DEVELOPMENT AND APPLICATION OF A WIRELESS DATA ACQUISITION SYSTEM FOR STRUCTURAL IDENTIFICATION

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The purpose of this study is to develop a portable structural identification instrument using a wireless data acquisition technique and to implement the existing structural system identification algorithms into the developed instrument. As an example this instrument is set up to a three stories frame structure and the absolute accelerations are observed at each floor and ground surface. In this study, the Kalman filter is applied to identify dynamic characteristics of a three stories steel frame structure using microtremor observation data.

Keywords: *Wireless Data Acquisition System, Structural Identification, Kalman Filter, Microtremor*

1. INTRODUCTION

In civil engineering, health monitoring of structure have been treated as an important subject. Health monitoring by using experimental measurements such as strain, acceleration, velocity, displacement, rotation and other parameters has been used for detecting changes, which may indicate damage or degradation.

In recent, the applications of health monitoring of large structure have been facilitated by the developments in measurement, communications and computational technology gradually. Especially, large civil structures as bridges are damaged by fatigue loads or unexpected load such as earthquakes and finally reach to failure. Thus, a structural health monitoring and damage detection methods have been developed and attracted a great deal of public attention in recent decades. Actually many research efforts have been conducted to develop a health monitoring and damage detection techniques of existing civil structures[1),2)]. However, these methods are needed to improve to apply to a real civil structure. The purpose of this study is to develop a practical instrument to identify dynamic parameters of real civil structural systems.

2. IDENTIFICATION TECHNIQUE USING KALMAN FILTER

The state transfer and observation equations to be used in Kalman filter are defined as

$$x_n = \Phi_{n-1} x_{n-1} + \Gamma_{n-1} w_{n-1} \tag{1}$$

$$y_n = H_n x_n + v_n \tag{2}$$

in which x_n is the state variable vector and y_n is the observation vector, w and v are system noise and observation noise vectors, each other, Φ is the state transfer matrix, Γ is the state transfer matrix

for system noise, and H is the observation matrix.
The Kalman filter algorithm is defined as follows,

Step 1. Define an initial value of the state vector $\hat{x}_0$ and its covariance matrix P_0 as well as the covariance matrix of the observation noise R_n .

Step 2. Calculate the pre-estimation value of the state variable vector $\bar{x}_n$ and its covariance matrix M_n as follows,

$$\bar{x}_n = \Phi_{n-1}\hat{x}_{n-1} + \Gamma_{n-1}\hat{w}_{n-1}$$

$$M_n = \Phi_{n-1}\hat{P}_{n-1}\Phi_{n-1}{}^T + \Gamma_{n-1}\Omega_{n-1}\Gamma_{n-1}{}^T$$

Step 3. Calculate the post-estimation value of the covariance matrix P_n of the state variable vector as follow,

$$P_n = (M_n{}^{-1} + H_n{}^T R_n{}^{-1} H_n)^{-1}$$

Step 4. Calculate the Kalman gain K_n as follow,

$$K_n = P_n H_n R_n{}^{-1}$$

Step 5. Calculate the most likelihood estimation value of the state vector $\hat{x}_n$ as follow,

$$\hat{x}_n = \bar{x}_n + K_n(y_n - H_n\bar{x}_n)$$

Step 6. Return to step 1 after renewal of the time step.

3. WIRELESS DATA ACQUISITION SYSTEM

A wireless data acquisition system is an instrument that transmits signals of observed structural responses using wireless transmission technique.
This system has functions to convert the analog signals obtained from sensors to the digital signals and send these signals to the host computer through a signal processing unit. Structural identification is directly carried out at the host computer. Figure 1 shows the wireless data acquisition system.
The main wireless signal processing unit uses LAN standard (IEEE802.11b) and each unit composes of the four wireless components. Because we have 4 units right now it is possible to process digital signals from 32 channels simultaneously.

The power of the wireless signal transmission system is possible to use both DC and AC sources. In this observation we use the AC 100V 20VA source because the structure is well facilitated for experimental purpose. The distance limit of communication between the host and user wireless signal transmission system is restricted within 30m in-doors and 1km outdoors.

The processing unit carries out the sampling in the 100 Hz and its decomposability is 16-bit. The size of measurement unit is 200(W) x 190(D) x 145(H) mm. The communication protocols use UDP (User Datagram Protocol) and TCP (Transmission Control Protocol), and the command part and data part of two protocols are used simultaneously. The sampling precision is possible to maintain during 10 minutes in the range of 1 ms and the broadcast method defined in UDP is used for sampling of analog time histories.

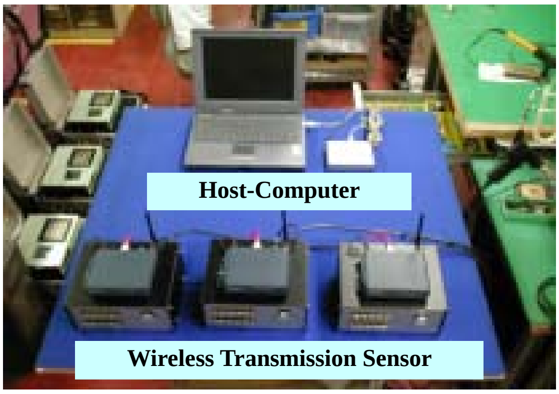


Figure 1. Wireless data acquisition

Figure 2. Three-story steel frame structure

4. STRUCTURAL IDENTIFICATION USING OBSERVATION DATA

We measured microtremor responses of a three stories steel frame structure (located in the Uji campus of Kyoto University, JAPAN) as shown in Figure 2[3)]. The wireless transmission systems and accelerometers are positioned around the near of the center of each floor and ground surface. The servo-accelerometer (Akashi, JAE – 6A3) is used to observe the microtremor of the structure. We selected the observation data carefully to reduce the wind effect as possible as we could.

The absolute accelerations for each floor and ground surface were observed and the observation data are processed using a band pass filter (BPF) with the range of 1~10Hz by which the base-line correction for time integration is performed.
The relative accelerations were obtained by subtracting the ground acceleration from the absolute acceleration of each floor. The relative velocity and displacement of each floor were obtained by time integration from the observed relative accelerations. Those time histories were used to identify dynamic characteristics of this structure.

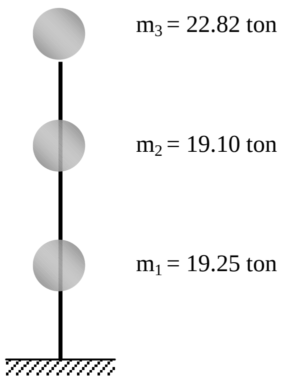


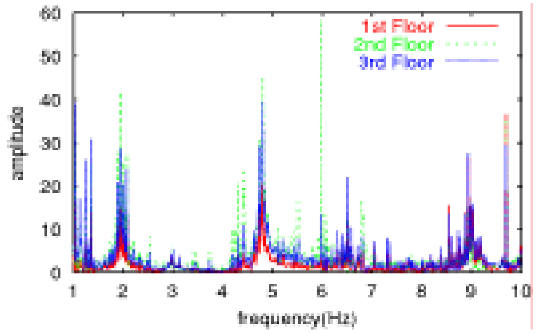
Figure 3. Shear building model

The shear building model of three degree of freedom system as shown in Figure 3 is used for identification of the three stories steel frame structure. The mass of each story is given as shown in the figure. We identify the damping coefficient and stiffness of each layer under the condition that the relative acceleration and velocity of each mass are measured.

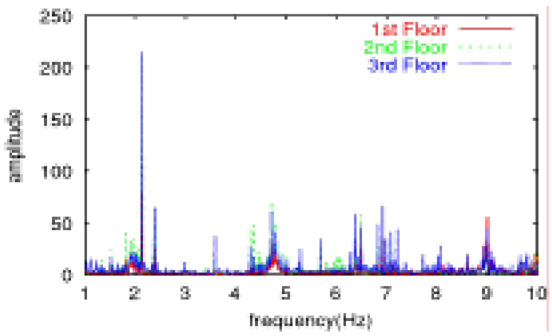
The frequency transfer functions between the ground and each floor are shown in Figure 4 which is calculated using the processed time history of microtremor. Based on the observation conducted different times four different transfer functions are shown in the figure to make clear non-stationary characteristics of microtremor. For all the cases, we can find large amplitudes at 2Hz, 4.9Hz and around 6.5Hz which may correspond to the first, second and third vibration modes of the structural system. The spike noise seen several places might be general noises. Reason of those spike noises is not clear at present but the wireless system might pick up environmental noises. We plan to use a proper digital filter to filter out these noises.

The Kalman filtering technique[4,5] is used for structural parameter identification.
The state variable vector at time step n is given by,

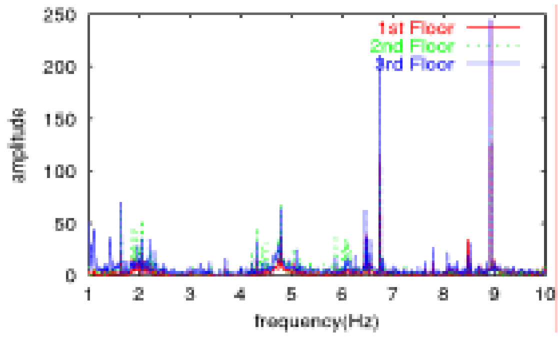
$$x_n = \{y_i, \dot{y}_i, c_i, k_i\}^T \quad (i = 1, \cdots, ndof)$$



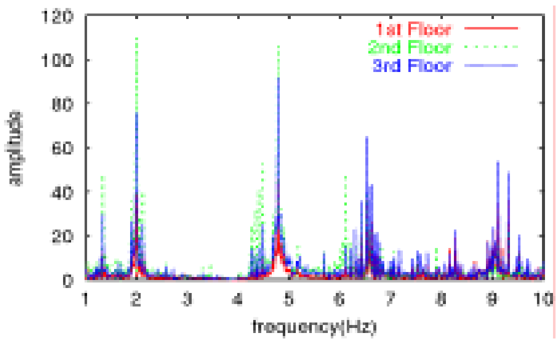
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4

Figure 4. Transfer function for the different measurement time

where ndof is the numbers of degree of freedom.
The reference values of the stiffness and damping coefficient of each floor are defined as follows,

$$c_0 = \{95.28, 35.47, 20.59\}^T \ (KN \cdot \mathrm{sec}/m)$$

$$k_0 = \{43960, 43420, 32912\}^T \ (KN/m)$$

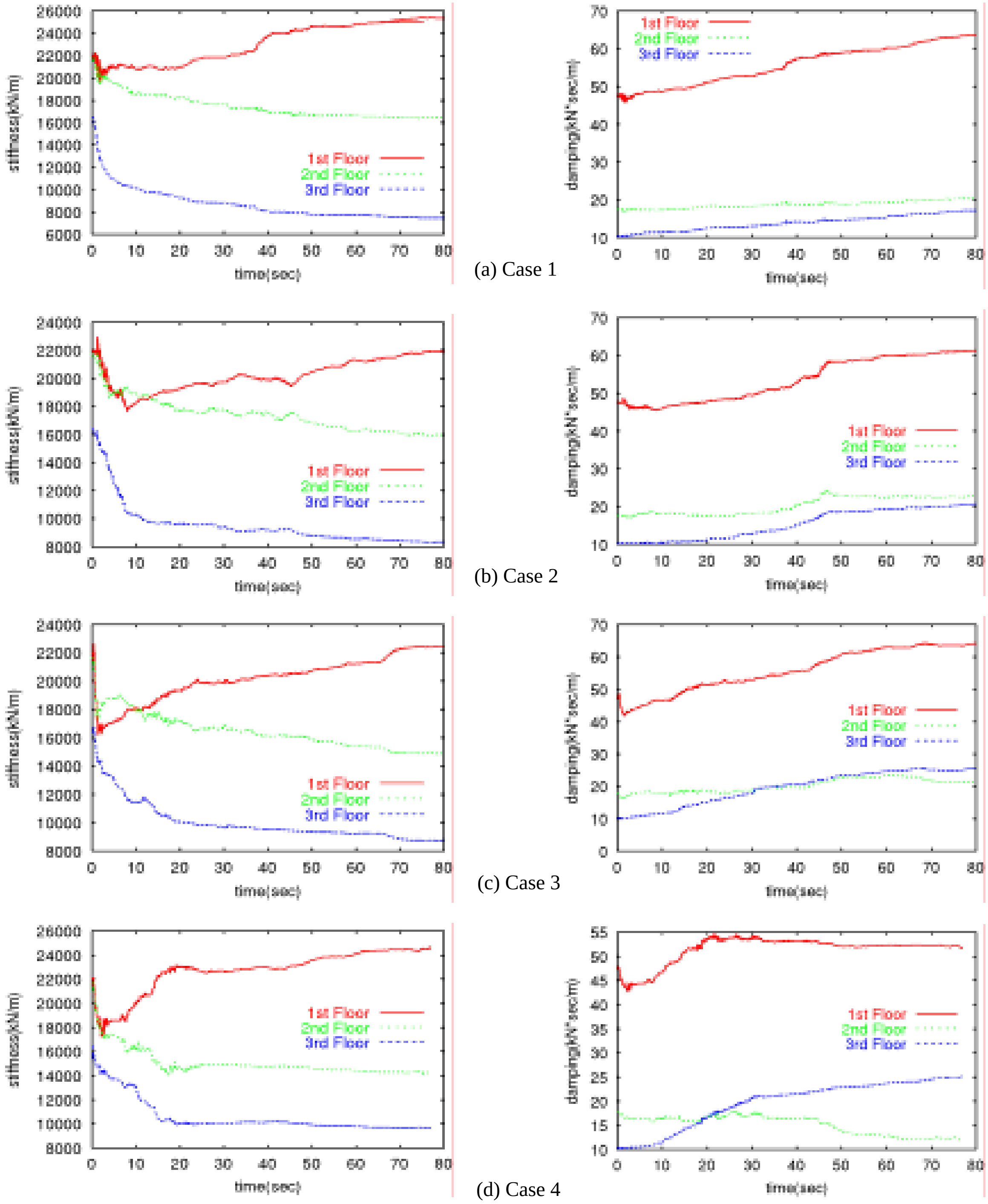
The initial values of the state vector is defined as follows in which the initial values of stiffness and damping coefficient of each floor are half of the reference values,

$$\hat{x}_0 = \{0.0, 0.0, c_i \times 0.5, k_i \times 0.5\}^T \quad (i = 1, \cdots, ndof)$$

The initial covariance matrix of the state vector is assumed as,

$$P_0 = \{0.01, 0.01, 50^2, 20000^2\}^T$$

The covariance matrix of the observation matrix (R_n) is a diagonal matrix with its component of 0.01. The identified time histories of the damping coefficient and stiffness of each layer are shown in Figure 5. There are four cases of time histories of identified stiffness and damping coefficient that are identified using same initial values. In the Figure 5, the converged stiffness values of each layer have similar values whereas the damping values are changed time to time. This means that the stiffness identification is more robust than that of damping coefficient. As general identification of damping coefficient is not stable comparing with stiffness identification because the sensitivity of damping is related to velocity response whereas that of stiffness is related to displacement response.



(a) Case 1

(b) Case 2

(c) Case 3

(d) Case 4

Figure 5. Time histories of identified stiffness (left) and damping coefficient (right) for each case

Table 1. Mean and variance values of the identified stiffness and damping coefficient for all measurement cases

Case	Mean			Variance			Case	Mean			Variance		
	1st floor	2nd floor	3rd floor	1st floor	2nd floor	3rd floor		1st floor	2nd floor	3rd floor	1st floor	2nd floor	3rd floor
1	25177.56	16500.77	7558.96	39425.05	2938.25	8372.39	15	20606.05	14371.91	10839.97	247539.46	232955.43	49802.00
2	26432.14	15502.37	7111.43	134225.63	10105.38	2259.45	16	31401.21	17903.90	6198.86	13500.97	7174.17	389.21
3	22026.91	15068.65	8955.91	236543.35	43179.94	45454.55	17	22542.93	15616.55	8721.94	4912.31	1157.80	85.52
4	24411.84	14307.04	9710.50	9921.08	1045.42	991.74	18	35983.36	16131.22	5555.32	224454.30	172728.42	12206.64
5	17840.62	17861.34	12259.96	112989.77	137760.03	48849.80	19	31709.40	16413.16	6191.40	2902.52	17846.68	122.53
6	20159.44	17372.92	9022.28	4061.53	21227.53	1041.09	20	20311.82	14021.79	11349.26	185179.91	59223.04	78754.81
7	20408.06	17559.40	8616.48	73275.82	60012.41	3708.80	21	24096.32	15820.40	7910.85	1337.19	2354.30	1449.14
8	13794.89	21179.04	12183.16	3755.71	17797.27	10604.64	22	24888.05	14239.95	9141.20	46775.40	6793.70	12284.24
9	16661.59	16257.67	15678.78	3090.31	12311.05	2060.41	23	20081.84	15111.54	11093.53	1153.98	202.31	824.16
10	25005.09	13549.74	8487.79	5186.83	12725.00	173.90	24	21846.33	14114.41	10231.65	40454.56	4670.63	11969.13
11	26844.01	15576.58	6953.54	81654.06	20380.68	6473.43	25	29882.18	15981.89	6745.86	31253.92	3827.68	418.69
12	26048.02	13810.80	8793.79	63989.11	3801.64	3910.92	26	34618.96	17297.77	5945.39	75655.75	1359.25	2322.43
13	28955.98	12933.54	9139.08	11184.13	3160.83	3713.24	27	17067.40	14329.68	21974.36	3092.94	2159.58	4700.21
14	24347.15	13411.27	10151.33	2737.51	665.73	51.10	Average	24261.77	16045.31	9595.44	54675.66	27500.02	11266.67

(a) Identified stiffness (KN/m)

Case	Mean			Variance			Case	Mean			Variance		
	1st floor	2nd floor	3rd floor	1st floor	2nd floor	3rd floor		1st floor	2nd floor	3rd floor	1st floor	2nd floor	3rd floor
1	62.23	19.99	16.52	1.52	0.10	0.30	15	54.66	19.17	35.70	2.93	6.70	26.67
2	66.01	25.42	20.48	0.21	0.10	0.05	16	58.16	19.06	22.27	0.09	0.19	0.10
3	63.59	22.13	25.15	0.24	0.63	0.11	17	52.24	38.12	30.69	0.02	0.10	0.03
4	52.22	12.30	24.41	0.02	0.05	0.19	18	67.75	13.28	13.93	1.51	1.03	0.24
5	49.97	18.73	21.31	0.23	0.79	3.66	19	64.70	14.92	17.86	0.10	0.88	0.06
6	59.52	20.98	20.98	0.13	0.15	0.01	20	64.32	26.96	25.86	1.02	0.85	2.55
7	64.82	24.25	19.97	4.17	0.34	0.74	21	68.01	21.57	20.89	0.08	0.12	0.03
8	72.54	28.52	26.62	0.86	0.06	0.51	22	74.48	24.26	37.00	0.45	0.44	0.38
9	59.10	21.68	38.51	0.53	0.15	1.32	23	54.12	29.63	58.02	0.38	0.44	0.46
10	59.66	14.06	31.22	0.09	1.09	0.11	24	38.77	4.77	44.85	0.69	1.10	5.01
11	79.12	34.70	23.52	3.83	2.02	0.50	25	66.04	22.48	18.34	0.17	0.37	0.12
12	62.32	20.32	23.37	0.29	0.47	1.14	26	59.09	16.95	17.89	1.19	1.86	0.91
13	59.70	19.90	26.38	0.19	0.39	0.68	27	39.31	9.95	71.06	0.32	0.31	9.03
14	48.36	7.70	39.83	0.05	0.05	0.47	Average	56.12	17.71	30.71	1.85	1.13	2.68

(b) Identified damping coefficient (KN·sec/m)

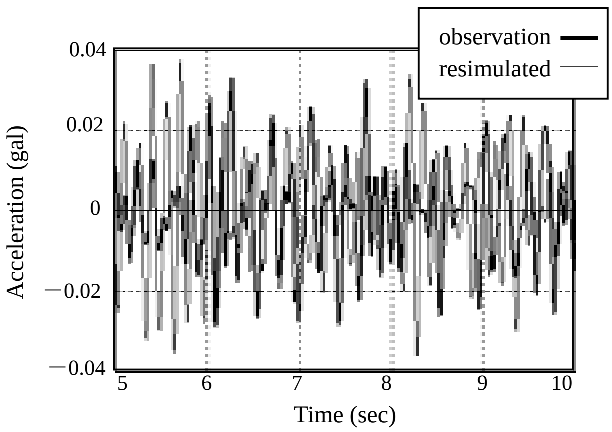


Figure 6. Comparison of resimulated and observed values

For each case, the identified values of the stiffness and damping coefficient of each story are estimated as the mean values after 60 seconds. For all the measurement cases, the mean and variance values of the identified stiffness and damping coefficient are summarized in Table 1.
The average values of identified stiffness and damping coefficient of each floor are given by,

$$k_1 = 24261.77 kN/m,\ k_2 = 16045.31 kN/m,$$

$$k_3 = 9595.44 kN/m$$

$$c_1 = 56.12 kN \cdot \sec/m,\ c_2 = 17.71 kN \cdot \sec/m,$$

$$c_3 = 30.71 kN \cdot \sec/m$$

Using the identified stiffness of each floor, we calculate the natural frequencies of the first, second and third modes as follows, respectively,

$$f_1 = 2.14Hz,\ f_2 = 5.14Hz,\ f_3 = 7.89Hz$$

The natural frequency of first mode is similar. However, the natural frequencies of the second and third modes are different because of the effect of the torsional mode or the wind.

Using these values, we also resimulated the structural response of the third story of analytical model with the input value as acceleration of the ground. The resimulated response is compared with the observed microtremor response as shown in Figure 6. The resimulated acceleration time history, especially amplitude, dose not agrees well with the observed time history although the arrival time of peaks and troughs are almost same. The reason of this disagreement is not clear at present.

5.CONCLUSIONS

Using a wireless data acquisition technique, a portable structural identification instrument is developed. To identify the efficiency of the developed identification instrument, we measured microtremor response of a three stories steel frame structure. Using the Kalman filtering technique we conducted a quasi-online identification of structural stiffness and damping and found that stiffness identification is stable but not for damping.

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