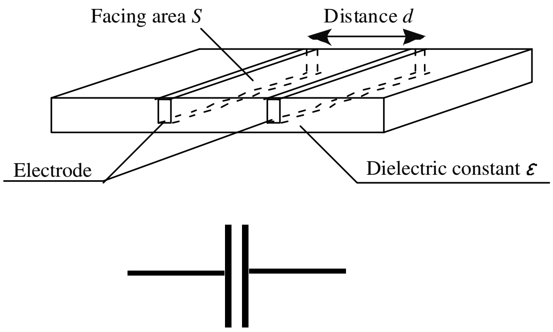

Figure 2. The condenser model of a steel wire belt of a tire.

are the electrodes of an electrical condenser. The electrical capacitance of the condenser is calculated as follows:

$$C = \varepsilon \frac{S}{d} \quad (1)$$

where ε is a dielectric constant of the rubber, S is the area of the electrodes, and the d is the spacing between the adjacent steel wires. When the steel wire layer is elongated, the spacing d is enlarged; this means that the capacitance is reduced from that of equation (1). When the steel wire layer is shrunk, an increase of the capacitance is observed. The tire deformation causes a change of the electrical capacitance of the tire.

In the previous study, an L–C-type oscillator circuit was employed as a wireless data-sending tool. 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:

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

This means that decrease of the capacitance C causes an increase of the oscillating frequency when the inductance L is fixed. Instead of the condenser, 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 radio waves wirelessly, the oscillating waves can be measured with a receiver. The received oscillating radio 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 establish the change of the capacitance of the tire, which means deformation of the tire. This method is simple and has high reliability. This method, however, requires a battery to activate the oscillator circuit.

In the present study, a simpler passive filter circuit is adopted for sending the capacitance change of the tire to a receiver wirelessly. A schematic image of the present passive filter system is shown in figure 3. Two oscillator circuits, which are placed outside of the tire that we want to monitor, are employed here to emit radio waves. The radio wave emitted from the left circuit comprises two frequencies. The radio wave is picked up with the antenna of the filter circuit. The filter circuit comprises the inductance of a coil, the capacitance of a tire specimen, and a resistance. This is a pure L–C-parallel resonator circuit, and the resonance frequency is exactly the same as that given by equation (2). When the capacitance of the tire is adequately selected to resonate with the emitted radio wave frequency using equation (2), the total impedance of the resonant filter circuit rises to infinity for the resonant frequency signal. This allows the oscillator electric current to flow into the resistance (B in figure 3), and the radio wave is emitted from the antenna. The other non-resonant signals can pass the filter circuit (A in figure 3). The emitted radio wave is picked up at the receiver. When the applied stress deforms the tire specimen, the capacitance of the tire specimen changes, and the change causes deviation from resonance of the filter circuit. The movement of the resonance frequency due to an applied load is illustrated in figure 4. The deviation from resonance causes loss of signal owing to the electric current through the filter (A in figure 3). This loss means that the resonant radio wave present before loading fades away with increase of the applied load.

There are several ways to measure the movement of the resonance frequency. The easiest way is to measure the amplitude of the received radio wave. The deviation from the resonant frequency of the filter causes loss of the radio wave amplitude. Measurements of the amplitude of the radio wave picked up with the receiver enable us to establish the movement of the resonance frequency of the filter and hence the applied strain for the tire specimen. This method is very simple, but experimental noise has large effects on the precision of the measurements of the amplitude change due to applied load.

The other method is to make use of a radio wave comprising multiple waves of different frequencies. For

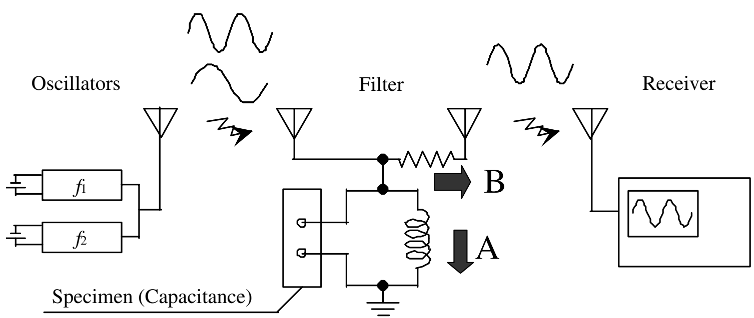

Figure 3. A schematic image of the wireless strain measurement system with a passive tuning circuit.

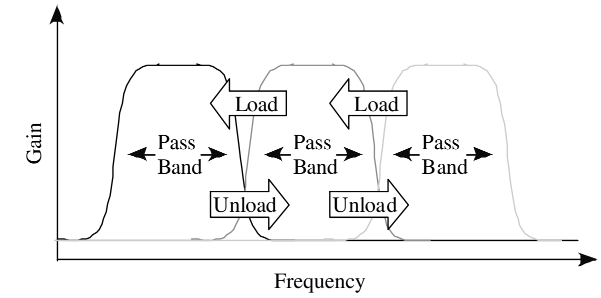

Figure 4. A schematic image of the effect of capacitance change on the passive tuning circuit.

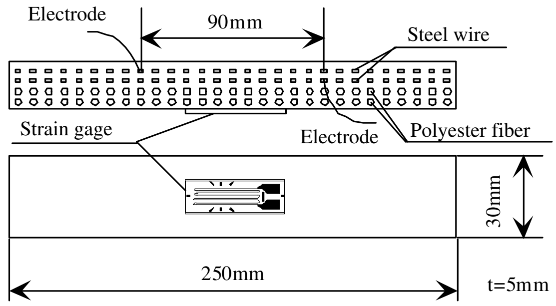

Figure 5. The specimen configuration.

example, consider the case where five kinds of wave are emitted from the oscillators; the frequencies are ω_1, ω_2, ω_3, ω_4, and ω_5. First, the resonance frequency of the filter is set to ω_1. FFT analysis of the measured received radio wave shows that the most clearly distinguished frequency in the radio wave received through the filter is ω_1. When a load is applied and the tire specimen deforms, the resonant frequency of the filter moves to ω_2, and the most clearly distinguished frequency in the radio wave received through the filter changes to ω_2 (from ω_1). When a larger load is applied, the most clearly distinguished frequency in the received radio wave shifts to a higher frequency such as ω_3, ω_4, or ω_5. If we know the frequency of the most clearly distinguished radio wave then we can infer the change of capacitance of the tire specimen; the capacitance change can be translated into a strain change of the tire specimen. This method is robust against noise, but a large change of the capacitance is necessary to allow judgment of which is the most clearly distinguished frequency. If the capacitance change is small, it is very difficult to find the most clearly distinguished radio wave. Moreover, this method requires a large number of oscillators to obtain highly precise resolving power, although this defect is not fatal.

A mixed method is the most convenient, and our mixed method is shown in figure 3. In the mixed method, two oscillator circuits are used to make a combined radio wave comprising two radio waves with two different frequencies: ω_1 and ω_2. The frequency ω_1 set for one of the radio waves corresponds to the capacitance of the tire specimen under the lowest loading. The frequency ω_2 set for the other radio wave corresponds to the capacitance of the tire specimen under the highest loading. Let us consider the case where the loading is performed from the lowest to the highest value. In this case, the resonant frequency of the filter circuit moves from the ω_1 to ω_2. The movement of the resonant frequency causes changes of the amplitude of each radio wave. First, the amplitude of the radio wave of frequency ω_1 is very large, and this increases with increase of the applied load. The amplitude of the radio wave of frequency ω_2 is at first small, and this increases with increase of the applied load. Using the amplitudes of the two radio waves (A_1 and A_2), more precise information on the capacitance change can be obtained by reducing the effect of noise. For example, the ratio of the amplitudes (A_2/A_1) can be useful as a parameter to describe the relationship between the applied strain and capacitance change.

The new system also makes use of the tire itself as a sensor. This does not cause debonding of the sensor for a long period of service, and this system does not cause disturbance of the stress and deformation field of the tire.

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, two steel wire layers are placed like angle plies of composite laminates. The fiber angle is approximately $\pm 20°$ to the specimen longitudinal direction. Two electrodes are placed on the first and the second layers as shown in figure 5. The lead wires are connected to the steel wires with solder. The spacing between the electrodes is approximately 90 mm. A conventional strain gage designed for rubber is attached on the specimen surface between the two electrodes to measure the applied strain.

Two types of the test are performed here. First, a static tension test is performed to measure the capacitance change of the specimen during tensile loading. Second, wireless strain measurements are performed to check the feasibility of the system, as shown in figure 6. The specimen is connected to an L–C parallel resonator filter and a resistance of 1 MΩ is connected to the filter circuit.

For the first test, electrical capacitance is measured with an LCR meter (LCR meter No 3522) produced by Hioki Electric Company Limited. For the measurement, the charging alternating current is 100 kHz and the charging voltage is 1.0 V. Applied strain is also measured with the conventional strain gage attached on the surface. The test is performed with a static material-testing machine produced by Shimazu Company Limited. The 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 electrical capacitance is measured without stopping the loading. To prevent electrical shorting between the specimen and the jigs of the testing machine, a silicon rubber sheet is inserted between the jig and the specimen.

A Hartley-type oscillator circuit is adopted as a source of radio waves. The oscillator circuit is shown in figure 7. This circuit has the ability to emit oscillating waves of from 20 to 30 MHz on tuning 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 M s^{-1}; the limit of resolution is set to 10 kHz and the measurement area is set to extend from 0 to 50 MHz. The frequency of the

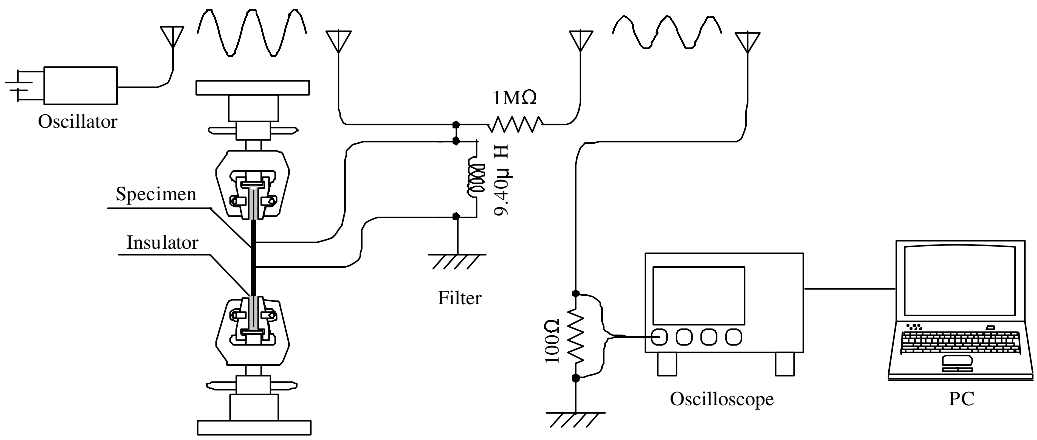

Figure 6. The experimental setup for the wireless test.

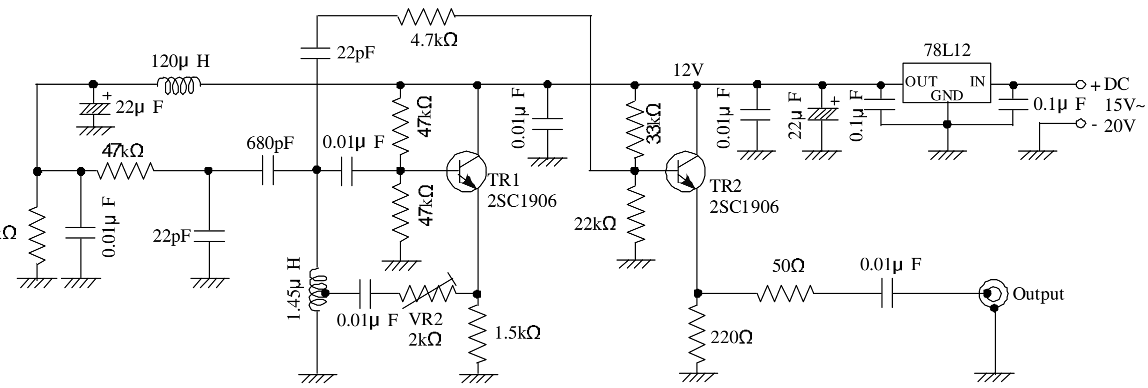

Figure 7. The Hartley-type *L*–*C* oscillator circuit.

oscillating waves is measured with FFT analysis by averaging 500 analytical results. The tensile tests are similar to the first test. The oscillating frequency measurements, however, are performed stopping the loading every 0.5 mm of elongation.

Two radio wave frequency types are generated and emitted to the filter circuit. In the filter circuit, the tire specimen is connected in parallel as one of the parts of the *L*–*C* resonator filter circuit as shown in figure 5. A resistance of 1 MΩ is connected in parallel. This resistance of 1 MΩ is large enough to allow the flow of most of the radio waves, which are picked up but not resonant with the filter circuit, into the filter circuit. Since the impedance of the filter circuit to the resonant radio wave is quite large, the resonant radio wave flows for a resistance of 1 MΩ and it can be emitted to the receiver oscilloscope. The only parts embedded in the tire, therefore, are the coil used in the filter and the resistance of 1 MΩ in the new passive sensor system. This new passive system does not require electrical power for the operation of the circuit embedded in the tire.

4. Experimental results and discussion

4.1. Measurement of the electrical capacitance change

Figure 8 shows the results of the test used to measure 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

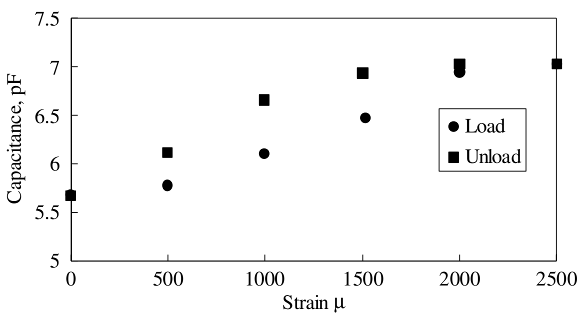

Figure 8. The electric capacitance change due to tensile loading of the tire specimen.

figure reveals that the capacitance increases with increase of the tensile loading from approximately 5.6 to 7 pF. From equation (1), the increase of the capacitance indicates decrease of the spacing between the steel wires during tensile loading. This decrease of the spacing can be recognized as simply the effect of a decrease of thickness with increase of tensile strain. When the tensile load is applied, the thickness of the specimen decreases to maintain Poisson's ratio.

The results show that there is only small difference between the capacitance during loading and that during unloading. This small hysteresis could be caused by the hysteresis loop of the stress–strain relationship of rubber.

As shown in figure 8, the change of the electrical capacitance has an upper 'shelf' in the strain region above 2000 μ.

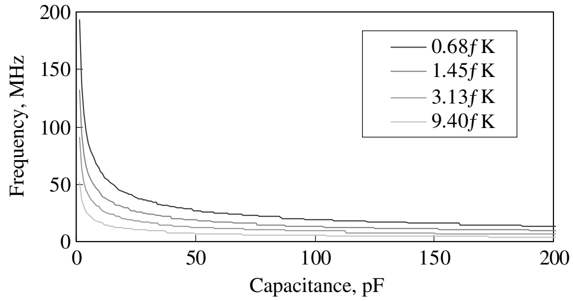

Figure 9. The calculated variation of the tuning frequency for various inductances of coil.

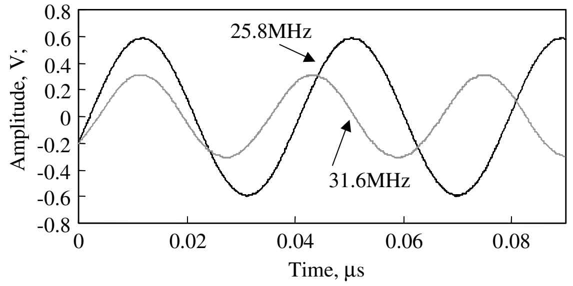

Figure 10. Oscillating waves from the oscillator circuit.

This upper shelf is produced by the change of capacitance being small over the region, and this in turn is caused by the change of the thickness of the specimen being small over the high-tensile-strain region. This smallness of the change of the thickness over the region is caused by the high stiffness of the tire with reinforcement of steel wires in the high-strain region.

Figure 9 shows the changes of the frequencies of the resonant circuit calculated from equation (2). The figure shows that the frequency does not change with increase of the capacitance when the capacitance is larger than 30 μF. Alternation of the coil has only a slight effect on the frequency change, as shown in figure 9. In the present study, therefore, a commercially available coil of 9.4 μH is used, to obtain radio waves of about 20 MHz.

Two kinds of radio wave are carefully selected here: these have frequencies of 25.8 and 31.6 MHz. For the radio wave of frequency 25.8 MHz, the amplitude of the wave decreases with increase of the capacitance of the filter circuit. The capacitance of the filter circuit increases with increase of the tensile strain as shown in figure (8). This means that the amplitude decreases with increase of the tensile loading. For the radio wave of frequency 31.6 MHz, the amplitude of the wave increases with increase of the capacitance: this means that the amplitude increases with increase of the tensile loading. Although the two kinds of radio wave are not made to enter the filter circuit at the same time here, this can be done.

Figure 10 shows the emitted oscillating radio waves of two frequencies adopted here. The oscillated waves are directly measured from the two oscillator circuits.

4.2. The amplitude change of filtered radio waves

Figure 11 shows the results for the filtered radio waves of frequency 25.8 MHz measured with the receiver under the various loading conditions. The abscissa is time, and the ordinate is amplitude of the measured oscillating electric voltage. As shown in this figure, the amplitude of the oscillating radio waves decreases with increase of the applied tensile load. Figure 12 shows the results for the filtered radio waves of frequency 31.6 MHz measured under the various loading conditions. As shown in this figure, the amplitude of the oscillating radio waves increases with increase of the applied tensile load. For the new passive system, electrical power is not used by the circuit embedded in the tire specimen, and it has two wireless data-sending paths, which means large power loss. These causes of decreasing electrical wave power make it indispensable to confirm the feasibility of measuring the amplitude change. In spite of these difficulties, the radio waves received with the oscilloscope clearly reveal the changes of the amplitudes due to the applied tensile strain. These figures indicate that the new passive filter system successfully monitors the applied strain wirelessly.

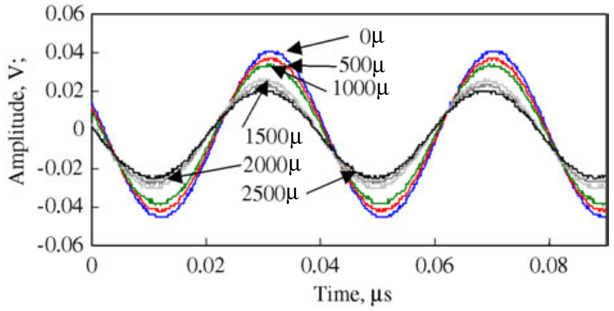

Figure 11. Measured received waves of frequency 25.8 MHz at various tensile strains.

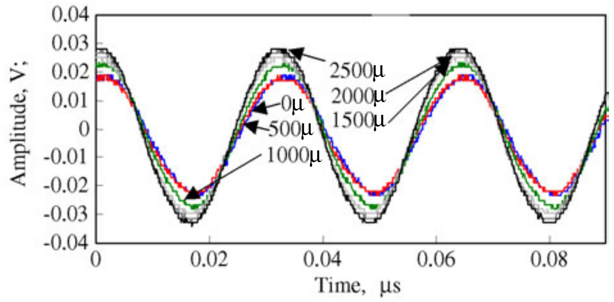

Figure 12. Measured received waves of frequency 31.6 MHz at various tensile strains.

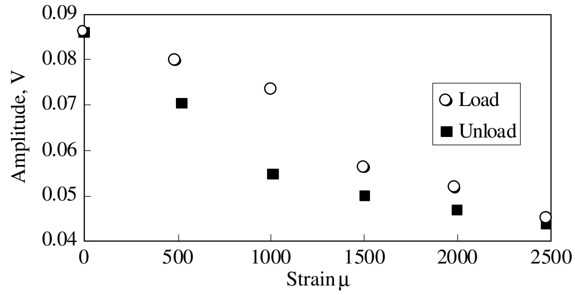

Figure 13. The measured relationship between the applied tensile strain and maximum amplitude of the received waves of frequency 25.8 MHz.

Figures 13 and 14 show the resulting relationships between applied strain and measured amplitudes for the two radio waves, respectively. In both figures, the abscissa is the applied

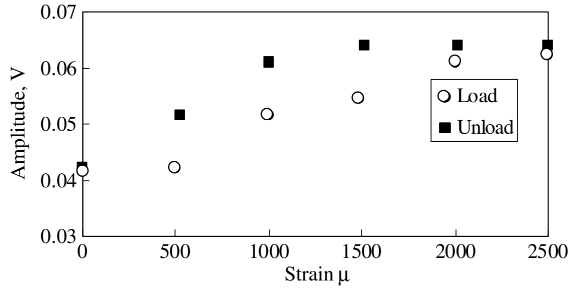

Figure 14. The measured relationship between the applied tensile strain and maximum amplitude of the received waves of frequency 31.6 MHz.

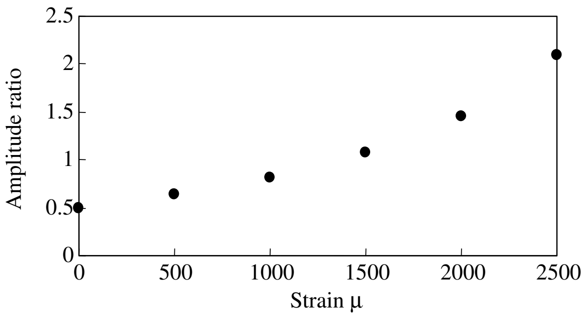

Figure 15. The measured amplitude ratio change of the received waves due to the applied tensile strain (amplitude ratio: $A[25.8\text{ MHz}]/A[31.6\text{ MHz}]$).

strain measured with the attached conventional strain gage, and the ordinate is the amplitude of the radio waves measured with the receiver oscilloscope. In both figures, open symbols show the results obtained under the loading conditions, and the solid symbols show the results obtained under the unloading conditions. Figure 13 obviously shows that the radio wave of frequency 25.8 MHz is wirelessly received by the receiver oscilloscope, and the amplitude of the received radio wave decreases with increase of the applied strain owing to the change of capacitance of the filter circuit. Figure 14 shows clearly that the radio wave of frequency 31.6 MHz is wirelessly received by the receiver oscilloscope, and the amplitude of the received radio wave increases with increase of the applied strain owing to the change of capacitance of the filter circuit. These figures have hysteresis loops. These hysteresis loops arise owing to the hysteresis loop of the rubber itself.

Since the amplitude is sensitive to the noise, the comparison of the amplitude of the measured radio waves is assumed to be sensitive to the noise or conditions. To circumvent the problem of the noise and conditions sensitivity of the amplitude, the ratio of the amplitudes of the two frequencies is investigated here. The ratio of the amplitudes is plotted in figure 15. The abscissa is the applied strain, and the ordinate is the ratio of amplitudes: the amplitude for the 25.8 MHz wave is divided by the amplitude of the 31.6 MHz wave. In this figure, averaged loading and unloading data are used just for simplicity. Using the ratio of the amplitudes, we do not need to pay attention to the amplitude change due to the conditions for the wireless data sending.

5. Concluding remarks

In the present study, a new passive method for measuring the strain of a tire wirelessly is proposed. The method does not require additional sensors, and employs the tire itself as a sensor. The steel wires of the tire are adopted as electrodes for charging with a high-frequency oscillating electric current. Deformation of the tire causes change of the electrical capacitance of the tire. The tire is connected to the passive filter circuit for radio waves as the condenser of a simple L–C resonator filter circuit. The capacitance change of the tire is converted to a change of the band of the filtering frequency. Since this method does not require additional sensors, this method does not disturb the stress and deformation field of the tire, and this method does not cause debonding of the sensor. Moreover, since the method does not require batteries to activate the embedded passive filter, the method is appropriate for use in producing sensors to be embedded in commercial tires for a long period of service time. The method is applied to a rectangular specimen cut from a commercially available tire, and the method is investigated experimentally. The capacitance change due to the loading is shown to cause a change of the resonance frequency, and the change is shown to cause increase or decrease of the radio wave amplitude received by the oscilloscope. Using the ratio of amplitudes of the two different frequencies, this method may be used to monitor the applied strain without showing high sensitivity to noise.

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