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Implant Wireless Sensors System for Active Vibration Control of Construction Structure - System Application and Vibration Test -

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ABSTRACT

This is a preliminary study for developing a real-time feedback vibration control system for building structures. For this purpose, a wireless acceleration sensors system and an AMD system were developed. The wireless acceleration sensor unit is an MEMS based device with an integrated Bluetooth communication module. The prototype AMD, with an AC servo-motor, was constructed in house. A controller, hardware and software with a simple control law, was also developed. The controller provide real time feedback control signal to the prototype AMD system based on real-time acceleration measurement Basic performance levels of these systems were evaluated with a model building structure. The result of the evaluation tests showed that there is substantial vibration reduction with the 1st and 2nd modal frequencies as well as with a earthquake type random frequency excitations of the model structure. Thus, we could confirm the potential of the developed wireless acceleration sensors system and the prototype AMD system for active vibration control of real building structure.

Keywords: Wireless Acceleration Sensor System, Real-time Feedback Vibration Control, Active Mass Damper

1. Introduction

The broad meaning of structural maintenance and inspection technology is total technical endeavors that can be applied to preserve the design strength of a specific structure and to prolong the persisting period. For this purpose, Korean government has developed a manual for periodic safety inspections of important buildings and structures in accordance with the Korea Infrastructure Safety Corporation and, based on it, enacted “Special Act on Safety Control for Infrastructure”.

Structures and buildings are subject to external loads, continuously due to user activities, and, sometimes, to extreme loads such as earthquakes and wind blasts. Thus, it is very important to have a fast and reliable method to diagnose the safety and integrity of buildings and structures to deal with an unexpected possible disaster and to prevent it. For fast and reliable safety inspection of a given structure, efficient means of acquiring structural response are most important. Moreover, assuming the structural integrity is still intact, there must be an effective way to reduce structural stress, such

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as structural vibrations, to prevent an unexpected structural failure. In this respects, the technology for structural response acquisition and that for structural stress reduction are the keys of structural maintenance and inspection technology.

Currently available sensors and measurement systems, based on wired technology, have many advantages of their own, however, also have the following operating and maintenance disadvantages. Firstly, each sensor must be installed with an attached signal cable, requiring a counter-measure for noise inception as the cable becomes long, and a power supply system to work properly. Secondly, the available wire based sensors and measurement systems are mostly imported from US, Japan and a few European countries, which means that the acquisition cost is rather high and that operating and maintenance of the equipment could be inconvenient.

Until recently, structural vibration controls, due to harmful external loads, depend largely on passive technologies such as frictional vibration damper and seismic isolation support. The vibration reduction systems, based on such passive technologies, are inexpensive to build, in general, and work effectively given the limitations of the equipment. However, once the equipment's work limit was overridden and results in the failure of the equipment, the system has to be replaced, partly or on the whole. Moreover, the passive systems are incapable of dealing with diverse external loads that a structure may encounter.

Because of these limitations, several new ways and techniques have been developed. Typical of these are the wireless sensors and measurement system and the active vibration control system that can deal with diverse harmful external loads more effectively. Wireless sensors and measurement system was introduced to the construction field in the middle of 1990's, and attempts have been made, since then, to apply some of the newly developed systems to real buildings and structures in the developed countries. This is an effort to utilize conglomerated IT technologies (electrics, electronics, communications and mechanics) for more effective structural maintenance and safety inspection. Wireless sensors system was first studied by Straser (1996) and, later, by Kurata (2003) and Lynch (2003). These studies used MEMS device which is a silicon chip on which digital circuitry and a mechanical sensor converter were embedded. This sensor unit is cheaper, smaller and less power consuming than the usual wire type sensors and, thus, widely used in other fields as well. There are two kinds of active vibration reduction systems, one is a semi-active system and the other is an active system. For semi-active systems, MRFD (Magneto-Rheological Fluid Damper) was widely studied. AMD (Active Mass Damper) was studied for active vibration control system. Both of these systems are expected to have capabilities to actively deal with diverse external loads in real-time, overcoming the limitations of conventional passive system. Recently, Dyke (2004) studied MRFD and, based on this study, Wang (2007) and Lynch (2008) carried out response analysis and real-time vibration control test with a full scale 3-stories model structure. In Korea, Min (1998) studied vibration control performance of the speed feed-back algorithm for earthquake type excitation with wired measurement system and a single level shear type building structure. However, domestic research effort on this field, i.e., wireless sensors system and active vibration control, is immature and, especially in the construction field, the efforts to obtain these new technologies are much in need.

In this research, we developed a wireless acceleration sensor and measurement system for real-time structural response measurement and built a prototype AMD system with a servo-motor and, by combining the two systems, built a real-time feed-back active vibration control system. This system was tested on a laboratory scale 2-stories structural model for the desired vibration reduction effect and it was shown that both of the component systems, i.e., the wireless sensors system and the AMD, have the potential for real world application of vibration control.

2. Development of the active vibration control system

2.1 Wireless acceleration sensor system

A MEMS type wireless acceleration sensor system was developed to replace conventional wired type acceleration sensors. The developed sensor system is a universal 2-axis type, so that it could be widely used on general building structures. The acceleration range of the sensor is ±1.2g, the sensitivity is 1000mv/g, the frequency range is 0.2-50Hz, and the measurement accuracy is 0.001mg. The onboard Bluetooth wireless module has a range of 1.2 km. The unit is powered by a 3.4V Li-Ion rechargeable battery and has power consumption of 300mW giving 10 hours continuous operation for one charge. The unit size is 48×65×40mm (b×h×d) and weights 150 grams. It also includes 32kB of onboard memory. The developed acceleration sensor with integrated Bluetooth module is shown in Fig.1 and the specifications are shown on Table 1.

Index	Spec.
Internal Sensor	MEMS 2-Axis Accel.
Range	± 1.2g
Sensitivity	1000mV/g
Measure Distance	up to 1.2 km
Measure Freq.	0.2 ~ 50 Hz
Operate Mode	Wake/Sleep
Operate Voltage	3.4V
Power dissipation	300mW
Resolution	16 bit
Internal Flash	32 Kbyte
Measure Accuracy	1.0 mg(rms)
Battery Life	10 hr
Size(b×h×d)	48×65×40 mm
Body Weight	150gram

Table 1 Specifications of the Wireless acceleration Sensor (MEMS)

Fig.1 The Wireless Accel. Sensor Unit (MEMS)

Fig.2 The Unity Logger system

An integrated logger and logging software were also developed for efficient and reliable data logging for the acceleration sensors and measurement system. The integrated logger, equipped with a tablet computer, a Bluetooth access point(MSP), a wire and wireless router and a battery power pack, is capable of connecting to 14 channels without sacrificing portability. A shockproof, humidity and temperature resistant hard case was used to encase them.

The usability and field adaptability was considered in the development stage of the logger. First of all, the sensors unit and the logger have self-contained battery power system and, thus, they can be operated several hours in the field without external power supply. This type of wireless sensors and measurement system has many advantages over the conventional wired sensors and measurement system in the field use. Fig.2 and Table 2 show the completed unity data logger system and its specifications.

No	Spec.
1	Bluetooth Access Point Including
2	Serial, LAN, PAN & Dialup Networking
3	Wire/Wireless Shear Point Including
4	12“ Wide Touch Panel Tablet PC Including
5	Battery Including(Duration : 5hr)
6	Multi-Point Access Support (7CH.～14CH.)
7	Carrying & Water-off Case

Table 2 Specifications of the Unity Logger

Finally, a data logging software, for processing the data transmitted from the wireless acceleration sensors was developed. The computer software can provide several measurement modes, for each channel as needed, and, also, includes many windows functions and filtering functions for efficient data processing. The programs also include several signal processing functions that can be used, real-time, when monitoring signal from the acceleration sensors. Finally, a self-diagnose routine is also included in the software. Fig.3 shows the data logger program in use and the specifications are shown on table 3.

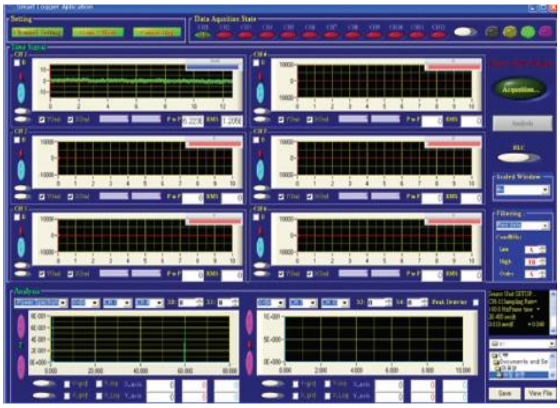


Fig.3 the Logger Program, for the Wireless Acceleration Sensors, in use

Index	Spec.
Measure Mode	Manual/Trigger/Period
Window Function	Hanning/Hamming/Blackman
Filtering Function	Butte-Chebyr Worth LFP/BPF
Signal Analysis	Power Spectrum/FFT/Integrate
Etc.	Auto Save/ CH-Battery Check

Table 3 Specifications of the Logger Program

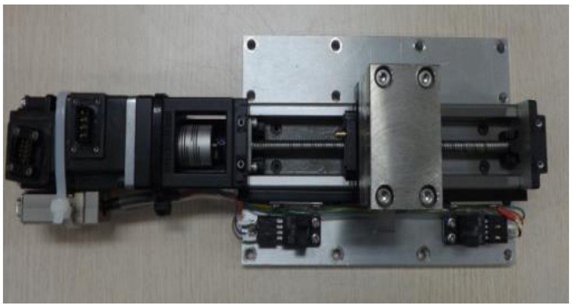


Fig.4 Prototype AMD Body

Fig.5 Prototype AMD Control Rack

2.2 The prototype AMD system

The prototype AMD system consists of a moving mass mechanism, a servo motor and a control rack. The moving mass part was constructed with an LM guide (Samik-THD, KR20). The servo-motor is an AC type (Mitsubishi, KP053). These two parts were combined together making up main body of the AMD system. Two (2) limit sensors (Omron, EE-SX674) were installed, at both ends of the AMD body, to limit the stroke of the moving mass. The control rack provides necessary electric power and control signal to the AMD body. An MR-J3 servo driver module was used for the rack controller, and the associated input parts for the driver were developed in-house. The prototype AMD body and the control rack are shown in Fig.4 and Fig.5, and the technical specifications of the AMD body are shown on Table 4 and Table 5.

Index	Spec.
Rated Output	50W
Rated Torque	0.16N·m
Max. Torque	0.48N·m
Rated Rotate Speed	3000RPM
Max. Rotate Speed	6000RPM
Rated Current	0.9A
Max. Current	2.7A
Body Weight	0.35kg

Table 4 Specifications of the AC Servo-motor

Index	Spec.
Move-Axis Type	ball-screw
Ball Lead	6 mm
Body Length	209 mm
Outer Rail Length	150 mm
Stroke Range	91.5 mm
Body Weight	0.58 kg
Positioning Accuracy	±0.01 mm
LM-Friction Factor	0.001 ~ 0.003

Table 5 Specifications of the LM-Actuator

2.3 The real-time feedback vibration control system.

A communication system from a PC to the AMD control rack and a wireless rink from the PC to the acceleration sensors were provided. For the PC to the control rack communications, a DIO module (Comizoa, ceNM-SE) and a D/A converter (Comizoa, ceAO02A) were used. The DIO module is used for transmitting control signal from the PC thru an Ethernet link and the D/A module is used for providing real-time analog control signal, after converting digital signal from the DIO module, to the servo-motor in the AMD body. For the Bluetooth connection to the acceleration sensors, a multi-channel link system (SENA, Parani- MSP1000) was employed. This system performs the function of transmitting data to and from the acceleration sensors and, then, to the PC thru an Ethernet connection. The communication system afore mentioned are shown in Fig.6 and Fig.7.

Fig.6 Real-time DIO & D/A Convert Module

Fig.7 Bluetooth Multi Channel Access Point

The communications apparatus as shown in Fig.6 and Fig.7 are installed into the unity logger system hard case as shown in Fig.2. The data processing and output software, required for the operation of the AMD control, was also included in the data logger software as shown in Fig.3. As a result, the data logger system can perform the functions of acquisition of data (from the acceleration sensors), data processing, and providing the control signal (to the control rack of the AMD body), with seamlessly integrated manner and in real-time as shown in Fig.2. The flow diagram of the real-time feedback vibration control system is shown in Fig.8.

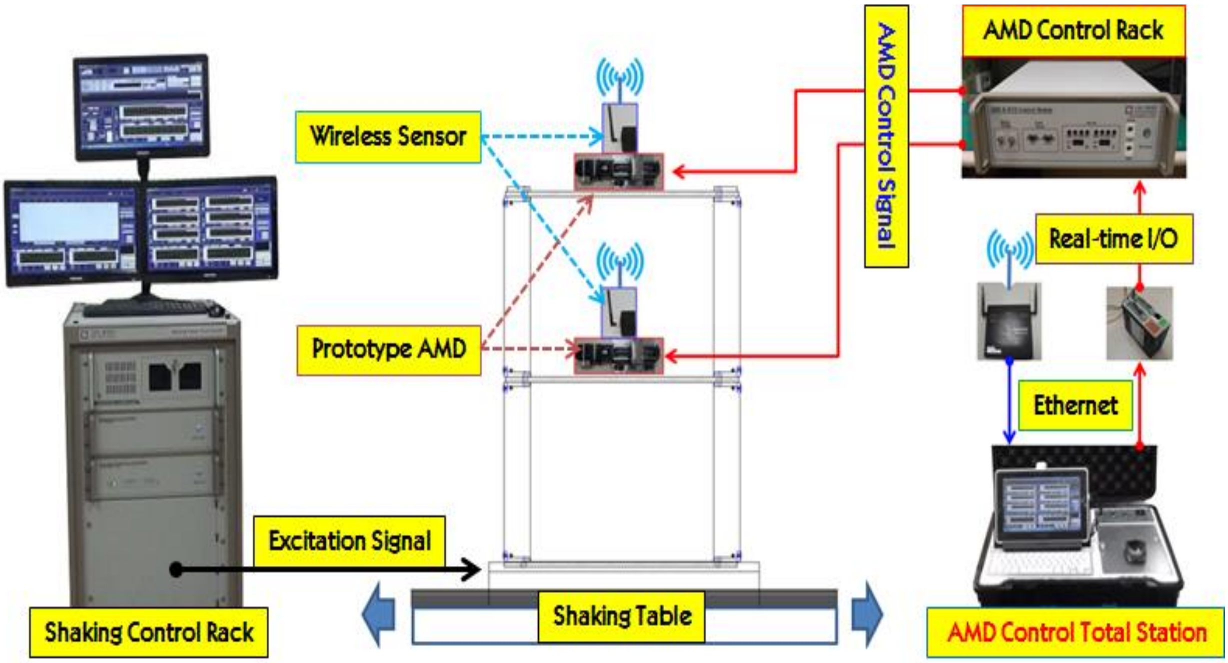


Fig.8 Flow Diagram of the Real-time Feedback Vibration Control System using the Wireless Acceleration Sensor & the Prototype AMD

3. Tests and Evaluations

3.1 Test and evaluation of the laboratory scale active feedback vibration control system.

A series of tests was carried out to evaluate the developed wireless sensors and the AMD vibration control system. Firstly, the developed acceleration sensor and a commercially available wired acceleration sensor, of known accuracy, were installed on the prototype AMD body. Using a function generator, sinusoidal waves of 1-10 Hz, in a step of 1 Hz, were applied to the AMD controller. At these conditions, response data was obtained from both the wireless and the wired acceleration sensors. Table 6 shows the response curves of the sensors. We could confirm the reliability and accuracy of the developed wireless sensor as the response of the wireless sensor agreed very well with that of the wired acceleration sensor. The AMD system also showed good tracking ability to the diverse forms of input signals, along with an excellent mechanical reliability. After the dependability of the sensors and the AMD systems are verified, these systems are installed on a 2-stories laboratory scale structure model as shown in Fig.8. The structure model is not a simple scaled down model of a real building structure but was designed to give the characteristic 1st and 2nd low frequency bending modes similar to a real building structure. Hence, the structural parts, beams and pillars, of the model are rather small in size and the overall rigidity is quite low for the size. Fig.9 shows the structural model, equipped with the sensors and the AMD system ready for the test. The external loads were applied to the model structure by a shaking table (Smart Controls & Sensing Co., S/T-ER-2.) The tests were carried out at the R&D facilities of Smart Controls & Sensing Co., located in Korea Research Institute of Standards and Science (KRISS, Daejeon, Korea).

The Modal characteristic of the structural model was verified before the main experiment. One AMD body was installed on each story of the structural model and the model was hit, horizontally, at the 2nd story by a hammer. Structural response of the model was obtained from the wireless acceleration sensors. The mass of one AMD body was 1.8 kg, which is comparable to that of each story of the structural model itself. Thus, the AMD mass will significantly affect modal characteristics of the model, and should be considered in the test. Fig.10 shows the time histogram of each story of the structural model. Fig.11 shows the results of spectral analysis. The two dominant modes, typical of a 2-DOF system, are clearly visible from both the 1st and 2nd story spectrum at the same frequencies. The 1st dominant mode frequency was 2.39 Hz and that of the 2nd was 6.35 Hz. Possible damping effect of the cables, such as the power cable and the encoder cable attached to the AMD body, were not considered. The result showed that each system works reliably, both mechanically and electronically, meeting the anticipated performance level.

After checking basic performance of the wireless sensors and the prototype AMD system, as described before, all these equipment were integrated into one working real-time active feedback vibration control system ready for the performance evaluation.

In general, an active vibration control device achieve the desired vibration reduction by, first, predict potentially dangerous response of each structural parts due to external loads such as earthquake, wind blast and other live loads, then, calculate optimal controlling force in real-time and, finally, provide control signal to a damper mechanism so that the desired controlling force is applied to the structure.

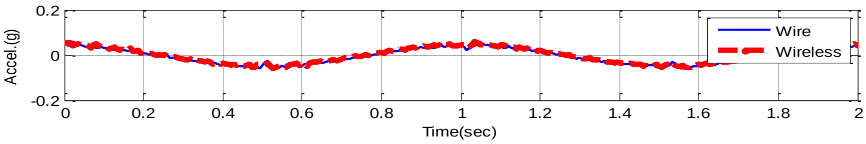
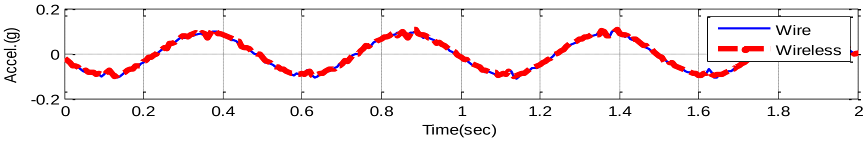
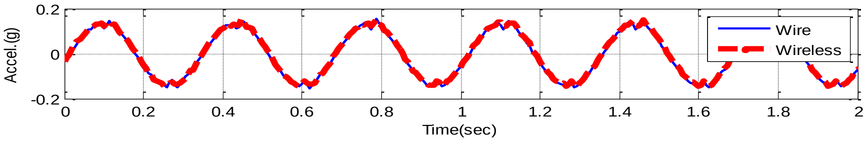
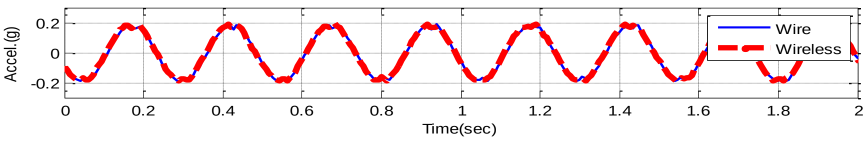
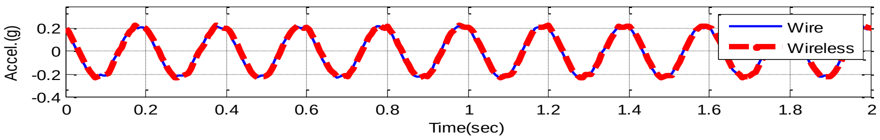
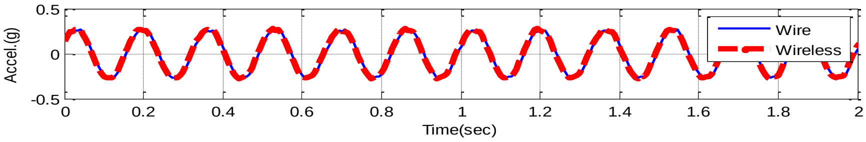
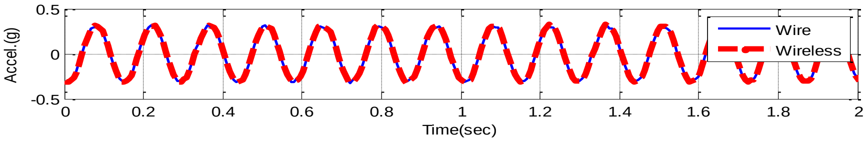
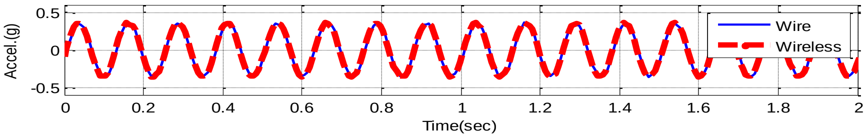
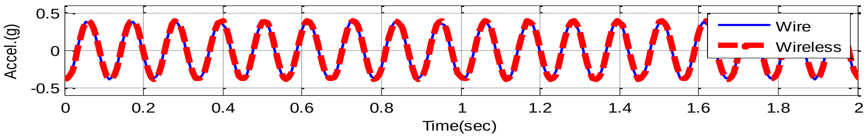
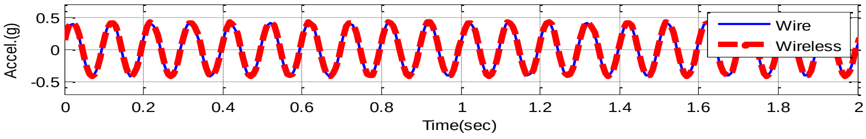
Freq. : 1Hz	
Freq. : 2Hz	
Freq. : 3Hz	
Freq. : 4Hz	
Freq. : 5Hz	
Freq. : 6Hz	
Freq. : 7Hz	
Freq. : 8Hz	
Freq. : 9Hz	
Freq. : 10Hz	

Table 6 Wire vs. Wireless Acceleration Sensors, Response curves using the Prototype AMD

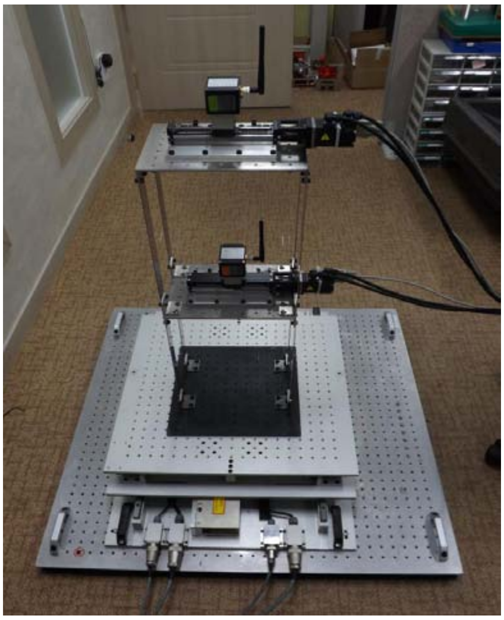
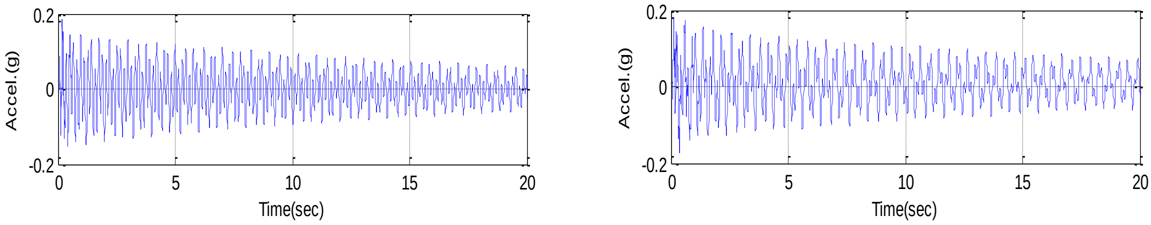
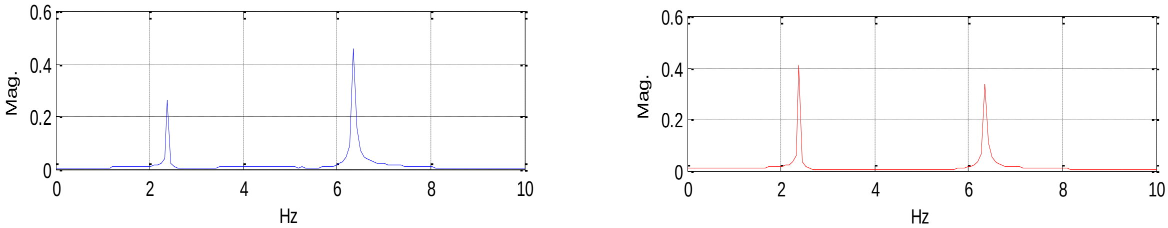


Fig.9 Test Setting of the Real-time Feedback Vibration Control System and the Structural Model, sitting on the Shaking Table.



(a) 1-Story Time History (b) 2-Story Time History

Fig.10 Time History to Each Story of Model



(a) 1-Story Spectrum (b) 2-Story Spectrum

Fig.11 Spectrum to Each Story of Model

A control law is needed for calculating the required control force. In this study, a simple conceptual control law was assumed by considering the basic operation mechanism of an AMD (inertial force of the moving mass is, in fact, the control force). This is, in practice, the acceleration signal of each story, is acquired in real-time, reverse the polarity of the signal and apply it to the structure, also in real-time. This simple control law is depicted in Fig.12.

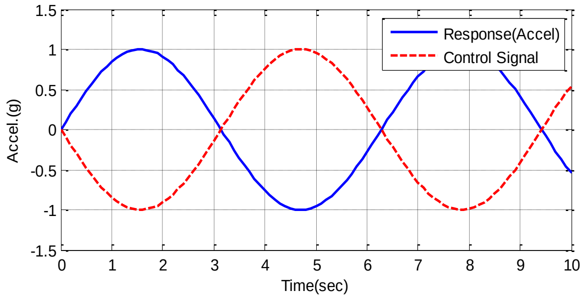


Fig.12 Concept of Simple Control Law

Control signal, applied to the AMD system, moves the moving mass in the opposite direction to the movement of the structure itself. As a result, control force (inertial force of the mass) will be generated in a way to reduce structural vibration. No attempt was made to quantitatively evaluate the system performance, i.e., setting up a performance goal and check for it. Rather, we aimed to confirm, by experiment, the feasibility of applying the wireless sensors system and the AMD system to a real structure. A more detailed study and quantitative analysis, by setting up the required degree of vibration reduction, of the system is due in near future.

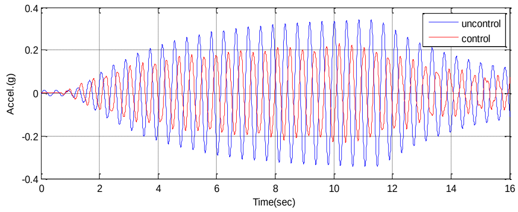
Using the simple control law, and with result of the modal analysis, excitation forces, corresponding to the 1st dominant mode, the 2nd dominant mode and the El-Centro earthquake wave form, were applied to the model structure. In these tests, ground excitation method was employed and the magnitude of exciting force, for each scenario, was determined after considering the capability of the exciter itself and the strength of model, so as there will be no permanent deformation of the structural parts of the model after the test. Only one AMD system was installed on one of the two stories of the model each time. The structural response (the acceleration amplitude) of the model was measured at the position of the AMD installation. The controlled structural response of each story, and with each excitation scenario, was compared to that of the uncontrolled case.

3.2 Performance test and Analysis of the test results

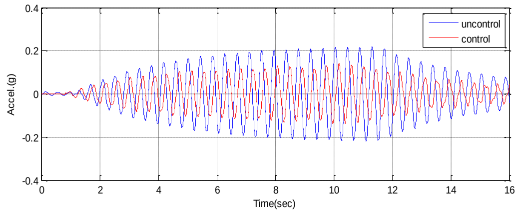
The structural response of each story, with each excitation scenario and by the AMD installation position, is depicted on Fig.13 - Fig.18. In the figures, '1(2)-story AMD' means that the AMD system was installed on the 1st (2nd) story only.

From Fig.13 and Fig.14, it can be seen that acceleration amplitude of the 2nd story is higher than that of the 1st story. This is because the excitation frequency was that of the 1st dominant mode. With the excitation frequency of the 2nd dominant mode, the response of the 1st story is greater than that of the 2nd story, which is as expected and can be seen from Fig.15 and Fig.16. When a random excitation of earthquake, the El-Centro waveform, was applied to the structural model, difference between the 1st story and the 2nd story responses was less pronounced as can be seen in Fig.17 and Fig.18.

For a quantitative evaluation of the performance of the developed system, two control indexes, the absolute maximum value index (J1) and the RMS value index (J2) were adopted. Mathematical formula for each index is given as Eq. (1) and Eq. (2), respectively.

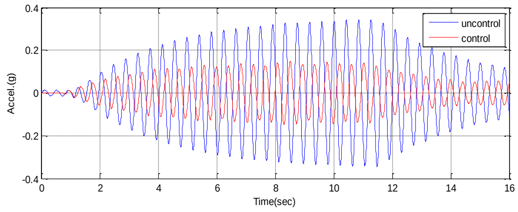


(a) 2-Story Accel. Resp.(Uncon. vs. Control)

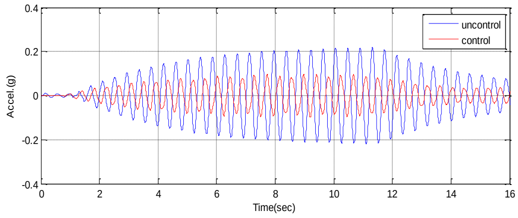


(b) 1-Story Accel. Resp.(Uncon. vs. Control)

Fig.13 1-Story AMD & 1st Mode Freq. Exciting

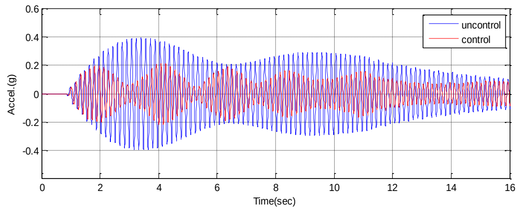


(a) 2-Story Accel. Resp.(Uncon. vs. Control)

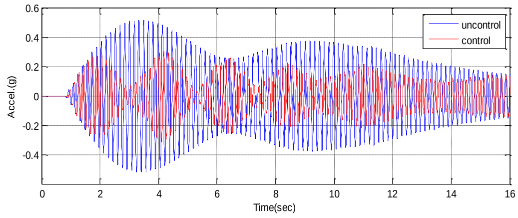


(b) 1-Story Accel. Resp.(Uncon. vs. Control)

Fig.14 2-Story AMD & 1st Mode Freq. Exciting

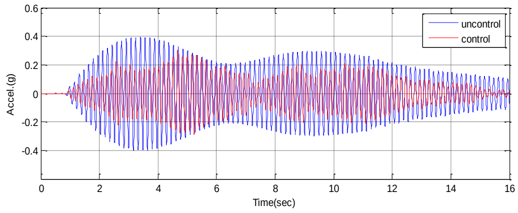


(a) 2-Story Accel. Resp.(Uncon. vs. Control)

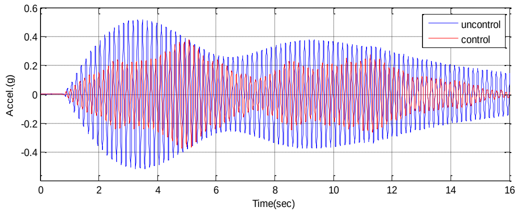


(b) 1-Story Accel. Resp.(Uncon. vs. Control)

Fig.15 1-Story AMD & 2nd Mode Freq. Exciting

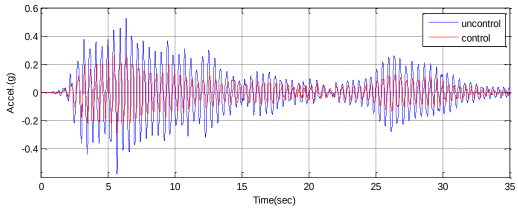


(a) 2-Story Accel. Resp.(Uncon. vs. Control)

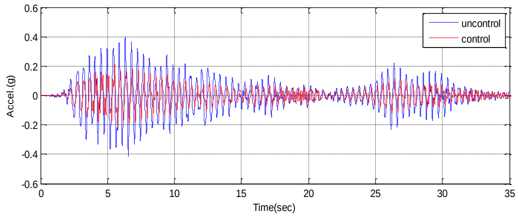


(b) 1-Story Accel. Resp.(Uncon. vs. Control)

Fig.16 2-Story AMD & 2nd Mode Freq. Exciting

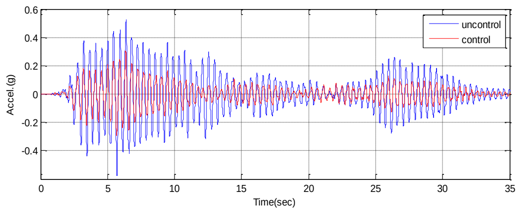


(a) 2-Story Accel. Resp.(Uncon. vs. Control)

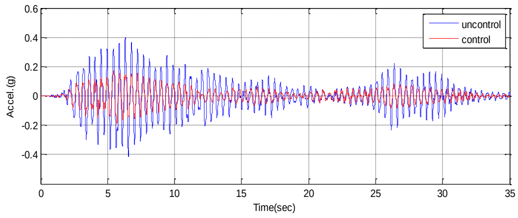


(b) 1-Story Accel. Resp.(Uncon. vs. Control)

Fig.17 1-Story AMD & El-centro Exciting



(a) 2-Story Accel. Resp.(Uncon. vs. Control)



(b) 1-Story Accel. Resp.(Uncon. vs. Control)

Fig.18 2-Story AMD & El-centro Exciting

$$J_1 = \max\left\{ \frac{\left| x_i^{a} \right|}{x^{a,\,\max}} \right\} \qquad (1)$$

$$J_2 = \left\{ \frac{x_i^{a,\,RMS}}{x^{a,\,RMS}} \right\} \qquad (2)$$

Estimate Results / Control Scenario		Model Response		Control Index		Control Effect	
		Max. Accel. (g)	RMS Accel. (g)	J_1 (%)	J_2 (%)	Max. Accel. (%)	RMS Accel. (%)
Un-control (1st Mode)	1story Resp.	0.2186	0.1150	100	100	0	0
	2story Resp.	0.3442	0.1790	100	100	0	0
1st Mode (1sty Con.)	1story Resp.	0.1653	0.0858	75.61	74.60	24.39	25.40
	2story Resp.	0.2329	0.1110	67.66	62.01	32.34	37.99
1st Mode (2sty Con.)	1story Resp.	0.1007	0.0476	46.07	41.39	53.93	58.61
	2story Resp.	0.1472	0.0755	42.76	42.17	57.27	57.83
Un-control (2nd Mode)	1story Resp.	0.5213	0.2348	100	100	0	0
	2story Resp.	0.3996	0.1810	100	100	0	0
2nd Mode (1sty Con.)	1story Resp.	0.3098	0.1192	59.42	50.76	40.58	49.24
	2story Resp.	0.2186	0.0872	54.29	48.17	45.71	51.83
2nd Mode (2sty Con.)	1story Resp.	0.3802	0.1391	72.94	59.24	27.06	40.76
	2story Resp.	0.2984	0.1094	74.32	60.44	25.68	39.56
Un-control (El-centro)	1story Resp.	0.4166	0.0965	100	100	0	0
	2story Resp.	0.5760	0.1374	100	100	0	0
El-centro (1sty Con.)	1story Resp.	0.2158	0.0506	51.81	52.43	48.19	47.57
	2story Resp.	0.3020	0.0688	52.43	50.07	47.57	49.93
El-centro (2sty Con.)	1story Resp.	0.1878	0.0440	45.08	45.59	54.92	54.41
	2story Resp.	0.2889	0.0636	50.15	46.28	49.85	53.72

Table 7 Vibration Amplitudes and Control Indexes (J1&J2), with and without Control Force

Here, $x^{a,\max}$ is the absolute maximum amplitude of acceleration of the uncontrolled case, while x_i^a is the acceleration value at time step *i*. And, $x^{a,RMS}$ is the RMS acceleration value of the uncontrolled case and $x_i^{a,RMS}$ is the RMS acceleration value at time step *i*. These indexes are convenient tools for comparing performance of vibration reduction systems because the performance appears as vibration amplitude ratio. Dyke et al. (2003) used these control indexes on their bench-mark analysis of the vibration problem of a cable-stayed bridge. The absolute maximum value index (J1) is useful for evaluating the response of a structure subject to an impact type (short duration) load. However, if a waveform is defined as the time variation of an external load or the structural acceleration due to it, the maximum value of a waveform does not usually conform to the time variation rate of a waveform. RMS value for a specific time period is widely used to represent the magnitude of the structural vibration because it is closely related to the destructive power (energy) of a structural vibration.

The absolute maximum index (J1) and the RMS value index (J2), as calculated from the data obtained by the excitation tests, are shown on Table 7. The two control indexes (J1 and J2) were used for the quantitative evaluation of the vibration reduction performance of the developed system.

When the model structure was shaken with the excitation frequency of the 1st dominant mode and the 1st story AMD was controlled (1sty Con.), both the 1-story J1 and J2 values of the controlled case were about 75%, respectively and in average, of those of the uncontrolled case (the AMD not actuated), which means that about 25% of vibration reduction was achieved. The controlled 2-story J1 and J2 values were about 65% those of uncontrolled cases, meaning about 35% vibration reduction. With the same frequency and the 2nd story AMD controlled(2sty Con.), the controlled 1-story J1 and J2 values are about 44%(about 56% vibration reduction) of those of the uncontrolled case. The controlled J1 and J2 values of the 2-story were about 43 %(about 57% vibration reduction) of those the uncontrolled case. Overall, the case of 2nd story AMD control showed about 56% greater vibration reduction at 1-story than the case of 1st story AMD control. At the 2-story, the vibration reduction was 39% greater. From the above observations, it can be concluded that installation of the AMD on the 2nd story has definite advantage over the 1st story installation for counteracting the vibration of structure with 1st dominant mode.

When the model structure was shaken with the 2nd dominant mode frequency and the 1st story AMD was controlled, both the controlled 1-story J1 and J2 values were about 55%(45% reduction) of those of the uncontrolled case. The controlled 2-story J1 and J2 values in this case were about 51 %(49% reduction) those of the uncontrolled case. With the same frequency and the 2nd story AMD was controlled, the controlled 1-story J1 and J2 values are about 66 %(34% reduction) of those of the uncontrolled case. The controlled J1 and J2 values of the 2-story were about 67 %(about 33% vibration reduction) of those the uncontrolled case. Overall, with the 2nd modal frequency excitation, the 1st story AMD control showed about 24% greater vibration reduction at 1-story than the 2nd story control. At the 2-story, the vibration reduction was 33% greater. From the above observations, it can be concluded that installation of the AMD on the 1st story is better for counteracting the 2nd dominant mode vibration.

Lastly, when the model structure was shaken by an earthquake type excitation(the El-Centro waveform) and the AMD control at the 1st story, the controlled 1-story J1 and J2 values were 52%(48% reduction) of those of the uncontrolled case. The controlled 2-story values were 51 %(49% reduction). With the AMD control at the 2nd story, the controlled 1-story J1 and J2 values were about 45%(55% reduction) of those of the uncontrolled case and the controlled 2-story values were 48%(52% reduction) of those of the uncontrolled case. Overall, the 2-story AMD control showed 12% greater vibration reduction for 1-story and 6% greater for 2-story than the 1-story control. In conclusion, the 2nd story AMD installation has some advantage over the 1st story AMD installation for dealing with random frequency excitation such as earthquake.

4. Conclusions

In this study, we developed a wireless acceleration measurement system based on MEMS and a prototype AMD system with an AC servo-motor. Further, we combined the two systems together to build a wireless real-time feedback active vibration control system. To evaluate the basic performance of afore mentioned system, we build a laboratory scale 2-stories structural model and carried out a series of tests with the model. From the feasibility studies and the evaluation tests as described before, we arrived at the following conclusions.

1) The acceleration measurement of the developed wireless sensors showed excellent agreement with that of a conventional wired acceleration censor of known accuracy. Thus, the dependability of measured data with the developed wireless sensors system was confirmed. Also, the prototype AMD system, also developed for this study, showed good mechanical reliability and excellent tracking ability to the input control signals of diverse forms and frequencies.

2) It was checked that the developed wireless acceleration sensors system work efficiently picking up the structural response and providing input data to the controller for calculating the necessary control signal to the prototype AMD system, and, thus, is confirmed that the whole system has the potential for a real world active feedback vibration control device.

3) In the real-time feedback vibration control tests, both the absolute maximum value (J1) and the RMS value (J2) showed good vibration reduction performance. It was concluded that a more efficient vibration reduction is achieved with the AMD installed on the 2nd story when the excitation frequency was that of the 1st dominant mode. When the excitation was the 2nd dominant mode, it was more efficient with the AMD installed on the 1st story. When a random type excitation, the El-Centro waveform, was applied, the vibration reduction was greater with the AMD installed at the 2-story, however, the difference was rather small compared to the case with the AMD installed at the 1-story.

4) In this paper, we developed a wireless acceleration sensor system and a prototype AMD system and tested the systems for reliability and basic performance. Further, we built a real-time feedback active vibration control system with the before mentioned systems and carried out an experiment to evaluate the vibration reduction performance with a simple control law and a structural model. With a more

sophisticated control algorithm, optimized for a specific structure, and a multi-channel sensor, this wireless sensors based system can be used as a real-time multi-channel feedback vibration control system for a real structure.

5) Further studies on this subject include optimization of multi-channel vibration control with wireless sensors and AMD system. Reliability of the wireless communication and the power supply will be improved in the new system considering the before mentioned conditions.

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