Sensor Review

Force sensor system for structural health monitoring using passive RFID tags

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Research article

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Abstract

Purpose – The purpose of this paper is to describe the development of a contactless and batteryless loading sensor system that can measure the internal loading of an object structure through several covering materials for structural health monitoring.

Design/methodology/approach – The paper proposed an architecture by which two radio frequency identification (RFID) tags are used in the system. It has been difficult to realize sensing by RFID because of the low power supply. To solve the power supply problem, a method using functional distribution of RFID tags of two kinds of RFID for communication and power supply was proposed. One RFID tag is specialized as a power supply for communication of strain loading information through A/D conversion. Another is specialized to supply power for driving the strain gauges bridge circuit.

Findings – By using developed system, the measurement of the structural internal loading with 20.0 mm depth was possible through covering materials such as concrete, but also plaster board, flexible boards, silicate calcium board, blockboard, and polystyrene with a resolution performance from 10×10^{-6} to 40×10^{-6}.

Originality/value – A sensor system was developed using passive RFID, which enables measurement of load-deformation information inside a structural object. Moreover, the inexpensive wireless, batteryless devices used in this system require little maintenance, and applications for the user interface are also included in the developed system for uniform management of structural health monitoring. The developed system was evaluated in an actual situation using not only concrete but also other materials as covering materials on a structural object.

Keywords Structural analysis, Strain measurement, Loading (physics), Radio frequencies, Low voltage

Paper type Research paper

1. Introduction

Recently, demands for maintenance of structural objects such as buildings, bridges, and living spaces have been increasing.

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It is important to detect the underlying danger of structures and to monitor the physical fatigue of materials. However, materials of living spaces are almost always covered with concrete. For that reason, it is difficult to measure the internal loadings and status of such structures.

Among existing methods for structural health monitoring, the interior structural state is estimated using surface measurement of changes of measurement objects. Direct monitoring is difficult because the measurement objects are generally covered with decorative laminate such as paint, veneer, plaster, siding, and concrete. Some studies have developed structural health monitoring systems using wireless devices embedded into measurement objects. Such devices, however, require batteries or scheduled power supply maintenance, which requires removal of decorative laminate materials. To maintain the health and safety of the structural objects and to predict the destruction moment, time-series sensing of the internal loading monitoring, called structural health monitoring, is an important area of development (Doherty, 1987; Yuyin and Akira, 2007).

Structural objects in living spaces are damaged by natural hazards over a long-term and are affected by accumulation of damage. If the damage reaches the limit of the safety range or the demand standard, repairs or additional strength must be adequately performed (Figure 1). Therefore, rapid and easy scheduled maintenance are expected to be necessary. To enable convenient maintenance work, structural health monitoring systems should preferably have wireless and batteryless performance, which can be satisfied if passive radio frequency identification (RFID) tags are used because the user tries to sense the internal physical state of structures. However, it has been difficult to apply a passive RFID as a force sensor because RFIDs generally can drive only imperceptible electrical power devices such as temperature sensors (Nath *et al.*, 2006). Power supply problems must be considered consistently if an any-band RFID is used. We developed a force sensor system using passive RFID tags by physically separating a power supply module and a communication module to address these problems. For this study, we developed loading monitoring of measurement objects using a passive RFID tag.

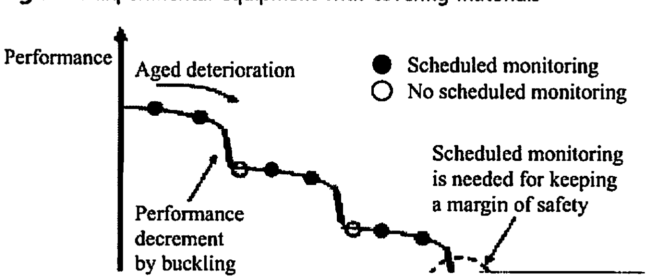
Two major contributions are provided by this study. First, we developed a sensor system using passive RFID, which enables measurement of load-deformation information inside a structural object. Moreover, the inexpensive wireless, batteryless devices used in this system require little maintenance, and applications for the user interface are also included in the developed system for uniform management of structural health monitoring. Second is evaluation of the developed system in an actual situation using not only concrete but also other materials as covering materials on a structural object. With those evaluations, the practical utility is indicated. In particular, the measurement of the structural internal loading with 20.0 mm depth through covering materials such as concrete, but also plaster board, flexible boards, silicate calcium board, blockboard, and polystyrene with a resolution performance from 10×10^{-6} to 40×10^{-6}.

2. Approach

2.1 Related works and the proposed system

Passive RFID is used to achieve remote measurement of interior load-deformation information. Some studies have used optical fiber (Hocker, 1979; Kurashima *et al.*, 1995; Kihara *et al.*, 2001;

Figure 1 Experimental equipment with covering materials



Measures, 2001), wireless LAN devices (Arai *et al.*, 2007), crack sensors (Thiel *et al.*, 2005), or ultrasound waves (Tan and Hirose, 2005) for maintenance of structures by placement in an iron frame, a concrete frame, a wall panel, or other material. In this study, passive RFID tags are examined (Marjonen *et al.*, 2006a,b; Deng *et al.*, 2006). They are expected to be used for structural health monitoring. Recently, studies using RFID tags for structural database management increases with RFID technology that sends and receives data without using physical contact with a wireless that uses electromagnetic fields, electric waves, etc. for communication. For instance, Yabuki described a system by which the construction process can be known immediately to users using the RFID tag for the checking and repairing structures (Yabuki *et al.*, 2004). The YRP Ubiquitous Networking Laboratory (2006), developed a system that can support management of a structural database and construction processes by putting an RFID tag on a steel column or wall panel; they developed an RFID tag that can be implanted into concrete (www.ubin.jp/press/pdf/UNL061204-04.pdf, 2006). Therefore, research using RFID tags, implant inside structures for structural maintenance has been actively pursued. Passive RFID with a sensor function is attracted and studied in recent years (Opasjumruskit *et al.*, 2006; Woochul *et al.*, 2006; Philipose *et al.* 2005). To apply those technologies to structural health monitoring, it is required to design lower power consumption circuit because a strain gage needs higher electrical power, comparing with thermistor and so on.

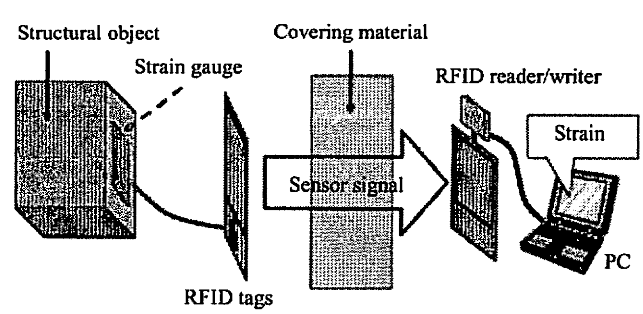
In this research, we develop the structural health monitoring system using passive RFID tags that can measure the strain loadings of structures (Figure 2) and evaluate the effectiveness using general covering materials. The developed system enables users to measure structural strain through the covering materials with no contact, and electrical wires in the signal for communication and a power supply is unnecessary. Especially, this study specifically addresses strain loading measurement using RFID, how to design the sensor circuits to reduce electrical power consumption, and evaluation in an actual environment with materials in popular use.

2.2 Problems and solution method

A strain gauge is used in the developed system to measure loading on the structure. The displacement range of a strain gauge is so minute that the sensor board consists of an amplifier circuit for detection of sensor output and a lowpass filter for high-frequency denoising, and a partial circuit to input to the lowpass filter and ADCIN terminal.

The strain gauges must be driven with a very small power supply from RFID tags. In addition to the power supply, this

Figure 2 Develop a structural health monitoring system using passive RFID tags



system needs a power supply to communicate: for transmission of the material's state data. The energy passed through an RFID decreases with the distance between the RFID reader/writer and the tags. It is, however, difficult to combine their power supply. Therefore, a contactless sensor system using RFID is limited to low power and responsible sensor devices such as a thermistor.

To solve the power supply problem and to realize stable communication using RFID, in the developed system, we propose a method using functional distribution of RFID tags of two kinds of RFID for communication and power supply. One RFID tag is specialized as a power supply for communication of strain loading information through A/D conversion. Another is specialized to supply power for driving the strain gauges bridge circuit. Herewith, using the separation of RFID functions, we develop structural health monitoring systems to realize contactless sensing with very small power.

3. Developed systems

3.1 System architecture

3.1.1 Overview of the architecture

Figure 3 shows architectonics of the developed system, which consists of an RFID sensor module put into a structure inside of covering materials; it also shows the measurement module for data acquisition. In the RFID sensor module, the strain gauge data are converted to A/D through a sensor on the RFID tag. The data are transported to the measurement module through the covering materials with RFID reader/writer devices. From the data, information about deformation volume and loading are calculated without computers. Details of devices used in this system are described in the Appendix section. The RFID tag can passively operate with electromagnetic induction and the radio wave frequency is 13.56 MHz band. The degree of power supply depends on the size of on-board antenna in the tag, 56 mm high and 84 mm wide. The available voltage and electrical power are 2.2 V and 4.4 mW, respectively, on specifications. In fact, since the tag output 2.25 V, this voltage value is used in developed equipment.

3.1.2 RFID sensor module

Each RFID sensor module comprises strain gauge sensors, a sensor board, and RFID tags. A bridge circuit is configured with strain gauge sensors in thesensor board. The sensor board consists of an amplifier circuit for detection of sensor output and a lowpass filter for highfrequency denoising, in addition to a partial circuit to input to the lowpass filter and the ADCIN terminal.

The most important problem for designing the modules is how the strain gauges on a sensor board are driven with a small power supply from RFID tags. Both the ADC function of RFID and the communication process using RFID tags require high power consumption. Therefore, sensor systems using an RFID tag with ADC functions are limited to applications such as a thermistor, which has low power consumption, without an amplifier. To solve these problems, we developed an RFID sensor module consisting of two kinds of RFID tags, one is for the power supply, another is for communications. To separate the functions is a utilitarian architecture because the electricity consumption is expected to be an important consideration when an RFID is used for sensing. This architecture realizes stable communication.

Figure 4 portrays the circuitry of the developed RFID sensor module. The voltages of a bridge circuit, an amplifier circuit, and a lowpass filter are supplied from the left side RFID tags of Figure 4. This circuit is driven by constant voltage, 2.25 V, between the VDD and GND terminal. The fixed resistance is inserted to input wiring to the bridge circuit to avoid carrying high level electric current. The drive current of the bridge circuit is set to 0.1 mA and the power consumption of the modules is set to 2.5 mW. The offset calibration is carried out by adjusting RV in the figure. The operational amplifier (NJU7016D) is used for

Figure 3 Developed system architecture

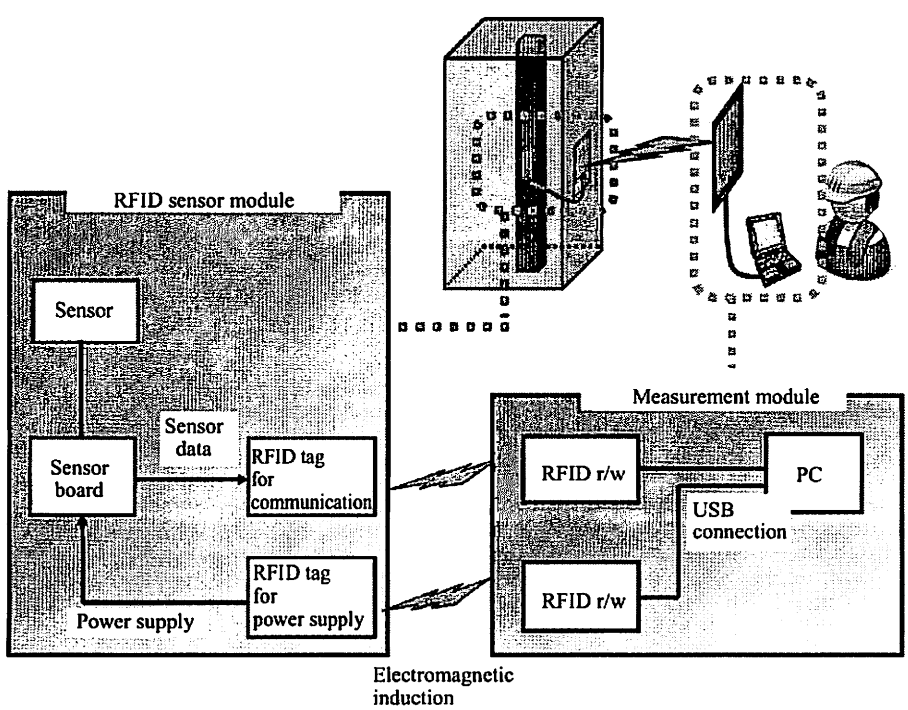


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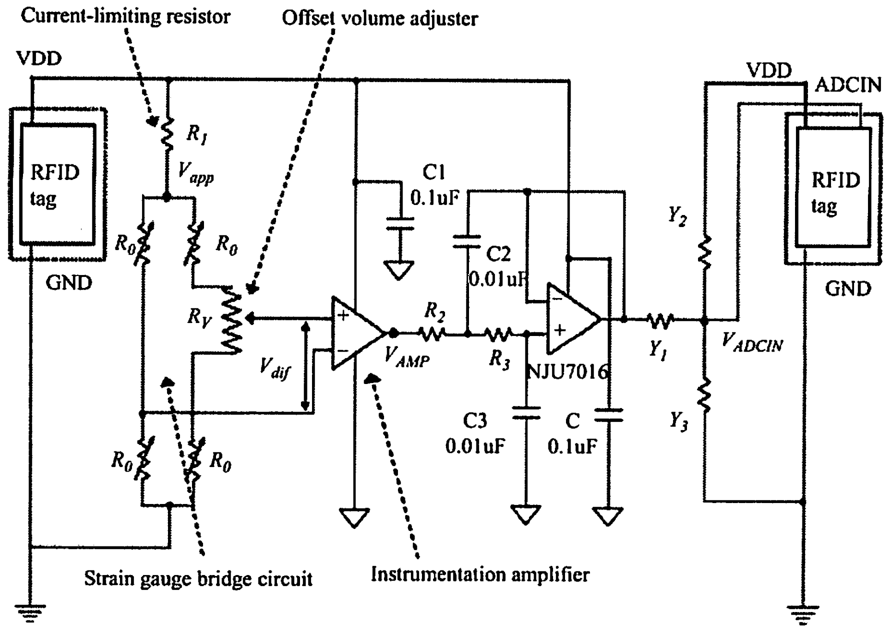
Figure 4 Developed RFID sensor module circuit



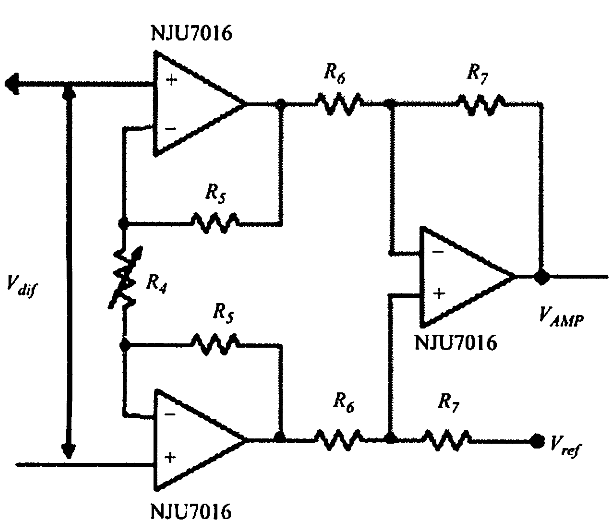
the amplifier circuit and is driven with low voltage. To filter out the noise from RFID electrical wave, three operational amplifiers are used for common mode noise rejection between both ends of a bridge circuit, as shown in Figure 5). The cutoff frequency of the lowpass filter is set to $fc = 1.6\,\text{kHz}$.

The right side RFID tags of Figure 4 are for data acquisition from a measurement module. The partial voltage with three resistances Y_1, Y_2, and Y_3 from the amplifier circuit is input to the ADCIN terminal.

In Figure 4, the input voltage to ADCIN terminal is described as below. In this regard, however, the effect of R_V, that is the offset volume adjuster, is approximately negligible because $R_V \ll R_0$.

Let ε be the strain of R_0 in Figure 4. The small resistance changes ΔR_0 occur and the relationship between the gauge coefficient of the strain gauge is described as:

Figure 5 Instrumentation amplifier circuit



$$\frac{\Delta R_0}{R_0} K\varepsilon. \quad (1)$$

Let V_{dif} be the difference of voltages generated by the bridge circuit. Before generating the difference of voltages, the bridge circuit is in an equilibrium state. Let V_{app} be the applied voltage to the bridge circuit; we have:

$$V_{\text{dif}} = \frac{R_0 R_0}{(R_0 + R_0)^2} K\varepsilon V_{\text{app}} = \frac{1}{4} K\varepsilon V_{\text{app}}. \quad (2)$$

The output voltage from the amplifier circuit V_{AMP}, as show in Figure 5, is described as follows using amplifier gain A:

$$V_{\text{AMP}} = A \times V_{\text{dif}}. \quad (3)$$

The amplifier gain A is described as follows:

$$A = \left(1 + \frac{2R_4}{R_5}\right) \frac{R_7}{R_6}. \quad (4)$$

R_4, R_5, R_6, and R_7 are determined to satisfy amplifier gain A based on strength of a measurement object. Let V_{ADCIN} be the input voltage from the ADCIN terminal and let Y_1, Y_2, and Y_3 be the conductances between V_{AMP}-ADCIN terminals, VDDADCIN terminals, and ADCIN–GND terminals. Thereby, we have:

$$\begin{aligned} V_{\text{ADCIN}} &= \frac{1}{Y_1 + Y_2 + Y_3}(V_{\text{AMP}} Y_1 + 2.25 Y_2) \\ &= \frac{1}{Y_1 + Y_2 + Y_3}\left(\frac{1}{4} K\varepsilon A V_{\text{app}} Y_1 + 2.25 Y_2\right). \end{aligned} \quad (5)$$

The output of V_{AMP} can be input to ADCIN terminal if we set $Y1 \gg Y2$. The developed system has 0.05 V 5 V_{AMP} 5 2.20 V because the output amplifier range is set as 0.05 V to 2.20 V. Figure 6 shows the developed RFID sensor module, which is encapsulated in an acrylic package. The figure shows that they are located parallel with 30 mm distance to avoid interference between RFID tags. The component parts of the RFID sensor module are presented in Table I.

Figure 6 Developed RFID sensor module

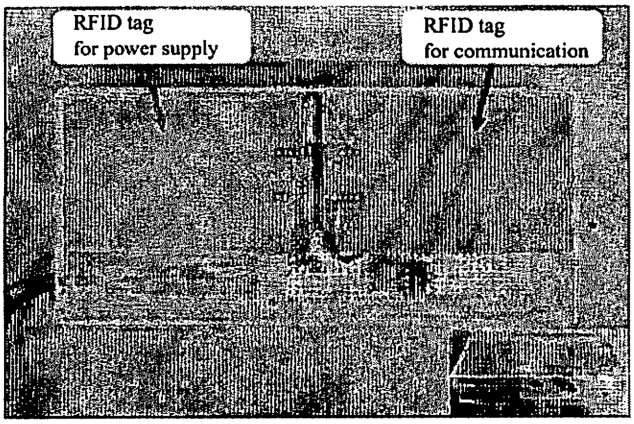


Table I Component parts of the RFID sensor module

Component	Quantity
RFID tag	2
Strain gauge	4
Operational amplifier (NJU7016D)	2
Fixed resistance (±0.1 percent)	12
Variable resistance	2
Multilayer ceramic capacitor	7

3.1.3 Measurement module

The developed measurement module consists of two RFID reader/writers and a computer for data processing and a user interface as Figure 3. One RFID reader/writer is for communication; another is for the power supply with an RFID sensor module. The measurement module obtains the value of V_{ADCIN} from the RFID module and the strain is calculated using the computer according to Equation (5). In the computer, the structure model, such as the parameters in Equation (5), is known for uniform management of structural health monitoring. The application for the user interface, which is one component of the developed system, is portrayed in Figure 7. Users can acquire the strain information of the target structure through covering materials. The application has materials parameters and transit from V_{ADCIN} to strain with (5).

3.1.4 Advantage of developed system

To drive both bridge circuit for sensing and communication circuit, large amount of power is needed, compared with the circuit without a sensor device. As a solution, with two RFID tags, we designed the circuit, that is physically separated to both functions. If above functions are forced in circuit with one RFID tag under conditions assumed in this developed system, the following problems are concerned. The RFID devices, that are equipped in developed system, carry out eight times of transmitting and receiving at one sensing process. When the communication circuit is driven, the voltage level of VDD terminal is forced to fluctuate according to communication state. During the communication, the available electrical power for driving bridge circuit is effected. When utilizing device specification electrical power to the full, both transmitting sensing data and driving bridge circuit cannot concurrently operate. Alternatively, if transmitting is achieved, it is expected that the data is partially reliable because sensing false positive is caused by lowering of electric power. The circuit design is complicated to realize stable voltage supply and it is difficult to exploit full electrical power of RFID.

In developed system, actually, the summation of the resistance in bridge circuit is $350\,\Omega$. In the case of that current limiting resistor is $R_1 = 1\,\mathrm{k}\Omega$ and available voltage supplied by a RFID tag is 2.2 V, that is the device specification, electrical power consumption is calculated as 3.6 mW. In this case, more than half of electrical power is used to drive bridge circuit because the electrical power supply of the RFID tag is 4.4 mW. In addition, the electrical power for driving amplifier circuit and voltage divider circuit is needed. Communication errors occur if the stable supply voltage 2.2 V cannot be kept. The architecture, that is physically separating those functions by two kinds of RFID tags, is developed to solve the above problems. From another reasonable standpoint, the developed system enables to utilize full electrical power supplied from the RFID tags.

4. Experiments

4.1 Experiments for evaluation of basic properties

4.1.1 Experimental overview

In this developed system, concern exists that the power supply to a sensor module decreases when the distance separating the RFID sensor module and a reader module increases. Therefore, unstable operation of each circuit and communication might occur from a low power supply. First, in this section, the effective distances for measurement without covering materials are evaluated as basic properties of the proposed system.

4.1.2 Experimental equipment

Figure 8 shows the experimental equipment In this experiment, cantilever examination is carried out using a general structural rolled steel (SS400). The vertical load is added gradually to the free end. The strain in the surface of the target member of framework is measured using the proposed system. Through this experiment, the effective distances without covering materials are demonstrated. In the fixed end, the member of the framework is fixed to the base with a precision vise. A digital force gauge (DS2-500N) is fixed to the same base to avoid momentum; it is used to measure the additional forces imparted to the free end.

In this experimental device, the strain ε is described as Equation (6) when F is added to the free end, as shown in Figure 9:

$$\varepsilon = \frac{6x}{bh^2E}\left(F + \frac{wx}{2}\right). \qquad (6)$$

In that equation, w represents the distributed load under its own weight, and E, b, and h, respectively, signify the Young's modulus, width, and thickness of the member of the framework.

4.1.3 RFID module settings

In this experiment, the four strain gauges are set into an x configuration in corners of the surface of the member of the framework so that all distance x between the strain gauges' position and the free end are equal, as shown in Figure 10. Then, the output value of V_{dif} in Equation (2) quadruples; we have:

$$V_{dif} = K\varepsilon V_{app}. \qquad (7)$$

Figure 7 User interface for uniform management of structural health monitoring

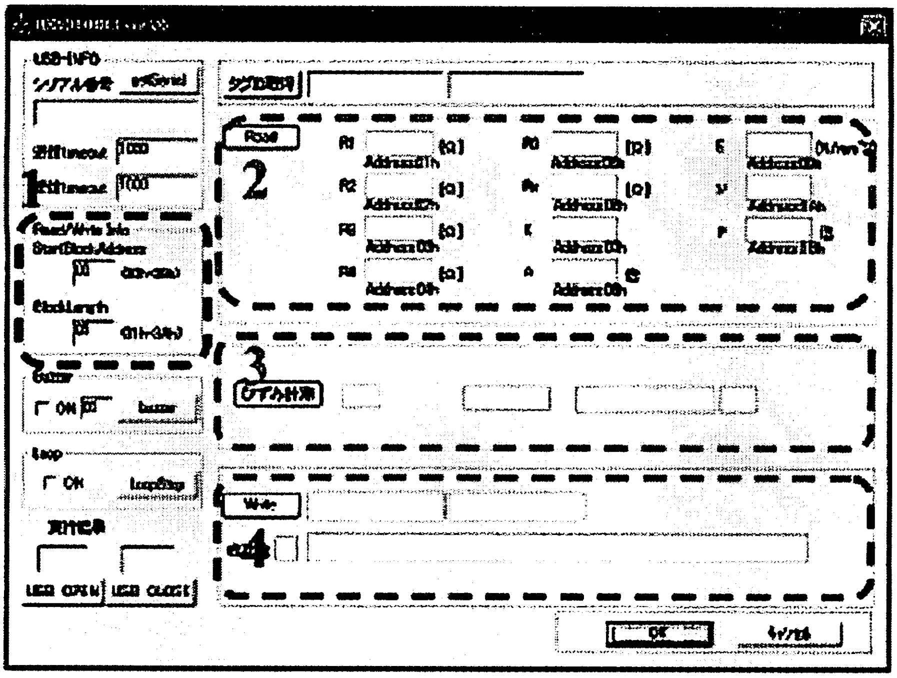


Figure 8 Experimental equipment

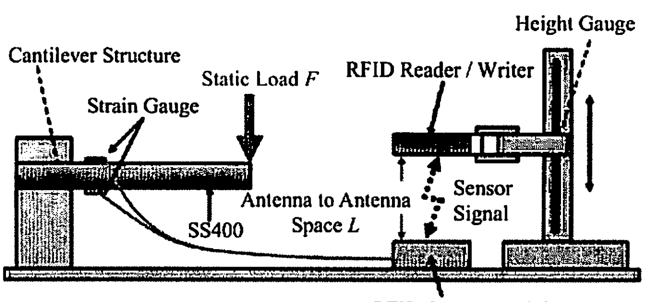
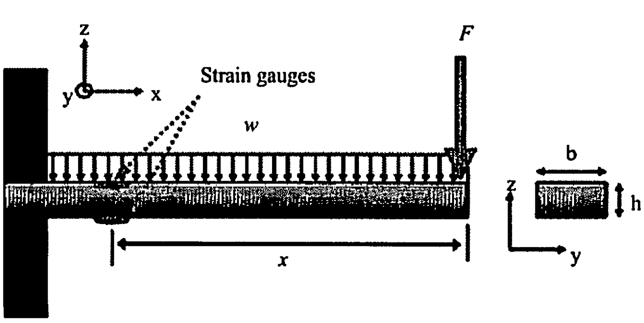


Figure 9 Cantilever beam examination



Actually, considering the effect of the offset adjusting resistance RV of Figure 4, we have:

$$V_{\mathrm{dif}} = \frac{R_1}{R_1 + \frac{R_V}{4}} K \varepsilon V_{\mathrm{app}}, \tag{8}$$

where it is approximated that $V_{\mathrm{dif}} = 0$ because the differences between the resistances of strain gauges are very small. Table II shows the parameter value set in this experimental condition and equipment. Then, Equation (5) is described as:

$$V_{\mathrm{ADCIN}} = 2.35 \times 10^3 \varepsilon + 0.35 \times 10^{-3}. \tag{9}$$

Figure 10 Strain measurement using the four active gauge method

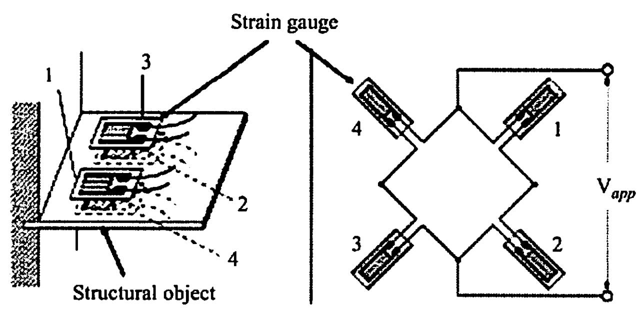


Table II Experimental parameter set

x	Distance of load-point	300 mm
h	Thickness of testing material	10 mm
b	Width of testing material	20 mm
w	Own weight	1.55×10^{-2} N/mm
E	Young's modulus	205×103 N/mm^2
V_{app}	Bridge applied voltage current-limiting resistor	$R_1 = 1{,}000\,\Omega$
R_0	Unloaded resistance of strain gauges	350 Ω
K	Gauge factor	2.1
R_v	Offset adjusting resistance	50 Ω
A	Gain	1,000
Y_1	Conductance of partial voltage resistance	1/100 s
Y_2, Y_3	Conductance of partial voltage resistance	1/630 s

The second terms of the right side of equation (9) are negligible because the resolution of ADC in a RFID tag is about 8.8 mV.

In addition, the strain gauge and gain A is determined based on design strength $F_{max} = 235\,N/mm^2 \times 80$ percent of SS400 of thickness 40 mm. In this measurement range, SS400 is within the elastic area.

4.1.4 Experimental methods

The sequence of experiments is explained as follows:

- The antenna of the reader module is moved close to the RFID tag antenna.
- The distance L between each antenna is 5.0 mm from 2.5 mm as the origin.
- A load is added to the free end by 10 N steps from 0 N to 200 N at each antenna distance.
- The strain is measured using the developed system ten times for each distance and load.

4.1.5 Results

The experimental results of evaluations of basic properties are shown in Figure 11. The black line shows a realistic value predicted using Equation (9). The m in the figure represents the mean squared error. When approaching $L = 32.5$ mm, m increases because of the power supply reduction. The developed system enables measurement of the forces from $L = 2.5$ mm to $L = 32.5$ mm.

To examine the relationship between the measured power reduces and distance L, the values of V_{ADCIN} against L increase are illustrated in Figure 12. Actually, V_{ref} in Figure 5 was measured. Although the loading is fixed to $F = 50$ N, other cases give nearly same results because power reduces depends on only distance L. When approaching $L = 32.5$ mm, m dramatically increases. Therefore, it is considered that the critical distance for power supply exists around over $L = 30$ mm. These results indicate the limitation of available measurement distance in developed system. If L 5 30 mm, the developed system can operate because of stable voltage by both RFID tags for power supply and the amplifier circuit.

4.2 Experiments for evaluation in actual environmental conditions

4.2.1 Experimental overview

It is necessary to evaluate the possibility that the developed system can work stably in an actual environment, which includes measurement through the covered materials. The assuming situation is to hold the reader module over a typical wall; the RFID sensor modules are present inside the wall. In this section, we configure situations of several covering materials inserted between reader modules and RFID sensor modules, and perform experiments to evaluate the developed system's function.

Figure 11 Experiments with out covering materials at $L = 2.5$ mm, $L = 12.5$ mm, $L = 22.5$ mm, and $L = 32.5$ mm

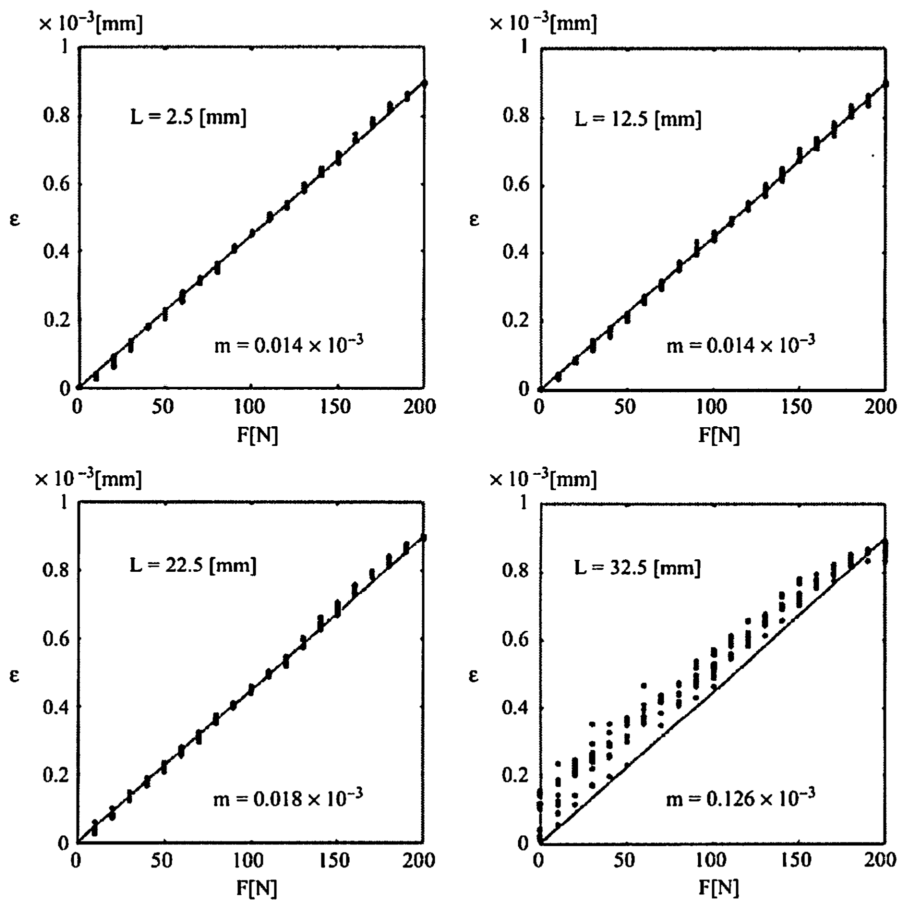
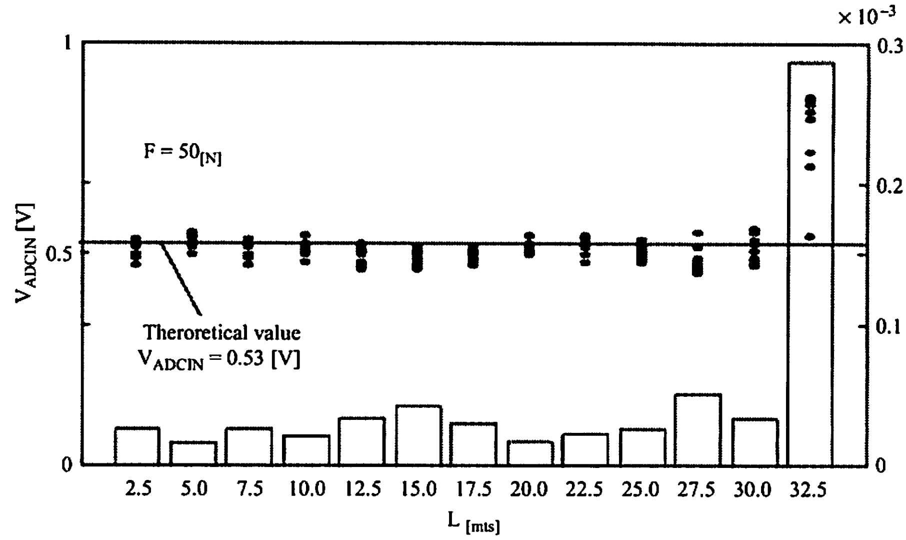


Figure 12 Relationship between distances L and voltage saturation of V_{ADCIN} at $F = 50$ N. The bar graph shows the mean squared error m at each L. The dots and a line mean measurement value by developed system and theoretical value, respectively



4.2.2 Experimental equipment

The equipment for experiments is shown in Figure 13. The reader module is located in parallel opposite from the RFID sensor module. The experiments are carried out in identical conditions (Figures 8-10). The loadings are added to free end and the equipment by 10 N steps from 0 to 200 N.

4.2.3 Experimental methods

Various covering materials are used: concrete, plaster board, flexible, board, silicate calcium board, blockboard, and polystyrene. These materials are often present in typical walls. The materials' thicknesses are all set to 20 mm. Therefore, the distance between reader modules and sensor modules is fixed at 20 mm.

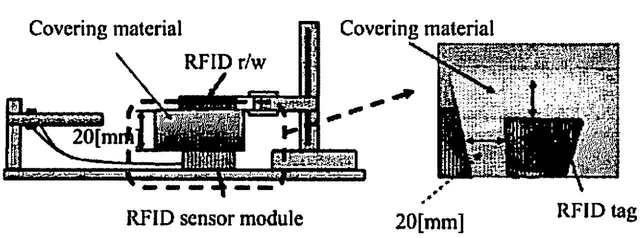
4.2.4 Results

The experimental results of using each covering material are portrayed in Figure 14. The theoretical values obtained by Equation (9) are shown as a continuous line on each figure. The m represents the mean squared error, as in previous experiments.

4.3 Summary of results

In this section, the performance and stability of the developed system are evaluated. The system can measure the internal loadings of the structure by $L = 32.5$ mm without covering materials. When covering materials are inserted and $L = 20$ mm, the measurement can be carried out. For details, when L increase from $L = 2.5$ mm to $L = 32.5$ mm. The measuring error also increased from 1 to 13 percent for the set measurement range. Within the range of L 5 30 mm, it is possible to measure with strain resolution from 10×10^{-6} to 40×10^{-6}. Although the ADC in the RFID sensor tag module has eight bit memory and 1/256 resolution performance of measurement range, the result of the range actually remains at a low level. It is considered that around over $L = 30$ mm is the limited for the power supply depending on the device specific characteristics. In addition, regarding the experiment with covering materials, the performance is evaluated toward use in an actual environment. The reason for differences of the mean squared error m on each material is considered that the transmission factors and fluctuations of power supply are different.

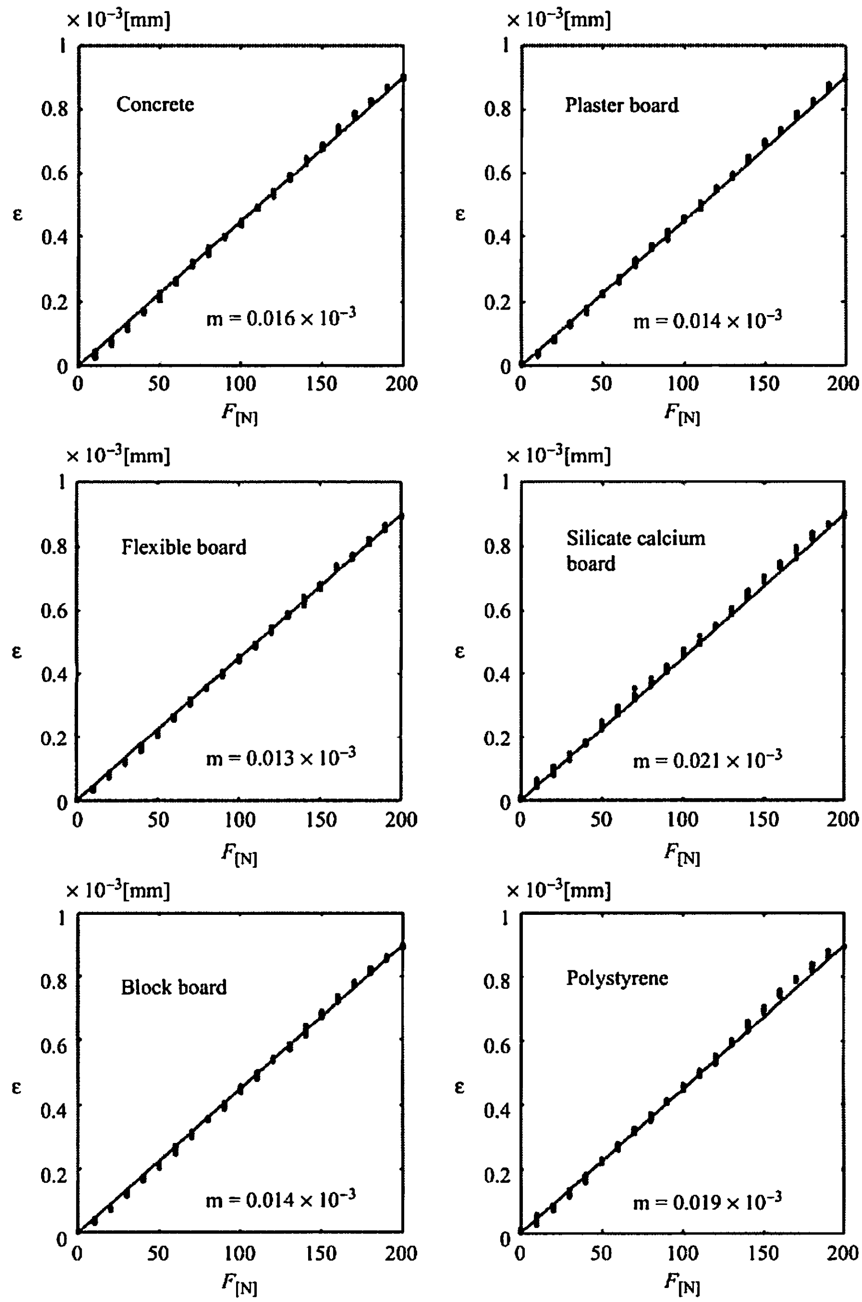
Figure 13 Experimental equipment with covering materials



5. Conclusion

For this study, we developed a force sensor system for structural health monitoring. Using an RFID, the system can measure the internal load of structural objects without contact. Additionally, we carried out an experiment through several covering materials that are assumed to be used in actual situations. To solve dissipation power problems, we proposed a simple idea: the separation of the RFID module to power supply and communications. Through circuit design for low electric power consumption, force sensing is realized on the conditions assumed for actual situations. The developed system can also be configured using commercially available and inexpensive devices. Regarding evaluations of developed system, it enables measurement of the forces with maximum distance of $L = 32.5$ mm In $L < 30.0$ mm. We confirmed the effectiveness of the proposed system, which enables measurement within 10×10^{-6} to 40×10^{-6} resolution performances, transmitting through covering materials that are used in actual building structures.

Figure 14 Experiments in actual environmental conditions



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Further reading

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Appendix: RFID devices used

The RFID tags and RFID reader/writer (RX5300; Yoshikawa RF Systems Co,. Ltd. products) devices enable contactless communication with ADC function. The basic specifications are presented in Tables AI and AII.

Table AI Specifications of RFID tags

Receiving characteristics	Center frequency	13.56 MHz
	Modulation method	ASK
	Coding method	PPM
	Subcarrier	None
	Communication rate	26.48 kbps
Transmitting characteristics	Center frequency	13.56 MHz
	Modulation method	ASK of subcarrier
	Coding method	Manchester
	Subcarrier	423.75 kHz
	Communication rate	26.48kbps
Available power		
Supply	Voltage	2.2 V
	Electrical power	4.4 mW

Table AII Specifications of RFID reader/writer

Interface of computers	**USB**
Antenna shapes	External diameter 40.0 × 70.0
	Internal diameter 34.5 × 63.5
Antenna output	Number of turns four
	Maximum100 mW

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