MODAL IDENTIFICATION OF STRUCTURES USING ARMAV MODEL FOR AMBIENT VIBRATION MEASUREMENT

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SUMMARY

A procedure is presented for evaluating the dynamic characteristics of structures from ambient vibration measurement by using ARMAV model. The coefficient matrixes of ARMAV model are estimated by a two-stage least-square approach, then the modal parameters are obtained from the coefficient matrixes of AR part by adapting the concept of Ibrahim time domain technique. Verification of the procedure is made by numerical simulation, in which the effect of nonwhite-noise input on identified results is also investigated. Finally, the procedure is applied to identify the dynamic characteristics of a five-story steel structure from the ambient vibration measurement. The identified results are compared with those from ARV model and forced vibration tests and the analytical solution from finite element analysis.

INTRODUCTION

Investigation of the dynamic characteristics of an existing structure system from field tests is a necessary and important task for checking the construction quality, comparing with analytical results to assure the correctness of an analytical model and to modify the analytical model if necessary, and even for damage assessment. It is well known that there are several popular methods to accomplish the field tests, namely, ambient vibration tests, forced vibration tests, free vibration tests, and earthquake response measurement. Among these field tests, ambient vibration tests are the most popular because of the easiness in set-up. However, the unknown or unmeasured input in the ambient vibration tests results in a big uncertainty in analyzing the measured data. For modal analysis from the ambient vibration measurement in time domain, one often used procedure is to incorporate the random decrement technique with the Ibrahim time domain scheme (ITD) [Ibrahim and Mikulcik, 1973; Huang, *et al*., 1999]. Time series models, AR and ARMA, are also frequently applied to analyzing the ambient vibration measurement [Piombo, *et al*., 1993; Loh and Wu, 1996; He and Roeck, 1997]. Among these techniques, ARMA model is base on the assumption of stationary input, while the others assume that the input is Gaussian white noise process. Hence, ARMA model has less restriction than the others.

The purposes of the paper are manifold. One is to extend the two-stage least square procedure for evaluating the coefficients of single output/single input ARMA mode developed by Gersch and Liu [1976] to the case of multivariate ARMA model (ARMAV). A procedure is also given for determining the dynamic characteristics of a structure system, namely, natural frequencies, modal damping ratios, and mode shapes, from the coefficient matrixes of AR part based on the concept of ITD. Another is to apply the proposed procedure to identify the dynamic characteristics of a five-story steel structure from the ambient vibration measurement. The identified results were compared with those obtained from multivariate ARV model. At the same time, the comparison was made among the results from ambient vibration tests, forced vibration tests, and finite element analysis.

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ESTABLISHEMENT OF ARMAV MODEL

The mathematics expression for ARMAV model is

$$\mathbf{X}_t = \sum_{i=1}^{n} \mathbf{\Phi_i} \mathbf{X}_{t-i} + \sum_{i=1}^{m} \mathbf{\theta_i} \mathbf{A}_{t-i} + \mathbf{A}_t \,, \tag{1}$$

where $\mathbf{X}_{t-i}$ is the actual measurement at time *t-i*, $\mathbf{A}_{t-i}$ is the white noise vector at time *t-i*, $\mathbf{\Phi_i}$ and $\mathbf{\theta_i}$ are the coefficient matrixes for AR and MA parts, respectively. The white noise process satisfies

$$E[\mathbf{A}_t] = \mathbf{0} \text{ and } E\,[\mathbf{A}_{t-i}\ \mathbf{A}_{t-j}^T] = \delta_{ij} \mathbf{W} \,, \tag{2}$$

where E[ ] denotes the mean-value operator, δ_{ij} is Kronecher symbol, and $\mathbf{W}$ is the variance matrix of $\mathbf{A}_t$, which may bot be a diagonal matrix.

The model represented by Eq. (1) will be denoted by ARMAV(*n*, *m*; *l*) when each $\mathbf{X}_{t-i}$ has *l* components. If the second summation in Eq. (1) is left out, then it becomes ARV model, and is denoted by ARV(*n*; *l*). Similarly, MAV(*m*; *l*) denotes the mathematics expression of Eq. (1) without the first summation.

Wang [1984] proved that like single output/single input system, in the case of multiple output/multiple input, ARMAV(*n*, *m*; *l*), ARV(∞ ; *l*), and MAV(∞ ; *l*) are equivalent in modeling stationary process. Hence, $\mathbf{X}_t$ can also be expressed as

$$\mathbf{X}_t = \sum_{i=1}^{\infty} \hat{\mathbf{\Phi}}_\mathbf{i}\ \mathbf{X}_{t-i} + \mathbf{A}_t \,, \tag{3}$$

or

$$\mathbf{X}_t = \sum_{j=0}^{\infty} \mathbf{H_i} \mathbf{A}_{t-i} \text{ , and } \mathbf{H_0} = \mathbf{I} \,, \tag{4}$$

where $\mathbf{I}$ is a unit matrix. Based on this equivalent relationship, the two-stage least square process for evaluate the coefficient of ARMA model developed by Gersch and Liu [1976] can be extended to the case of ARMAV model. By following the similar procedure used by Gersch and Liu [1976], one can obtain the following relationships [Huang, 1999]

$$\mathbf{R_{XX}}(k) = \sum_{i=1}^{n} \mathbf{R_{XX}}(k-i) \mathbf{\Phi_i}^T + \sum_{i=0}^{m} \mathbf{R_{XA}}(k-i) \mathbf{\theta_i}^T \,, \tag{5}$$

$$\mathbf{R_{XA}}(-k) = \sum_{i=1}^{n} \mathbf{\Phi_i}\ \mathbf{R_{XA}}(i-k) + \mathbf{\theta_k}\ \mathbf{W} \,, \tag{6}$$

where $\mathbf{R_{XA}}(-k) = \mathbf{H_k}\ \mathbf{W}$, for $k \geq 0$, and $\mathbf{R_{XA}}(-k) = \mathbf{0}$, for $k < 0$, (7)

$$\mathbf{H_k} = \sum_{i=1}^{M_{ar}} \hat{\mathbf{\Phi}}_\mathbf{i}\ \mathbf{H_{k-i}} \text{ and } \mathbf{H_k} = \mathbf{0} \text{ for } k < 0 \,. \tag{8}$$

At the first stage, one use traditional least square approach to evaluate $\hat{\mathbf{\Phi}}_\mathbf{i}$ in Eq. (3) [Wang and Fang, 1986]. The summation in Eq.(3) cannot go up to infinite terms for practical concern; thus, M_{ar} terms are used. Then, compute $\mathbf{W}$ from ARV model before evaluate $\mathbf{R_{XA}}(-k)$ from Eqs. (7) and (8). Finally, $\mathbf{\Phi_i}$ and $\mathbf{\theta_i}$ are estimated from Eqs. (5) and (6) by using least square approach, again. From the author's experiences, Eq. (6) had better not be used because $\mathbf{R_{XA}}(-k)$ and $\mathbf{W}$ in Eq. (6) are all estimated by using the results from the first-stage least square approach and no measured data are directly used in Eq. (6). Consequently, the error from this estimation may cause significant deviation in evaluating the coefficient matrixes of ARMAV model.

IDENTIFYING THE DYNAMIC CHARACTERISTICS OF STRUCTURES

If one correlates ARMAV model to equations of motion, one is able to discover that the AR part represents the free decay responses of the system under consideration (i.e., the responses due to nonzero initial conditions). Consequently, if one wants to evaluate the dynamic characteristics of the system, namely natural frequencies, modal damping ratios, and mode shapes, Ibrahim time domain system technique (ITD) could be suitable scheme to meet the need. By following the concept of ITD, it can be proved that [Huang, 1999] if one constructs a matrix as follows:

$$\mathbf{G} = \begin{bmatrix} \mathbf{0} & \mathbf{I} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & & & & & \\ \Phi_\mathbf{n} & \Phi_\mathbf{n-1} & & & & \Phi_\mathbf{1} \end{bmatrix}_{2N\times 2N} \tag{9}$$

Then, the eigenvalues and eigenvectors of **G** are related to the dynamic characteristics of the system. In Eq. (9), $2N = n \times N_m$, where N_m is the order of **X**, which also means the number of measured degrees of freedom. Each eigenvector of **G** has $2N$ components. If one divides the $2N$ components into n vectors by sequence, then these vectors are parallel with each other. Hence, anyone of the vectors is corresponding to one mode of the system.

Let the k^{th} eigenvalue of **G** be denoted by λ_k, which is usually a complex number and set equal to $a_k + i\, b_k$. The frequency and damping ratio of the system are computed by

$$\tilde{\beta}_k = \sqrt{\alpha_k^2 + \beta_k^2}\ , \quad \xi_k = -\alpha_k / \tilde{\beta}_k\ , \tag{10}$$

where $\tilde{\beta}_k$ is the pseudo-undamped circular natural frequency, ξ_k is the modal damping ratio,

$$\beta_k = \frac{1}{\Delta t}\tan^{-1}\left(\frac{b_k}{a_k}\right), \quad \alpha_k = \frac{1}{2\Delta t}\ln\,(a_k^2 + b_k^2)\ , \tag{11}$$

and $1/\Delta t$ is the sampling rate in measurement.

As a matter of fact, it can be mathematically proved that λ_k also satisfies the following equation

$$\left| \lambda_k^n\, \mathbf{I} - \lambda_k^{n-1}\, \mathbf{\Phi_1} - \lambda_k^{n-2}\, \mathbf{\Phi_2} \cdots - \lambda_k \mathbf{\Phi_{n-1}} - \mathbf{\Phi_n} \right| = 0 \tag{12}$$

Equation (12) is also often used to find natural frequencies and damping ratios [Wang and Fang, 1986].

NUMERICAL EXAMPLE

To verify the goodness of the proposed procedure, using Laplace transformation has numerically simulated a six-floor shear building subjected to white-noise excitation at the base. Modal damping ratio equal to 5% has been used in the simulation. The theoretical natural frequencies of the system are 0.801, 2.14, 3.15, 4.25, 5.04, and 5.37 Hz. The velocity output of the six degrees of freedom with 65000 data points for each degree of freedom was used in the following system identification. The sampling rate of data is 100Hz.

To check the effect of choosing M_{ar} on identifying the modal parameters, Table 1 lists the identified results by using ARMAV(2, 3; 6) with different values for M_{ar}, in which MAC (modal assurance criterion) is defined as [Allemang and Brown, 1983]

$$\text{MAC}(\boldsymbol{\varphi}_{\mathbf{iI}}, \boldsymbol{\varphi}_{\mathbf{iA}}) = \frac{\left| \boldsymbol{\varphi}_{\mathbf{iI}}^T \boldsymbol{\varphi}_{\mathbf{iA}}^* \right|^2}{\boldsymbol{\varphi}_{\mathbf{iI}}^T \boldsymbol{\varphi}_{\mathbf{iI}}^* \boldsymbol{\varphi}_{\mathbf{iA}}^T \boldsymbol{\varphi}_{\mathbf{iA}}^*}\ , \tag{13}$$

where $\boldsymbol{\varphi}_{\mathbf{iI}}$ is the identified i[th] mode shape from the impulse test, and $\boldsymbol{\varphi}_{\mathbf{iA}}$ is the corresponding analytical mode shape. The super-script "T" denotes the transport of a matrix, and "*" means the conjugate pair. Obviously, two corresponding modes are considered well correlated if the MAC value is close to one, and uncorrelated if close to zero. Table 1 shows that the identified results will not change with the change of M_{ar} as long as M_{ar} is sufficiently large. A simple rule of thumb is to select M_{ar} in the range $M_{ar} \cong (3 \sim 7) \times \max(m, n)$. All the identified results given in Table 1 show excellent agreement with the analytical ones.

To show the effects of non-white noise input on the results identified by the proposed procedure, the white noise was low-pass filtered by the function given in Fig.1, which makes the amplitude at $f_2 = f_{cut} + 5$Hz decrease by 90%. Then, the filtered signal was used as the base excitation input for the six-story shear building. Again, the velocity output was used for identification. Table 2 shows the identified results for different f_{cut} at the low-pass filter. The order of ARMAV model shown in Table 2 is the minimum order for ARMAV(m, m–1; 6) that produces the identified results meeting the following error criteria: less than 2% and 20%, respectively, relative errors for identified frequency and damping ratio, and larger than 0.9 of MAC. It is noted that the excellent identified results still can be obtained with the price of raising the order of ARMAV model even when f_{cut} = 2Hz, which results in much smaller responses for higher modes (i.e. 4th to 6th modes) than the first two modes.

Table 1: Identified results for white-noise input

	Mode No.	M_{ar} = 20	50	100
Frequency (Hz)	1	0.804	0.804	0.804
	2	2.13	2.13	2.13
	3	3.14	3.14	3.14
	4	4.23	4.23	4.23
	5	5.02	5.02	5.02
	6	5.37	5.37	5.37
Modal Damping (%)	1	4.7	4.7	4.7
	2	4.7	4.7	4.7
	3	4.8	4.8	4.8
	4	5.0	5.1	5.1
	5	5.0	5.0	5.0
	6	5.0	5.0	5.0
MAC	1	1.00	1.00	1.00
	2	1.00	1.00	1.00
	3	1.00	1.00	1.00
	4	0.98	0.98	0.98
	5	1.00	1.00	1.00
	6	1.00	1.00	1.00

Table 2: Identified results for filtered white-noise input

	Mode No.	f_{cut} (Hz) = 2, ARMAV (5, 4; 6)	5, ARMAV (4, 3; 6)
Frequency (Hz)	1	0.804	0.805
	2	2.13	2.13
	3	3.14	3.15
	4	4.23	4.26
	5	4.99	5.03
	6	5.39	5.41
Modal Damping (%)	1	4.8	4.5
	2	4.4	4.6
	3	5.0	4.7
	4	4.9	5.4
	5	4.5	4.0
	6	4.2	4.7
MAC	1	1.00	1.00
	2	1.00	1.00
	3	1.00	1.00
	4	0.98	0.99
	5	0.97	1.00
	6	0.98	0.94

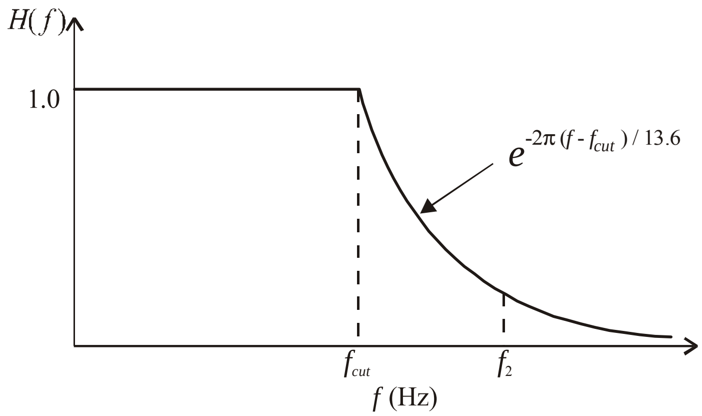

Figure 1: Low-pass filtering function

APPLICATION TO AMBIENT VIBRATION TEST

To show the validity of applying the identification procedure to ambient vibration measurement, the measured data from a five-story steel structure are processed. The moment resisting frame steel structure was built for the purpose of conducting researches on the structural control techniques by means of full-scale field tests organized by the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Hence, the structure was designed much softer than a common building, and there are no walls or bracing. As Fig. 2 shows the sketch diagram of the structure, the structure mainly consists of four corner columns and four girders, which are made of ASTM A36 material.

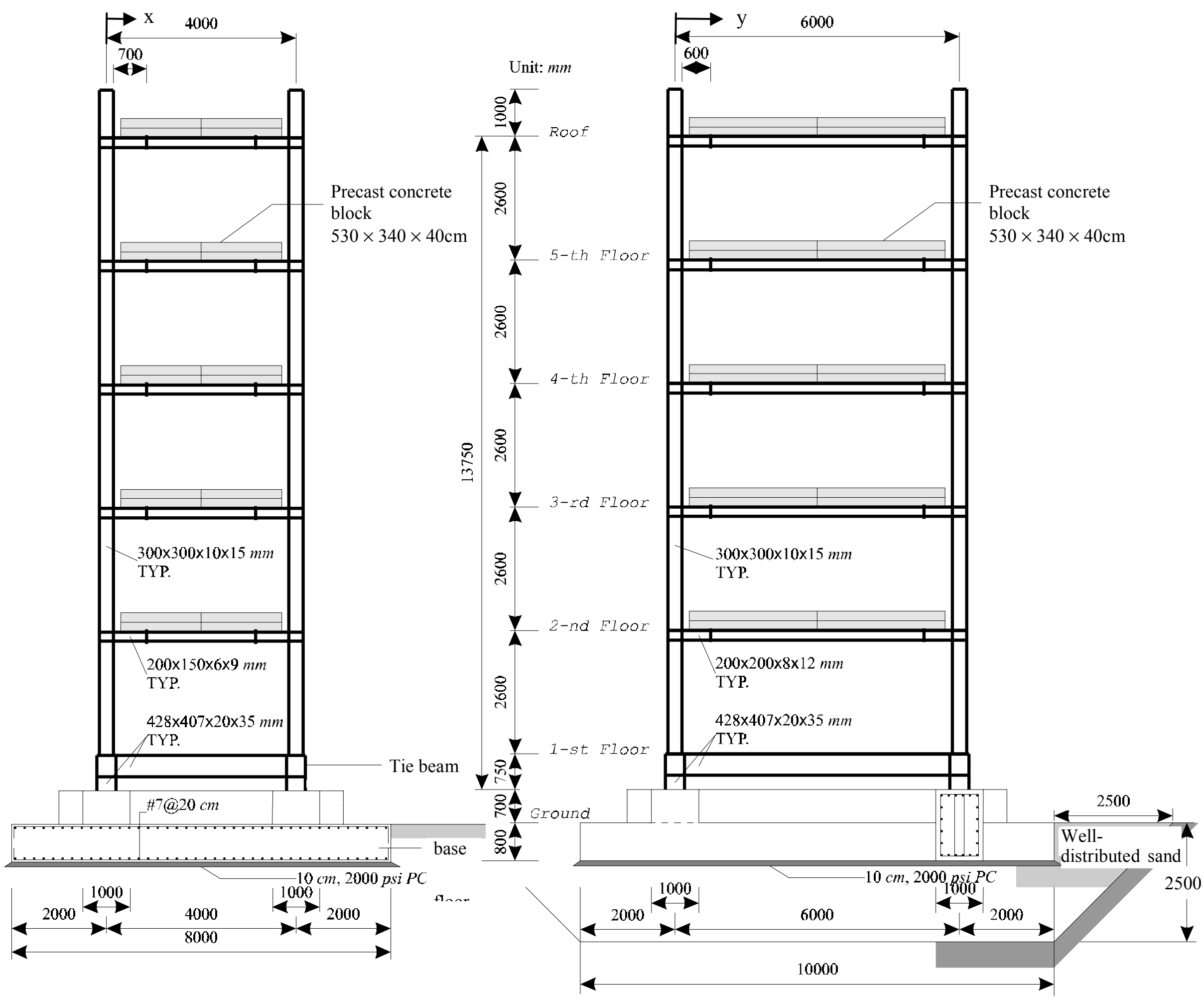

Figure 2: Sketch diagram for a five-story steel structure

Instrumentation for Measurement

To measure the ambient vibration of the structure, six to eight velocity type sensors with vary high sensitivity were attached at the appropriate locations. The analogue sensor signals were converted to digital data and recorded in a PC-based portable data acquisition system. The resolution for the whole measuring system can reach to 10^{-4} cm/sec. In the acquisition system, high-pass and low-pass filters are included, whose cut-off frequencies were set equal to 0.1 Hz and one-third of sampling rate, respectively.

Due to the symmetry of the structure and high stiffness of the floor diaphragms, it is reasonable to describe the motion of each floor by using three uncoupled degrees of freedom, namely, two translate motions and one torsion motion. Therefore, the responses of the three degrees of freedom for each floor could be independently measured. Six sensors were, respectively, placed at the geometry center of each floor, including the footing, to measure the translate motion once for each direction. To obtain the responses of torsion motion, two sets of measurements were carried out. One set was to place two sensors on each of the roof, 5^{th}, 4^{th}, and 3^{rd} floors. One sensor was placed on the geometry center, and another was placed at the edge of the floor. In another set of arrangement the sensors on the roof of the first set were moved to the 2nd floor, and the rest were the same as the first set arrangement. For each measurement, 10-minute responses were recorded with a sampling rate of 100Hz.

Results and Discussions

A set of measured data, which included six degrees of freedom output for translate motion or four degrees of freedom for torsion motion, were simultaneously processed by ARMAV or ARV model [Huang, 1999]. The identified results are given in Tables 3 ~ 5, in which y-direction means the direction along the long side of a floor, while x-direction is the direction along the short side (see Fig. 2). Tables 3 ~ 5 also show the results from finite element analysis of commercial package, ETABS [Hsu, 1994], whose input data were based on the structure design. The identified modal parameters for translation motion in y-direction from forced vibration test [Chung, *et. al*, 1999] are also given in Table 3.

The results obtained from ARV and ARMAV models are excellent agreement with each other. However, the order of ARV model needs to be higher than that in AR part for ARMAV model to reach the same accuracy of solution. The increase of the order in AR part will result in spurious modes, and increase the difficulty to find correct structural modes. In identifying the torsion modes, high order of ARV and ARMAV were used due to the slight directional misalignment of the sensors causing that the torsion responses were somewhat contaminated by translation responses. Table 3 shows that, as one expected, the forced vibration tests provided smaller modal frequencies and larger modal damping ratios than the ambient vibration tests did because the input energy to the steel frame was larger for the former. Nevertheless, the identified results from the two types of tests show reasonable agreement, especially for the lower modes, which somewhat supports the feasibility of applying ARMAV to processing the ambient vibration measurement.

Comparison of the identified results with those from ETABS reveals that the discrepancy in the modal parameters for higher modes is rather severe. It is surprised to observe the significant difference in the first frequency of y-direction. The identified modal damping ratios are much smaller than the designed values. These facts show the needs for improving the finite element mode in some ways.

Table 3: Identified results for translation motion in y-direction

Mode No.	Frequency (Hz)				Mode Shape				Modal Damping (%)			
	Ambient		Forced Vib.	ETABS	Ambient		Forced Vib.	ETABS	Ambient		Forced Vib.	De-signed Value
	ARV (6; 6)	ARMAV (4, 3; 6)			ARV (6; 6)	ARMAV (4, 3; 6)			ARV (6; 6)	ARMAV (4, 3; 6)		
1	0.88	0.88	0.885	0.817	$\begin{Bmatrix} 1.0 \\ .85 \\ .68 \\ .42 \\ .16 \end{Bmatrix}$	$\begin{Bmatrix} 1.0 \\ .85 \\ .68 \\ .42 \\ .16 \end{Bmatrix}$	$\begin{Bmatrix} 1.00 \\ .880 \\ .678 \\ / \\ .164 \end{Bmatrix}$	$\begin{Bmatrix} 1.00 \\ .871 \\ .671 \\ .415 \\ .153 \end{Bmatrix}$	0.29	0.27	0.39	2
2	2.93	2.93	2.832	2.711	$\begin{Bmatrix} -.88 \\ -.057 \\ .78 \\ 1.0 \\ .53 \end{Bmatrix}$	$\begin{Bmatrix} -.88 \\ -.057 \\ .78 \\ 1.0 \\ .53 \end{Bmatrix}$	$\begin{Bmatrix} -.880 \\ -.042 \\ .765 \\ / \\ .534 \end{Bmatrix}$	$\begin{Bmatrix} -.958 \\ -.0648 \\ .774 \\ 1.00 \\ .520 \end{Bmatrix}$	0.21	0.22	0.37	2
3	5.55	5.55	5.198	5.139	$\begin{Bmatrix} .71 \\ -.86 \\ -.80 \\ .75 \\ 1.0 \end{Bmatrix}$	$\begin{Bmatrix} .71 \\ -.86 \\ -.80 \\ .75 \\ 1.0 \end{Bmatrix}$	$\begin{Bmatrix} .407 \\ -.883 \\ -.665 \\ / \\ 1.00 \end{Bmatrix}$	$\begin{Bmatrix} .796 \\ -.871 \\ -.765 \\ .778 \\ 1.00 \end{Bmatrix}$	0.46	0.46	1.58	2
4	8.36	8.37	7.743	7.638	$\begin{Bmatrix} -.35 \\ .97 \\ -.58 \\ -.41 \\ 1.0 \end{Bmatrix}$	$\begin{Bmatrix} -.35 \\ .96 \\ -.58 \\ -.41 \\ 1.0 \end{Bmatrix}$	$\begin{Bmatrix} -.201 \\ .863 \\ -.922 \\ / \\ 1.00 \end{Bmatrix}$	$\begin{Bmatrix} -.405 \\ .925 \\ -.576 \\ -.402 \\ 1.00 \end{Bmatrix}$	0.55	0.52	1.15	2
5	10.4	10.4	/	9.373	$\begin{Bmatrix} -.15 \\ .62 \\ -.96 \\ 1.0 \\ -.82 \end{Bmatrix}$	$\begin{Bmatrix} -.16 \\ .62 \\ -.98 \\ 1.0 \\ -.83 \end{Bmatrix}$	/	$\begin{Bmatrix} -.199 \\ .623 \\ -.948 \\ 1.00 \\ -.802 \end{Bmatrix}$	0.49	0.51	/	2

Note: “ / ” means no data available.

Table 4: Identified results for translation motion in x-direction

Mode No.	Frequency (Hz)			Mode shape			Modal damping (%)		
	Ambient		ETABS	Ambient		ETABS	Ambient		Designed Value
	ARV (6; 6)	ARMAV (4, 3; 6)		ARV (6; 6)	ARMAV (4, 3; 6)		ARV (6; 6)	ARMAV (4, 3; 6)	
1	1.15	1.14	0.890	$\begin{Bmatrix}1.0\\.81\\.63\\.37\\.14\end{Bmatrix}$	$\begin{Bmatrix}1.0\\.81\\.63\\.38\\.14\end{Bmatrix}$	$\begin{Bmatrix}1.00\\.816\\.589\\.338\\.114\end{Bmatrix}$	0.27	0.26	2
2	3.78	3.78	3.314	$\begin{Bmatrix}-.90\\.032\\.85\\1.0\\.52\end{Bmatrix}$	$\begin{Bmatrix}-.90\\.032\\.86\\1.0\\.52\end{Bmatrix}$	$\begin{Bmatrix}-.981\\-.0818\\.885\\1.00\\.479\end{Bmatrix}$	0.50	0.48	2
3	6.67	6.68	6.978	$\begin{Bmatrix}.66\\-.96\\-.65\\.81\\1.0\end{Bmatrix}$	$\begin{Bmatrix}.66\\-.96\\-.65\\.82\\1.0\end{Bmatrix}$	$\begin{Bmatrix}.732\\-.938\\-.644\\.885\\1.00\end{Bmatrix}$	1.3	1.4	2
4	8.35	8.35	10.47	$\begin{Bmatrix}-.39\\1.0\\-.84\\-.21\\.83\end{Bmatrix}$	$\begin{Bmatrix}-.39\\1.0\\-.83\\-.22\\.84\end{Bmatrix}$	$\begin{Bmatrix}-.351\\.881\\-.614\\-.352\\1.00\end{Bmatrix}$	0.22	0.22	2
5	8.77	8.77	12.54	$\begin{Bmatrix}-.12\\.35\\-.82\\1.0\\-.92\end{Bmatrix}$	$\begin{Bmatrix}-.12\\.35\\-.82\\1.0\\-.90\end{Bmatrix}$	$\begin{Bmatrix}-.175\\.591\\-.941\\1.00\\-.808\end{Bmatrix}$	0.52	0.50	2

Table 5: Identified results for torsion motion

Mode No.	Frequency (Hz)			Mode Shape			Modal Damping (%)		
	Ambient		ETABS	Ambient		ETABS	Ambient		Designed Value
	ARV (50; 4)	ARMAV (28, 27; 4)		ARV (50; 4)	ARMAV (28, 27; 4)		ARV (50; 4)	ARMAV (28, 27; 4)	
1	1.86	1.85	1.608	$\begin{Bmatrix}1.0\\.89\\.68\\.40\\.15\end{Bmatrix}$	$\begin{Bmatrix}1.0\\.90\\.67\\.41\\.15\end{Bmatrix}$	$\begin{Bmatrix}1.00\\.801\\.546\\.263\\.0202\end{Bmatrix}$	0.55	0.31	2
2	6.28	6.28	5.613	$\begin{Bmatrix}-.88\\.011\\.83\\1.0\\.50\end{Bmatrix}$	$\begin{Bmatrix}-.87\\.011\\.83\\1.0\\.49\end{Bmatrix}$	$\begin{Bmatrix}-.983\\.0490\\.863\\1.00\\.486\end{Bmatrix}$	0.20	0.18	2
3	11.7	11.7	10.52	$\begin{Bmatrix}-.70\\1.0\\.71\\-.84\\-.97\end{Bmatrix}$	$\begin{Bmatrix}-.69\\1.0\\.73\\-.85\\-.97\end{Bmatrix}$	$\begin{Bmatrix}.746\\-.929\\-.667\\.868\\1.00\end{Bmatrix}$	0.36	0.34	2
4	16.5	16.5	13.98	$\begin{Bmatrix}-.32\\1.0\\-.65\\-.42\\.93\end{Bmatrix}$	$\begin{Bmatrix}-.31\\1.0\\-.68\\-.42\\.90\end{Bmatrix}$	$\begin{Bmatrix}-.361\\.888\\-.609\\-.359\\1.00\end{Bmatrix}$	0.18	0.20	2
5	18.9	18.8	15.53	$\begin{Bmatrix}-.07\\.35\\-.51\\1.0\\-.36\end{Bmatrix}$	$\begin{Bmatrix}-.08\\.35\\-.53\\1.0\\-.36\end{Bmatrix}$	$\begin{Bmatrix}-.179\\.596\\-.942\\1.00\\-.808\end{Bmatrix}$	0.68	0.73	2

CONCLUDING REMARKS

The paper presented a system identification procedure for constructing ARMAV model and evaluating the dynamic characteristics of structures from ambient vibration measurement. From numerical simulation studies, the presented procedure even can accurately evaluate the modal parameters for those modes with the responses smaller than the lower modes' by one order in magnitude. Comparing the identified results with those obtained from forced vibration tests evidences the feasibility of the proposed procedure in processing ambient vibration measurement. From the ambient vibration measurement of a five-story steel structure, five translation modes in each of two horizontal directions and five torsional modes were identified in the frequency range of 0-12Hz by using the presented procedure.

ARV model can also be applied to processing the ambient vibration measurement as well as ARMAV model, but with the price of increasing order of the model, which produces extra spurious modes and usually causes difficulty to identify the real structural modes.

Comparison of the measured results with the solution from ETABS shows a significant discrepancy in the first mode in the y-direction translation motion and the higher modes. This indicates that the finite element model used in the structure designs needs to be refined, which can be through by experiments or by model updating techniques using the measured results shown here.

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REFERENCES

Allemang, R.L. and Brown, D.L. (1983), "A correlation coefficient for modal vector analysis," *Proceeding of 1st International Modal Analysis Conference*, pp. 110–116.

Chung, L.L., Lu, L.Y., Wu, L.Y., Yeh, C.H., Huang, C.S., Huang, K.Y., and Hsiao, S.L. (1999), "System identification by using force vibration tests," *Structural Engineering*, submitted.

Gersch, W. and Liu, S. (1976), "Time series methods for synthesis of random vibration systems," *ASME Trans. Applied Mechanics*, 43, March, pp. 159–165.

He, X. and De Roeck, G. (1997), "System identification of mechanical structures by a high-order multivariate auto-regressive model," *Computer & Structures*, 64, 1-4, pp. 341–351.

Hsu, M.C. (1994), "Analysis of high-rise buildings subjected to earthquake with considering soil-structure interaction," Master thesis, National Taiwan University, Taipei, Taiwan.

Huang, C.S., Yang, Y.B., Lu., L.Y., and Chen, C.H. (1999), "Dynamic testing and system identification of a multi-span highway bridge," *Earthquake Engineering and Structural Dynamics*, accepted.

Huang, C.S. (1999), "A study on techniques for analyzing ambient vibration measurement (II) — time series method," NCREE report, Taipei, Taiwan.

Ibrahim, S.R. and Mikulcik, E.C. (1973), "A time domain modal vibration test technique," *Shock and Vibration Bulletin*, 43, 4, pp. 21–37.

Loh, C.H. and Wu, T.S. (1996), "Identification of Fei-Tsui arch dam from both ambient and seismic response data," *Soil Dynamics and Earthquake Engineering*, 15, pp. 465–483.

Piombo, B., Giorcelli, E., Garibaldi, L. and Fasana, A. (1993), "Structural Identification using ARMAV models," *Proceedings of 11th International Modal Analysis Conference*, pp. 588–592.

Wang, Z.N. (1984), "Modal analysis of random vibrations and time domain identification of modal parameters," Doctoral Thesis, Northwestern Polytechnical University, Xian, Shaanxi, China.

Wang, Z.N. and Fang, T. (1986), "A time-domain method for identifying modal parameters," *Transaction of ASME, Journal of Applied Mechanics*, 53, March, pp. 28–32.