PRACTICAL STRUCTURAL HEALTH MONITORING SYSTEM OF LOW-COST SMART SENSORS WITH WIRELESS NETWORK

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ABSTRACT :

The monitoring system for RC structures is presented adopting two types of smart sensors which translate the measurements to the damage indices and transmit them in the minimum amount of data. The developed smart AE (acoustic emission) sensor is useful for local monitoring finding the crack of concrete, and new smart VA (vibration analyzing) sensor is used for global monitoring by detecting the change in dynamic properties of the building structure. The reduced amounts of data are sent via wireless network using the standard ZigBee®, which provides the reduced consumption of electricity.

KEYWORDS: Structural Health Monitoring, Damage Detection, Smart Sensor, Wireless Network, Acoustic Emission, Accelerometer

1. INTRODUCTION

Recently, we have experienced tremendous damages under frequent huge earthquakes in the world. To minimize the subsequent damage after an earthquake, securing refuges such as hospitals and schools and recovering lifelines like roads, bridges and water supplies are priorities as disaster prevention measures. However, it usually takes much time and cost to inspect many buildings and structures. Usual monitoring of such important facilities is expected to realize quick detection of their damage or trouble and to contribute to avoiding significant loss of lives and properties (Nakamura(2002)).

Local monitoring is useful in case that the fatal portion is possibly predicted and the sensors can be installed there in the buildings or structures. However, large-scale complicated structures are not easy to specify their monitored parts requiring a lot of sensors with high cost. On the other hand, global monitoring has merits in reducing the number of sensors and the cost by focusing on the change of the dynamic properties of structures. It is to be noted that global monitoring needs the sure idea of what to measure and how to estimate the damage.

The most important thing is that the judgment should be made just after a quake whether the structure has been losing its function and performance. The main goal of our monitoring system (En et al.(2007)) is accurate and quick decision and detection, whether the structure is damaged or not, what to extent the damage is, and where the damaged is. To realize the practical monitoring technology, the reliable system is indispensable.

In this paper, the monitoring system for RC structures is presented adopting two types of smart sensors which translate the measurements to the damage indices and transmit them in the minimum amount of data. Those sensors make the fail-safe system with redundant number of units installed in the wide area of the building and structure. The reduced amounts of data are sent by the wireless network using the standard ZigBee*, which provides the reduced consumption of electricity.

2. BASIC CONCEPT OF PRATICAL STRUCTURAL HEALTH MONITORING SYSTEM

2.1. Secure Damage Detection by Two Types of Smart Sensors

The structural health monitoring system should be reliable and practical to judge and detect the damage securely and quickly after an earthquake. In our system, two types of smart sensors are developed to translate the

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*:ZigBee is the registered trade-mark of ZigBee Alliance, Inc.

measurements to the damage indices. The minimum amounts of data are transmitted to the relay stations (router) and the central base. By reducing the data and information, the system can be simple and low-cost. “Smart sensor” not only measures the acceleration, strain, acoustic emission and so on at the sensing part, but also processes the data by CPU on the sensor board, translates the measurements, and transmits them via the network. Excessive accuracy is not necessary in sensing so that each sensor sends the reduced amount of data. On the other hand, the number of sensors is desired to be increased as much as possible. Those sensors can set up the fail-safe system with redundant units installed in the wide area of the building and structure. The redundancy contributes to reduce possible failure of detection or possibility of improper diagnosis.

The concepts of the monitoring system for RC structures are shown in Figures 1 and 2. Smart AE(acoustic emission) sensors (Yanase and Ikegaya(2006), Yanase et al.(2008)) are arranged just near the places where the concrete crack may occur under an earthquake. Those are for local monitoring. Smart VA(vibration analyzing) sensors (Ikegaya and En (2007), Nakamura et al.(2008)) are installed, for example, the top story and the bottom of the building, and the corners of the wide structures. The sensors will detect the changes in the natural frequency, the response values and other dynamic properties caused by the damage after an earthquake. These are for global monitoring. Combining both systems is quite effective for damage detection. The above two types of sensors measure the different data, but are based on the same design concept. The unified sensing and data-processing methods make it possible to realize the simplified reliable system.

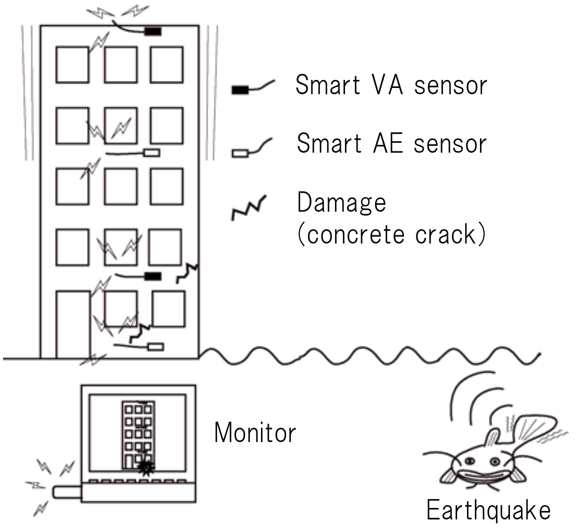


Figure 1 Concept of structural health monitoring system.

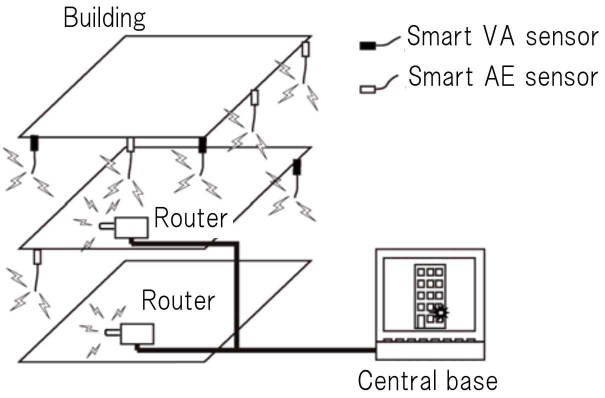


Figure 2 Image of the monitoring in the building.

2.2. Simplified Data Transmission via Network

The accelerometers used in the conventional earthquake observation system samples the time histories and send them to PC by way of the data processing devices. The data from all of the sensors are sent to the central base PC to be analyzed. The problems of the conventional system in applying to structural health monitoring are illustrated in Figure 3. First of all, the weak signal from sensors should be transmitted to the far station. The pre-amplifier may be necessary, in which the counter-noise measures are required. They may affect the size of the sensor itself. The second problem is the amount of data. Given the sampling time of 10 milli-seconds, some mega-bytes of data should be dealt with per 10 minutes. It is not so easy to manage the huge amount of data from a large number of sensors around the monitored building or structure. The flood of data rushing to the central base may provoke a data crisis just after an earthquake, and will finally stop the system caused by confusion, disorder and the delay of processing and judgment.

To solve the above problems, new damage-detection system is suggested as shown in Figure 4. Utilizing Smart VA sensors, the measured acceleration time histories are processed by CPU on the sensor board and translated to the damage indices. These indices are, as explained in the next section, the zero-crossing number, the maximum acceleration value and the cumulated absolute acceleration value. The computation of such indices is restricted to the case that the acceleration exceeds the pre-set trigger value. Requirements of data transmission are so limited that the load to the communication in the network is kept as the minimum. The gathered data from sensors are compared one another and compared with the previous data. The network is set up with wired and/or wireless system. The reduced amount of data enables to use new wireless standard ZigBee as shown below.

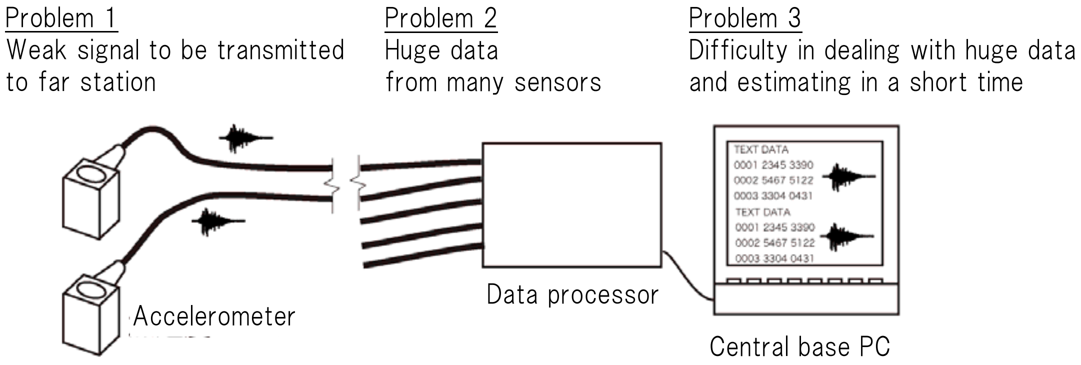


Figure 3 Problems of the sensing system using the conventional accelerometers.

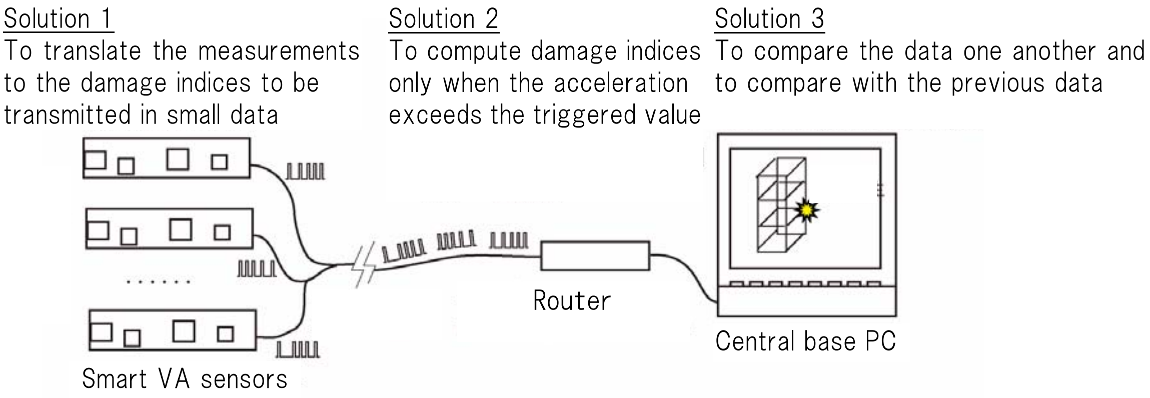


Figure 4 Features of the sensing system with smart sensors solving the problems shown in Figure 3.

3. DEVELOPMENT OF SMART SENSORS

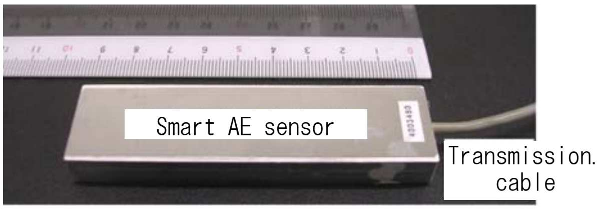
3.1. Smart AE Sensors for Local Monitoring

The conventional damage detection by AE method for RC structures identifies the location of the concrete crack by analyzing the data from the sensors. Those AE sensors are usually rather expensive and complicated in order to separate the AE signal from the noise. The amplitude and the frequency content of the signal, the number of occurrence and the time delay arriving from the source to the sensors are analyzed to obtain the information of the type, magnitude, extending conditions and the location of cracks.

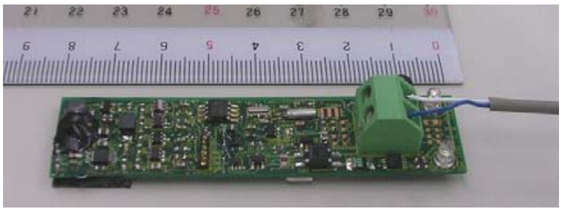
Newly-developed Smart AE sensor (SAE sensor) is shown in Picture 1 and 2. The sensor has the sensing, data processing, data transmitting devices in one board, the size of which is about 20mm by 90mm. Instead of conventional ceramic material, the composite transducer is adopted to minimize the size and secure the sensitivity. Although the region of the detection is limited to the vicinity of the sensor, the damage index is obtained by counting the number of exceedance of the threshold in AE signal. The thresholds are preset as 4 different levels, which are determined considering the thickness of the concrete material, the conditions of the arranged reinforcement bars and the forecasted response level under an earthquake. Those are also effective in distinguishing the signal with the noise. The sampling time is 100 micro-seconds, but the number of exceedance (frequency) is counted in the unit duration of 1 second, so that the amount of data is extremely reduced for the ease of processing and transmission.

To examine the effectiveness of the above index, the static and dynamic tests are executed. The Pictures 3 and 4 show the dynamic experiment (Shirai et al.(2006)) using the shaking table. One-fourth scaled RC specimen is shaken by the observed record of Hyogo-ken Nambu Earthquake 1995. The RC model of one by three spans has opened shear walls, wing walls and waist walls. The span is 1.5m, the height of each story is 0.75m and the effective weight is about 320 kN. SAE sensors are arranged at the foot of the walls of the base story where the cracks are expected to occur.

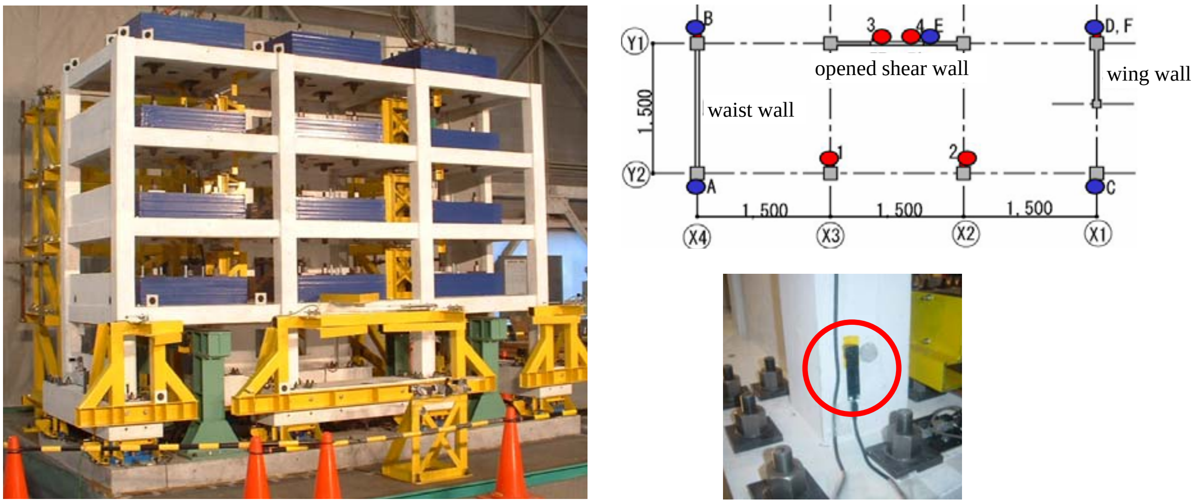
The results detected by SAE sensors are illustrated in Figure 5. It shows the AE frequencies for 4 thresholds in the cases of RUN2 to RUN9 corresponding to the inputs with amplified factors of 0.2, 0.4, 0.6, 0.8, 1.0, 1.25, 1.25 and 1.25. The AE counts vary depending on the location of the sensor and the damaged condition. Even in the case of RUN2 where some hair cracks are found, the sensors A and E respond as shown in Figure 6. The AE frequencies of SAE sensors in the upper figures are compared with the shear displacement obtained from the load-sell during the quake motion. From the very beginning of the concrete crack, SAE sensors can detect the damage with the minimum data showing the difference depending on the location and thresholds.



Picture 1 Appearance of Smart AE sensor.



Picture 2 Appearance of Smart AE sensor on the board.



Picture 3 RC building model on the shaking table in dynamic experiment(left) and Smart AE sensor(right). The upper right figure shows the arrangement of SAE sensors.

Picture 4 Cracked RC building model with sensor A at the foot of the column in the side of the waist wall(left) and sensor E at the foot of the opened wall(right).

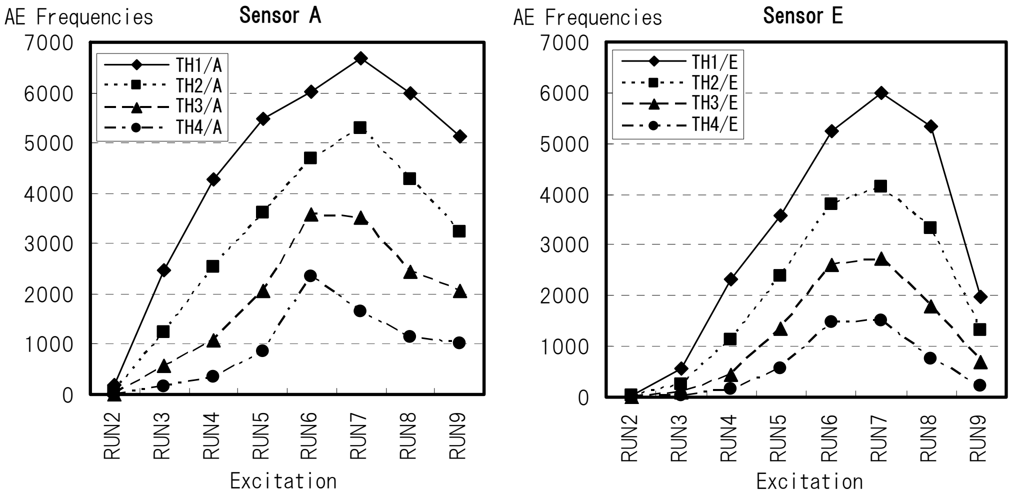


Figure 5 Variation of AE frequencies detected by SAE sensors with increasing the input level. Sensor A(left) and sensor E(right)

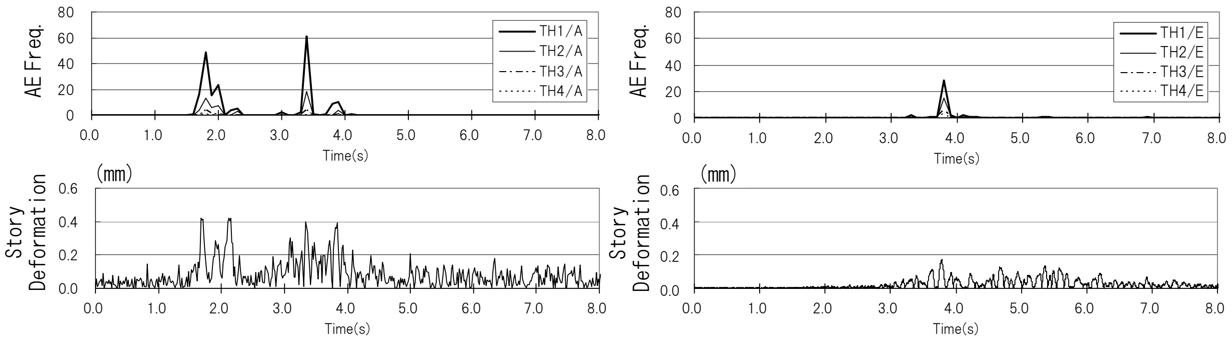


Figure 6 Comparison of AE frequencies detected by sensor A(upper left) and sensor E(upper right) with the corresponding relative shear displacement obtained from the load-sell during the quake motion.（RUN2）

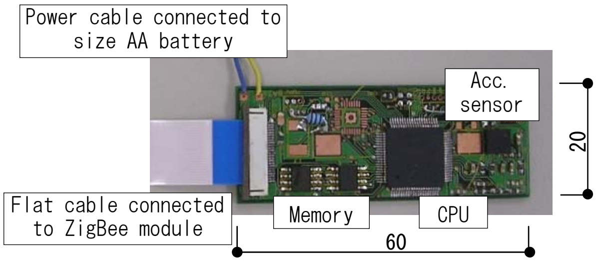
3.2. Smart VA Sensors for Global Monitoring

Smart VA sensor (SAE sensor) is developed to obtain the damage indices as explained in the previous section. The appearance is shown in Picture 5. The tri-axial accelerometers, CPU and the memory are installed in the board of 20mm by 60mm. The accelerometer measures in the range of plus-minus 1.5G and the sampling time is 100 Hertz. The zero-crossing number, the maximum acceleration value and the cumulated absolute acceleration value are computed from the accelerogram in CPU and reserved to transmit for every 10 seconds.

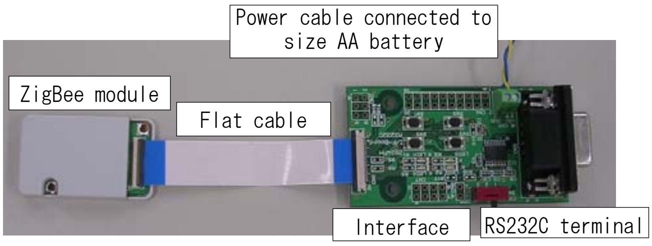
The global monitoring system using SVA sensors focuses on the change of the dynamic properties of structures after they experience the damage under an earthquake. The decreased stiffness of the structure is detected via the reduction of natural frequency, which can be obtained, for example, through Fourier transform. This requires complicated data processing. Instead of Fourier transform, counting the number of zero-crossing is adopted in the developed system. The elongated eigen period of the damaged structure can be captured by the decreasing zero-crossing number.

The zero-crossing number of the acceleration time history also reflects the frequency content of an earthquake input motion. The input motion has the main shock and the subsequent motion caused by the surface wave of relatively long period. The monitoring for damage detection also needs to measure the amplitude of the response, and both the maximum response and the cumulated absolute acceleration value representing the energy content should be processed. These indices can be computed only by summation and production of the acceleration data.

The relations of the zero-crossing number and the cumulated absolute acceleration value are examined for the dynamic experiment data. The location of the accelerometers on the specimen is shown in Figure 7. The responses of the sensors in the side of the waist walls (y15-y45) where the damage initially yielded and those in the side of the wing walls (y14-y44) are compared. The Figures 8 show the trend of decreasing zero-crossing number with increasing cumulated absolute acceleration value with the excited steps from RUN2 to RUN7. The typical change is seen at the stage of RUN4 and RUN5, where the damage yielded clearly. As the result, the concept of the judgment using the damage indices is shown in Figure 9.



Picture 5 Appearance of Smart VA sensor on the board.



Picture 6 Appearance of ZigBee module.

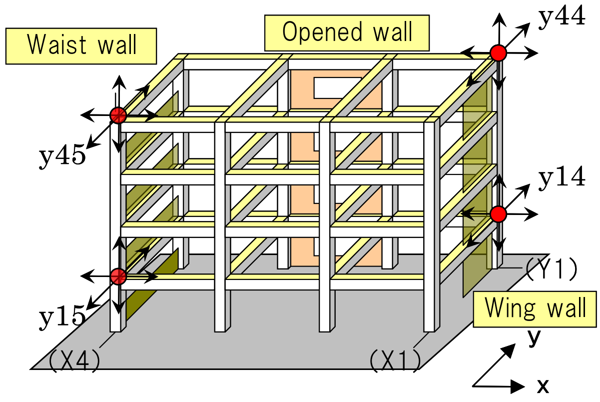


Figure 7 RC building model on the shaking table and the measured points by accelerometers. (slabs are not shown)

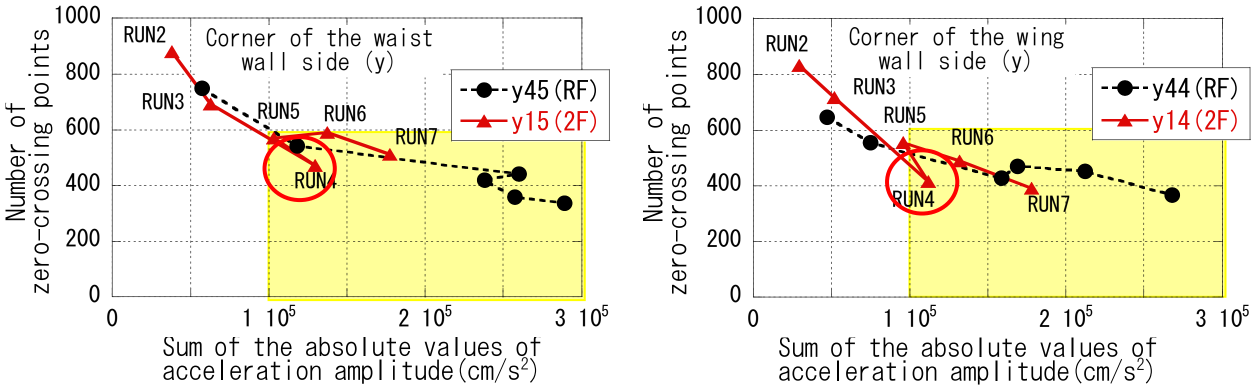


Figure 8 Relation of the zero-crossing number with increasing the cumulated absolute acceleration value with the excited steps from RUN2 to RUN7.

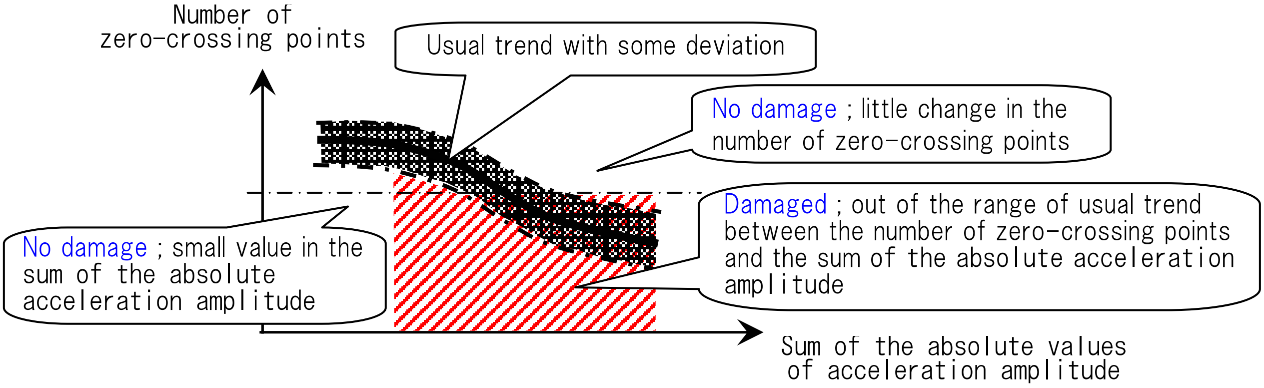


Figure 9 Concept of the judgment using the damage indices.

4. CONSTRUCTING WIRELESS NETWORK WITH ZIGBEE

As the transmission method, both wired and wireless system can be adopted. The merits of the wired system are as follows,

- By supplying electric power using the cable for data transmission, continuous measurement is possible.
- Highly reliable system is realized with high speed data transmission.

However, it has the following demerits.

- It is impossible to install the sensors where the cables cannot be laid down.
- Initial cost is necessary for wiring and construction.

On the other hand, the wireless system has the merit that the sensors can be arranged without wiring as long as the radio wave is receivable. However, highly speedy and reliable wireless system requires AC source or large capacity of battery. The power consumption depends on the energy consumption by sensors and transmission modules, transmission rate, and the amount of data to be transmitted.

The data sent from Smart VA sensor is extremely reduced by translating the accelerograms sampled in100 Hertz to three text data of indices. Same applies to Smart AE sensor. The consumed power is only 5 to 15 mA by each sensor including CPU and memory. Because of the data reduction on the sensor modules, the wireless standard ZigBee, which consumes limited power with relatively low speed data transmission, ca be adopted. The features of ZigBee are as follows,

- Low-power consumption, low speed (250 kilo-bytes per second) and low cost system
- Multi-hop transmission capable
- Using 2.4GHz frequency band
  (avoiding interference with wireless LAN by setting the different channel)

Althogh the electric power consumed by ZigBee is 50mA, the duration time for transmission is so short that the continuous measurement is possible for several months with three size AA battery for each sensor. The appearance of the ZigBee module is shown in Picture 6. The ZigBee module on the transmission side is connected to the sensor with flat cable. The ZigBee module on the receiver side is connected to PC through the flat cable, the interface and RS232C. The end devices of sensors, the routers and the coordinator set up the multi-hop relational network as shown in Figure 10. The ZigBee system can avoid the blockade by the obstacles with the function of self-recovering.

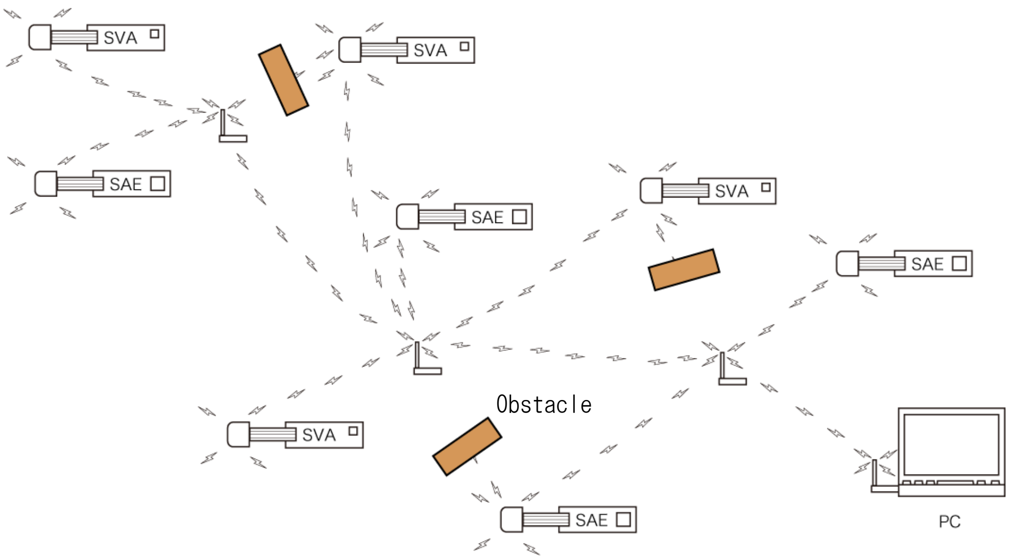


Figure 10 Concept of wireless network system using batteries with sensors.

5. CONCLUSIONS

The practical structural health monitoring system is suggested aiming to detect certainly the occurrence of damage and to identify the portion with the degree of damage. The developed system is highly reliable and simple of low cost adopting new sensors which translate the measurements to the damage indices and transmit them in the minimum amount of data. The developed smart AE(acoustic emission) sensor is useful for local monitoring responding to the crack of concrete, and new smart VA(vibration analyzing) sensor is used for global monitoring by detecting the change in dynamic properties of the building structure. The wireless network using the standard ZigBee provides the reduced consumption of electricity, and is expected to realize multi-hop transmission and mutual communication of sensors in the near future.

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