Development of a Wireless Sensor for Simultaneous Measurement of Fatigue and Corrosion

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Abstract In previous study, it was demonstrated that smart stress-memory patch and ACM (Atmospheric Corrosion Monitor) sensor are suitable and effective for fatigue and corrosion monitoring, respectively. However, some problems still exist on the smart patch and ACM sensor. First, although "sputtered smart patch", which can estimate crack length wirelessly, has been developed, the crack length could not be estimated accurately sometimes because the resistance of the metal film on it was unstable. Second, it has not been figured out whether the existing patch is applicable to some fatigue condition such as the landing gears of the airplanes. Third, until now the wireless monitoring by ACM sensor has not been developed, and the communication distance of smart stress-memory patch via RFID tag (30 mm) is not sufficient. Therefore, in this research, 1) the measurement accuracy of the ion-sputtered metal film was improved through FEM; 2) whether the existing smart patch is applicable to high-stress low-cycle fatigue environment or not has been figured out; 3) a new wireless device equipped with ZigBee has been developed. By using this device, the wireless monitoring by ACM sensor was realized and the communication distance has been improved to more than 30 m.

Keywords Structural health monitoring, Fatigue, Corrosion, Wireless, Smart stress-memory patch

1. Introduction

Many construction accidents, which are due to the degradation progress, occur to structures, such as bridges, ships, trains, aircraft, power plants and buildings every year. Since these failure accidents brought much risk to our daily lives and industry production, it is important to prevent them in advance. Moreover, it has been well known that fatigue and corrosion are fate factors of such failure. Thus, a sensor which is able to monitor fatigue and corrosion effectively at the same time for a long-term performance is desired. In previous study, it was demonstrated that smart stress-memory patch and ACM (Atmospheric Corrosion Monitor) sensor are suitable and effective for fatigue and corrosion monitoring respectively.

Smart stress-memory patch (hereinafter called "smart patch") is consists of a thin copper specimen with a pre-crack can estimate fatigue damage parameters such as number of cycles, stress amplitude of structures[1-5], which can be estimated from the fatigue crack growth of smart patch fixed on the structure by using two smart patches with different characteristics. Moreover, "sputtered smart patch", which has ion-sputtered metal film and insulating layer on smart patch as a thin crack gage, can estimate crack length by measuring electrical resistance change of the ion-sputtered metal film wirelessly via RFID tag.[6] However, some problems still exist for this application. First, the crack length could not be estimated accurately because sometimes the resistance of the ion-sputtered metal film was unstable and did not increase monotonically as the crack length increased. Second, the communication distance of smart patches via RFID tags only (30 mm) is not sufficient for wireless network system. Third, to prevent the fatigue failure of the landing gears of the airplanes, a sensor which is applicable for high-stress low-cycle fatigue environment is also necessary. It has not been figured out whether the existing smart patch is applicable to such fatigue condition or not.

For corrosion monitoring, ACM sensor consisting of a Fe-Ag galvanic couple was developed and applied for the evaluation of corrosion of atmospheric environments for long-term performance. By analyzing the magnitude and time variation of the sensor output, *I*, the occurrence and duration of rain, dew and dry periods, T_{rain}, T_{dew} and T_{dry}, could be distinguished and determined, respectively. And by referencing to the calibrating curve between output of ACM sensor (*I*) and relative humidity (*RH*) - empirical *I-RH* calibrating curve, the amount of deposited sea salt could also be estimated.[7] However, because ACM sensor was powered by battery, AC power or solar battery and the output data of ACM sensor was recorded by a microcomputer, the setting-up places has been restricted and the data collecting costs time and labor. Thus, it is necessary to develop a wireless monitoring method for ACM sensor which can be used for long-term performance as well as smart patch.

In this study, (1) the measurement accuracy of the ion-sputtered metal film on "sputtered smart patch" was improved by changing the shape of the ion-sputtered metal film through FEM; (2) a new wireless device was developed to improve the communication distance between smart patches; (3) fatigue experiments have been executed to figure out whether the existing smart patch is applicable to high-stress low-cycle fatigue environment or not; (4) the wireless monitoring by ACM sensor was realized by using the new wireless device as well as smart patch.

2. Principle

2.1. Estimation of cyclic number and stress amplitude by RFID-based smart patch

A schematic image of the sputtered smart patch is shown in Figure 1. This sensor is composed of an ion-sputtered metal film deposited on the smart patch (a thin copper specimen with a pre-crack).

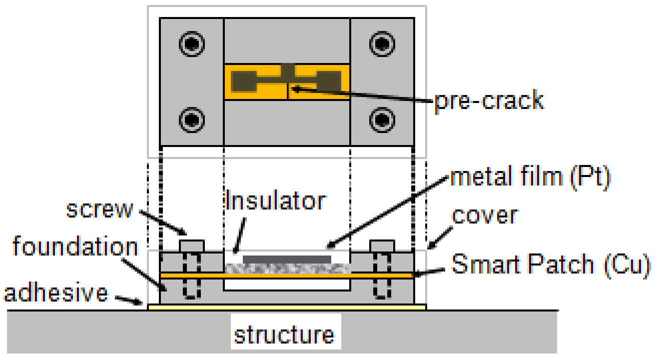

Figure 1. Schematic image of the sputtered smart patch. [6]

The details of the principle of smart patch is described in the previous paper.[1] The cyclic number (*N*) and stress amplitude ($\Delta\sigma$) of structures can be estimated from the crack length values detected from the two smart patches with different characteristics using the following equations:

$$\Delta\sigma = [C_2 \cdot C_1^{-1} \cdot W_1 \cdot W_2^{-1} \cdot (\pi W_2)^{-m_2/2} \cdot (\pi W_1)^{-m_1/2} \int_{\alpha_0}^{\alpha_1} \{\sqrt{\alpha} f(\alpha)\}^{-m_1} d\alpha \Big/ \int_{\alpha_0}^{\alpha_2} \{\sqrt{\alpha} f(\alpha)\}^{-m_2} d\alpha]^{1/(m_1-m_2)} \quad \text{......(1)}$$

$$N = [C_2^{m_1} \cdot C_1^{-m_2} \cdot W_1^{m_2} \cdot W_2^{-m_1} \cdot (W_2/W_1)^{m_1 m_2/2} \{\int_{\alpha_0}^{\alpha_1} \{\sqrt{\alpha} f(\alpha)\}^{-m_1} d\alpha\}^{m_2} \Big/ \int_{\alpha_0}^{\alpha_2} \{\sqrt{\alpha} f(\alpha)\}^{-m_2} d\alpha\}^{m_1}]^{1/(m_2-m_1)} \quad \text{......(2)}$$

where *W* is the width of specimen, α_0 is the normalized initial crack length, α is the normalized initial crack length, C and m are empirical constants of Paris law and $f(\alpha)$ is the shape factor of the stress intensity factor. Indexes 1 and 2 represent smart patch 1 and 2, respectively. By substituting the normalized crack lengths α_1 and α_2 detected from two smart patches into Eqs. (1) and (2), the cyclic number and the stress amplitude can be estimated as shown in Figure 2. Furthermore, fatigue life will be assessed by substituting the estimated cyclic number and stress amplitude into Miner's rule.[8]

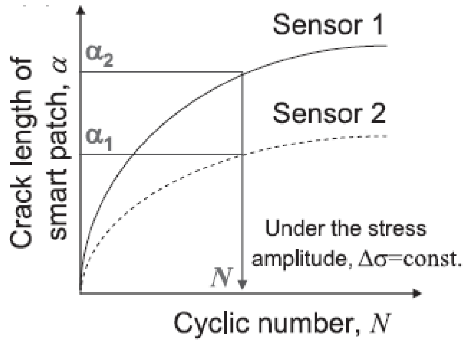

Figure 2. Principle of estimation of cyclic number from crack lengths in two smart patches.[6]

2.2. Estimation of corrosivity in atmospheric environment by ACM Sensor

An ACM (Atmospheric Corrosion Monitor) type corrosion sensor, consisting of a Fe-Ag galvanic couple was developed and applied for the evaluation of corrosivity of atmospheric environments. The sensor was designed considering mass-production and good reproducibility of results, making it convenient for long-term corrosion data acquisition. Besides the sensor output, I, temperature, relative humidity (RH) were also recorded by a microcomputer. By analyzing the magnitude and time variation of I, the occurrence and duration of rain, dew and dry periods, T_{rain}, T_{dew} and T_{dry}, could be distinguished and determined, respectively. And by referencing to the empirical I-RH calibrating curve, the amount of deposited sea salt, Ws, could also be estimated. It was also found that the corrosion loss could be estimated in both indoor and outdoor sites by analyzing sensor output. Corrosivities of some kinds of exposure sites, not only outdoor environments but also indoor environments, were evaluated by using the ACM sensor.

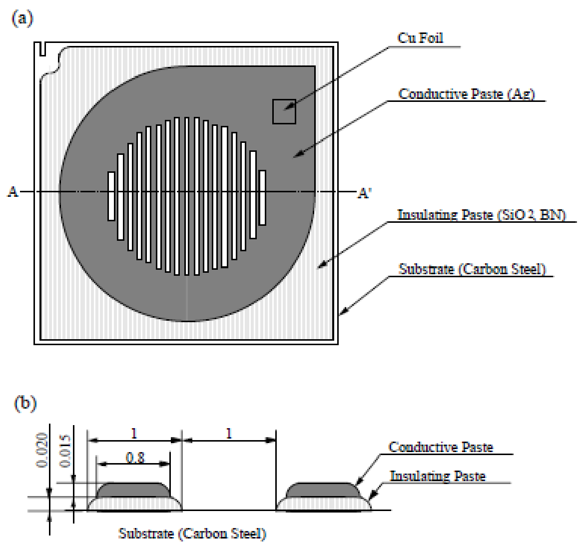

Figure 3. Schematic representation of the sensor.[7]

The sensor is shown schematically in Figure 3. A 0.8 mm thick carbon steel sheet was machined to the size of 64 mm x 64 mm to work as the substrate. After ultrasonically degreasing the substrate in acetone, an insulating paste with BN filler and epoxy resin, was printed on the substrate with a thickness of 20 μm. A conductive paste with Ag filler and epoxy resin was then printed on top of the insulating layer with a thickness of 15 μm. This conductive paste acted as the cathode, and the exposed area of steel substrate, as the anode.

3. Experiment and Simulation

3.1. FEM model to evaluate the measurement accuracy of the metal film

As showed in Figure 4, the crack length could not be estimated accurately because sometimes the resistance of the existing ion-sputtered metal film was unstable and did not increase monotonically as the crack length increased.

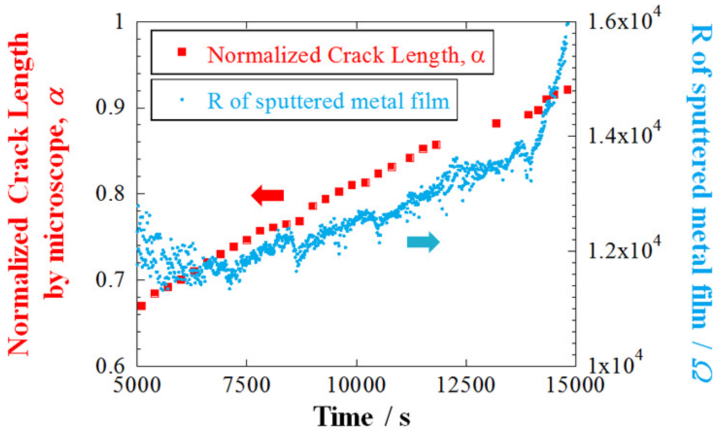

Figure 4. The correlation between normalized crack length observed by microscope and the resistance of sputtered metal film measured by digital multimeter (DMM).

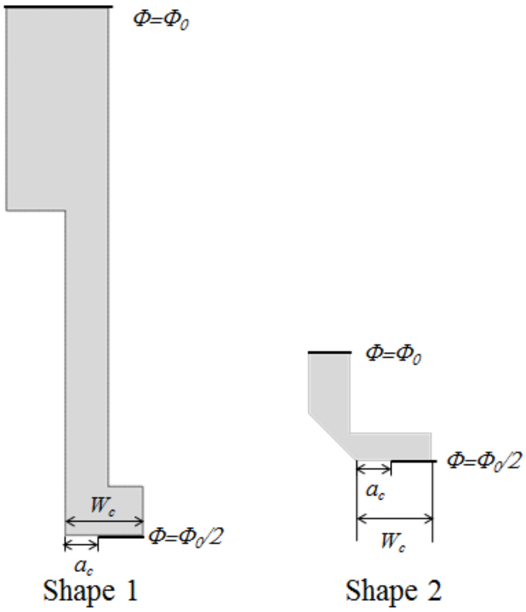

Figure 5. Definition of a_c and W_c in the ion-sputtered metal film, and the boundary condition on FEM.[6]

In order to figure out the optimum shape of the conductive film, electrical potential analysis by FEM was performed by changing the crack length a_c=0 to 1.9 mm under the fixed voltage. Because the shape of the ion-sputtered film is always laterally zygomorphic, it is suitable to calculate the electric current by adding half of the voltage to half shape of the film. The definition of a_c and W_c (W_c=1.9 mm) of the ion-sputtered film and the boundary condition for FEM are shown in Figure 5. The electric current of metal film was calculated by the integration of current density in analytical results, and the resistance was derived from Ohm's law.

3.2. Wireless Communication

3.2.1 . Using RFID tag

RFID (Radio Frequency Identification) is a technology that transmits information between a reader and tags attached to an object using electromagnetic induction for the purpose of identification. It is widely used as IC tag or IC card. The RFID system is well known for its benefits of low cost, simple measurement, easy configuration and so on. Since tag is powered by electromagnetic induction from the reader, tag itself does not need battery for sensing and data transmission. By using RFID tags, evaluating the fatigue damage has been realized in previous research.[5] The schematic of wireless system for measuring crack length using RFID tag is shown in Figure 6.

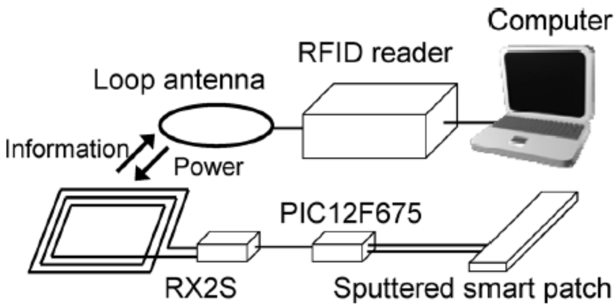

Figure 6. Schematic of wireless system for measuring crack length using RFID tag and reader.[6]

The wireless system composed of sputtered smart patch, RFID tag (RX2S, Yoshikawa RF Systems Co., Ltd.) and microprocessor (PIC12F675, Microchip Technology Inc.), in which the electrical resistance of the ion-sputtered metal film was converted to digital value and transmitted to the RFID reader (RX2100, Yoshikawa RF Systems Co., Ltd.). The RFID reader plays two roles of supplying power to RFID tag and acquiring the measured value from RFID tag by a unique protocol.

3.2.2. Using ZigBee

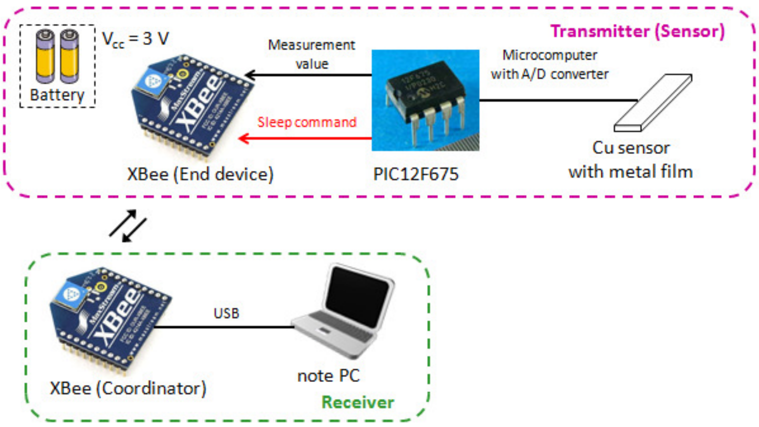

Figure 7. Schematic of new wireless system

To improve the communication distance, a new wireless device equipped with ZigBee (IEEE

802.15.4) was developed. The schematic of new wireless system for measuring crack length using ZigBee is shown in Figure 7. The transmitter contains sputtered smart patch and microprocessor (PIC12F675, Microchip Technology Inc.) as the same as the method.

Moreover, several wireless devices need to transmit with one receiver at the same time, to build the wireless system. The wireless communication among 1 receiver and 4 wireless transmitters has been tested as shown in Figure 8. The distance from transmitters to receiver are 20 m, 30 m, 30 m, 20m, respectively. Moreover, two transmitters were put at about 1 m above the ground, and two were on the ground.

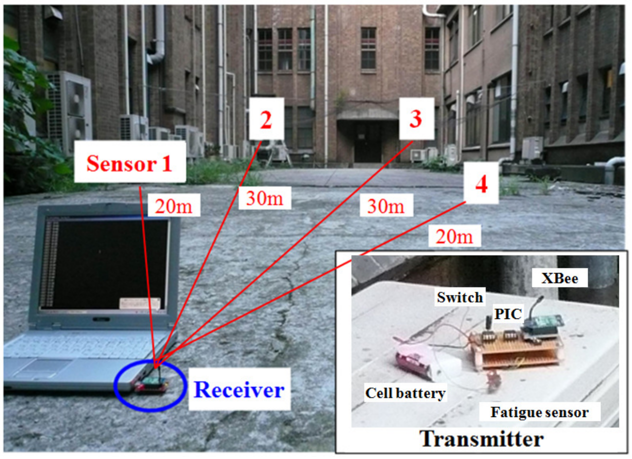

Figure 8. The wireless communication among 1 receiver and 4 new wireless devices and the composition of the new wireless device.

3.3. Fatigue experiment

To figure out whether the existing smart patch is applicable to high-stress low-cycle fatigue environment or not, fatigue experiments have been executed. Smart patch was clamped at both ends on fatigue testing machine with an electro-magnetic actuator (MMT-500N, Shimadzu), and fatigue pre-crack was introduced under maximum strain of 0.002 and strain ratio of 0.5 until total crack length reached about 2.7 mm. Afterwards, fatigue experiments were carried out under constant amplitude strain with maximum strain of 0.004 twice and 0.006 once respectively, strain ratio of 0.5 and frequency of 19 Hz. During fatigue experiments, the crack length of the sputtered smart patch was observed by optical microscope from the ion-sputtered side.

3.4. Wireless monitoring of ACM sensor

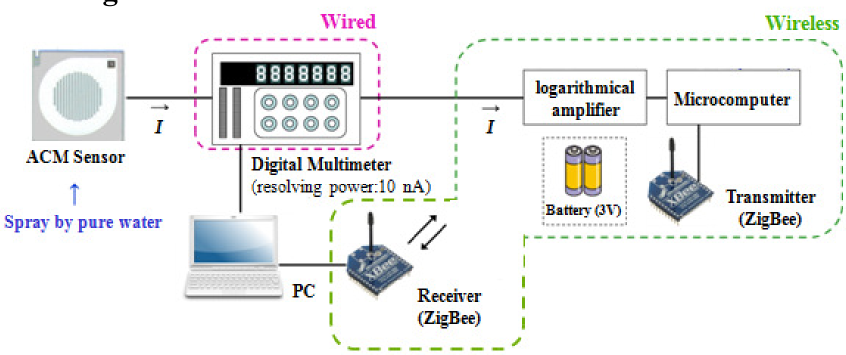

Figure 9. The schematic of the wireless system for ACM sensor

The wireless monitoring by ACM sensor was tested by using new wireless device. Because the output I from ACM sensor is galvanic electric current, and is so small that it is easy to be affected by noises while wireless communication, a wireless device which combines the new wireless device and logarithmical amplifier (AD8304) was proposed. The schematic of the wireless system for ACM sensor is shown in Figure 9.

The accuracy was evaluated by two measurement systems. One is wired, consisted of digital multimeter. The other one is wireless, consisted of logarithmical amplifier (AD8304), microprocessor (PIC12F675, Microchip Technology Inc.), Battery (3 V), transmitter ZigBee (IEEE 802.15.4) and receiver ZigBee. To imitate different corrosion conditions in the atmosphere (Rain, Dew, Dry), pure water was sprayed to ACM sensor by different times.

4. Results and Discussion

4.1. Evaluation of the measurement accuracy of the metal film by FEM

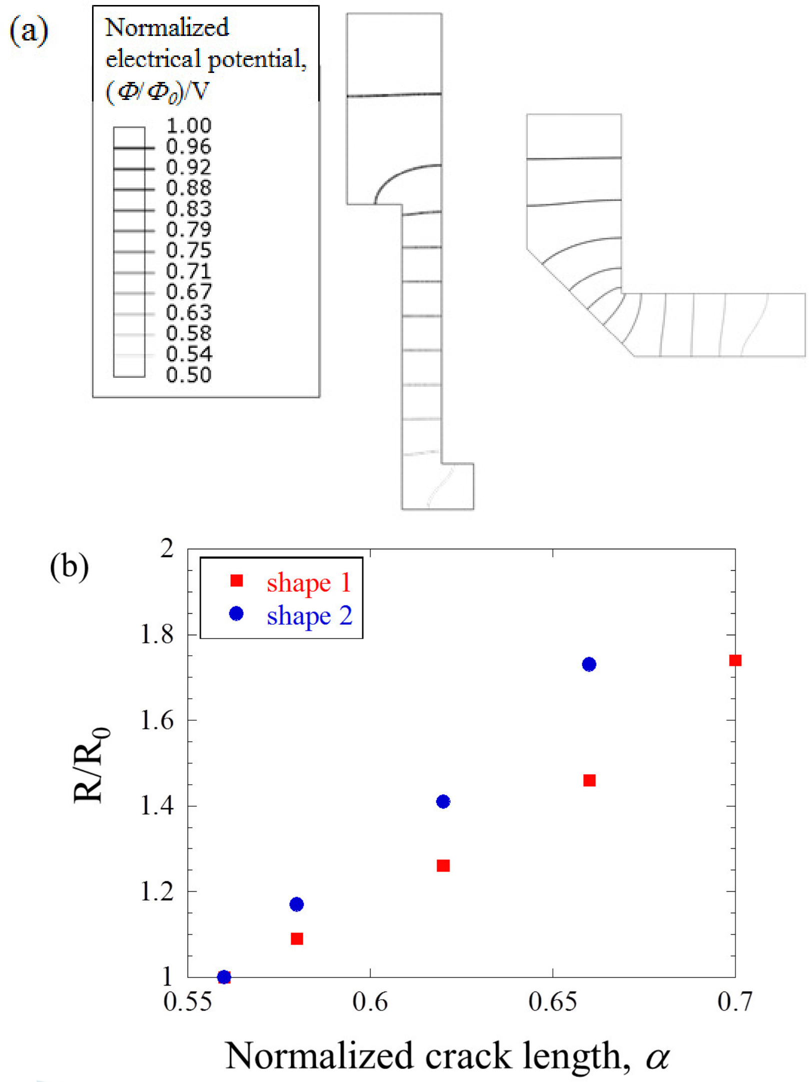

Figure 10. (a) Electrical potential distributions in the ion-sputtered metal film calculated by FEM (a_c=1.3 mm); (b) Relationship between the normalized crack length in sputtered smart patch and the normalized resistance of the ion-sputtered metal film through FEM.

The examples of analytical results about the normalized electrical potential (Φ/Φ_0) distribution are shown in Fig. 10 (a). The relationship between the normalized crack length in sputtered smart patch and the normalized resistance of the ion-sputtered metal film is shown in Fig.10 (b). By changing the shape of the ion-sputtered metal film from shape 1 to shape 2, the increase amount of normalized resistance R/R_0 at the beginning of crack growth has been improved to about 1.5 times as the conventional. As a result, it is supposed to be an effective way to solve the unstable phenomenon at the beginning of crack growth shown in Figure. 4.

Therefore, the measurement accuracy of the ion-sputtered metal film on “sputtered smart patch” was improved by changing the shape of the ion-sputtered metal film through FEM. Fatigue experiments will be conducted to verify the effectivity of this shape.

4.2. Wireless communication

4.2.1. Using RFID tag

The conventional wireless measuring system, which composed of the ion-sputtered metal film, AD converter and RFID tag, was successfully applied to measure the crack length of sputtered smart patch during fatigue test. However, the communication distance was only 30 mm, and is not sufficient for wireless network system.

4.2.2. Using ZigBee

By using the new wireless device, the communication distance was improved to more than 20 m. The wireless communication was proved to be possible among 1 receiver and 4 wireless devices. Moreover, within 20 m, the loss rate was almost 0, and more than 30 m, the loss rate was near to 5 percent. It could be expected to build a wireless fatigue monitoring system, which will be applied to the real structure such as bridge and ships, by using these new wireless devices.

4.3. Fatigue experiment

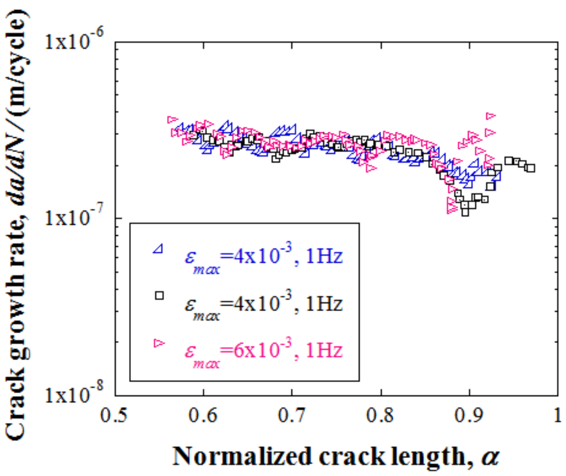

Figure 11. Relationships between the normalized crack length and the crack growth rate

In the high-stress low-cycle fatigue environment, the fatigue crack path of the sensor exhibited a straight line and is possible to measure the crack length easily. Figure 11 shows the relationships between the normalized crack length and the crack growth rate calculated by the incremental polynomial technique under each test condition. Tests performed two times under the same condition (ε_{max}=4x10^{-3}) showed good repeatability. The crack growth rate was almost constant with fatigue cycles in the range of α=0.54 to 0.86, and it decreased slightly before increasing in the range of α>0.86. The crack growth rate did not change a lot even through the maximum strain changed. This tendency is quite different from that of the low-stress fatigue environment. Further research is needed to figure out the reason for this result.

4.4. Wireless monitoring of ACM sensor

It was possible to make ACM sensor wireless by using the new wireless device and logarithmical amplifier. Figure 12 shows the output of ACM sensor estimated by wireless and wired systems. Both of them show very good coincidence during three periods (Rain, Dew, and Dry). Moreover, by using the logarithmical amplifier, the electricity in the dry period could be distinguished more remarkably than by multimeter. Thus, it was confirmed that the output of ACM sensor can be transmitted wirelessly by the combination of the new wireless device and logarithmical amplifier.

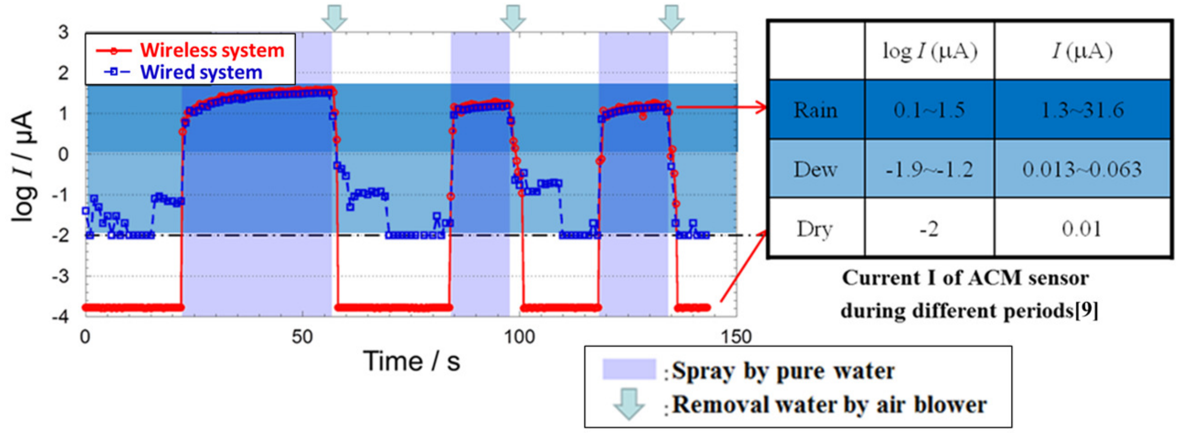

Figure 12. The output of ACM sensor estimated by wireless and wired systems

5. Conclusion

In this study, (1) the measurement accuracy of the ion-sputtered metal film on "sputtered smart patch" was improved by changing the shape of the ion-sputtered metal film through FEM. (2) a new wireless device equipped with RFID and ZigBee was developed. By using this device, the communication distance between smart patches was improved to more than 20 m. The wireless communication among 1 receiver and 4 transmitters has been tested and proved to be possible. (3) the existing smart patch was proved to be not applicable to high-stress low-cycle fatigue environment through fatigue experiments because the crack growth rate did not change a lot even through the maximum strain changed, which tendency is quite different from that of the low-stress fatigue environment. Further research is needed to figure out the reason for this result. (4) the wireless monitoring by ACM sensor was realized by combining new wireless device and logarithmical amplifier.

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