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IDENTIFICATION OF DYNAMIC PARAMETERS OF A 2DOF LINEAR SYSTEM WITH CLOSELY-SPACED NATURAL FREQUENCIES FROM FREE-VIBRATION DATA

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The extended Kalman filter (EK-WGI method) is employed to identify dynamic parameters of a 2DOF linear system with closely-spaced natural frequencies from free-vibration data. Its applicability is examined through numerical simulations. It is found that accurate and stable estimation is possible when displacement records of both degrees of the model are available. The simulation results show that the identification from response data of only one of the degrees is difficult, while the 2-stage estimation method suggested in this paper is effective in the structure-TMD system, which is a typical system with closely-spaced modes.

Key Words : *closely-spaced modes, extended Kalman filter, free-vibration, identification, simulation*

1. INTRODUCTION

It is necessary to identify the dynamic properties of structures from field test results when their safety against wind and earthquake loads has to be evaluated in detail. Therefore many research works on the identification techniques have been made recently [1]. The identification techniques are broadly classified into two types; one is the frequency domain technique based on the spectrum analysis and the other is the time domain technique in which the dynamic parameters are estimated using a mathematical model of a structural system such as differential equations and AR/ARMA models.

As structures are larger and more complex, the structural systems consisting of main- and sub-structures with closely-spaced natural frequencies are increasing. The examples are cable-stayed bridges with many cables [2] and the structure-TMD systems [3].

Free-vibration tests are often carried out when examining the dynamic properties of a structure experimentally. The free-vibration data on the closely-spaced modes systems are frequently accompanied with beatings in time-history responses. It is difficult to estimate the dynamic parameters, especially the damping ratios, from such data. Frequency domain identification methods which are often used cannot accurately separate modal motions from the original data.

Shibata and Hara [4] and Sanuki [5] proposed simple time domain methods to estimate the modal frequencies and the modal damping ratios from free-vibration data with beatings. In these studies the time history with beatings is treated as the composition of damped free-vibration time histories of two SDOF systems and the modal properties are calculated from the maximum peak and minimum peak amplitude values of the beating waves and the beating period. However, these values observed from experimental data are not necessarily clear, and

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an error in evaluating them influences the accuracy of estimating modal properties directly [6]. Ota and Katsuchi [2] proposed a technique to obtain the free-vibration time history of one mode by superposing the weighted response waves of two components of a system, and applied it to estimating dynamic properties of a cable-stayed bridge.

The time domain techniques above-mentioned are for estimating the modal properties. However, it is often the case that we need not the modal properties but the dynamic properties of each component of a structure directly; in a case of the girder-cable system of a cable-stayed bridge, not the dynamic properties of coupled modes of girder and cable but the dynamic properties of girder/cable. Direct identification of the dynamic parameters is necessary for computing the dynamic response of the system. Modal properties can be also obtained by an eigen-analysis using the identified parameters.

In this study direct identification of the dynamic parameters of the closely-spaced modes system using free-vibration data is attempted. The extended Kalman filter (EK-WGI method) [7)-9)] is employed and its applicability is examined through the simulation; free-vibration data of 2DOF linear system models of known parameters as shown in **Fig.1** is numerically simulated and used for the identification study.

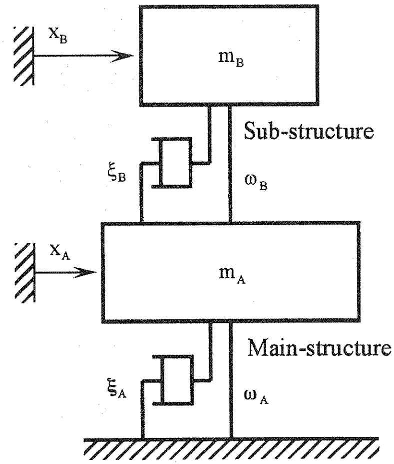


Fig.1 Structural model of 2DOF linear system

2. NECESSITY OF IDENTIFICATION APPROACH

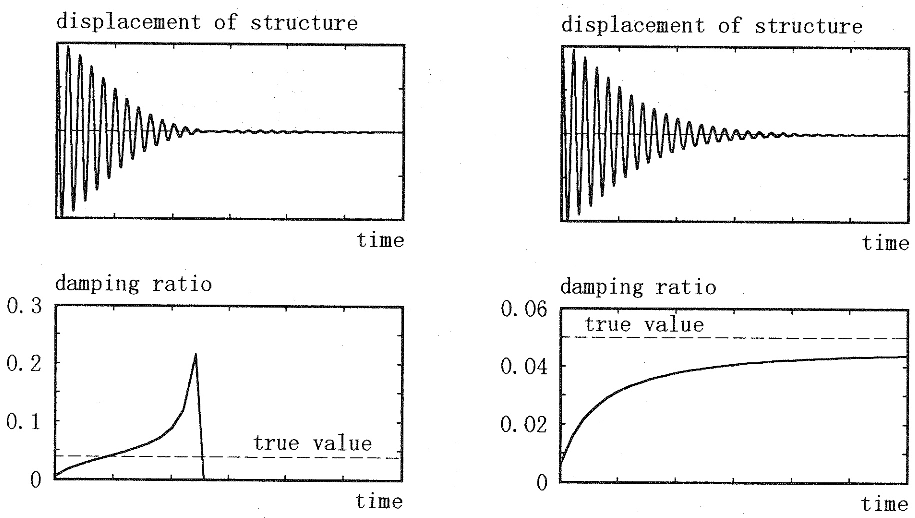
When evaluating the dynamic properties of a system from response data with beatings, it is necessary to treat the system as a 2DOF system and to apply some identification techniques. However, the fact is that, if the responses do not have strong beatings, the system is usually treated as a SDOF system in practice. Typical example is a structure-TMD system. TMDs are used for the vibration control of structures generally. When checking the effect of a TMD from free-vibration test data, modal properties of the system such as damping are evaluated as a SDOF system [10]. Fujino and Abe [11] showed that the estimation of the dynamic parameters of the structure-TMD system as a SDOF system may bring a large error, and that it is necessary to treat that as a 2DOF system.

Fig.2 shows free-vibration time histories of a structure with a TMD simulated numerically and the modal damping ratios calculated from the peak amplitude value of each wave in them. The conditions of the simulation are as follows: the mass ratio = 0.01, the frequency ratio = 1, the damping ratio of the structure ξ_{ST} = 0 and the damping ratio of TMD ξ_{TMD} = 0.08 and 0.10. It seems that the beating in the time histories in the figure is very weak, but the damping ratios calculated as a SDOF system are different from the exact values. Additionally, as the damping ratio seems to vary according to the amplitude of the response, the system may be misunderstood to be a non-linear system.

3. EXTENDED KALMAN FILTER (EK-WGI METHOD)

The extended Kalman filter is a time domain estimation algorithm obtaining least squares estimated values. Hoshiya and Saitoh [9] proposed the extended Kalman filter weighted global iteration method (EK-WGI method). They applied it to identification problems of structures under seismic and moving loads and confirmed its usefulness and accuracy [9),12),13)]. Yamada et al. [14] and Iwamoto and Fujino [15] applied the EK-WGI method to the identification problem of flutter derivatives of bridge decks.

In order to use the Kalman filter, it is necessary to formulate the mathematical models both of the structural system and of the observation. The extended Kalman filter is based on a nonlinear continuous state equation and a nonlinear discrete observation equation as follows.



a) $\xi_{TMD} = 0.08$ b) $\xi_{TMD} = 0.10$

Fig.2 Free-vibration waves with beatings and damping ratio directly measured from the waves

$$\frac{d\mathbf{X}_t}{dt} = f(\mathbf{X}_t, t) \quad (1)$$

$$\mathbf{Y}_k = h(\mathbf{X}_k, t) + \mathbf{v}_k \quad (2)$$

in which $\mathbf{X}_t$, $\mathbf{X}_k$ = continuous and discrete state vectors at $t = k\Delta t$; $\mathbf{Y}_k$ = a discrete observation vector at $t = k\Delta t$; Δt = time interval; $\mathbf{v}_k$ = an observation noise vector which is represented by a white noise Gaussian process with $E[\mathbf{v}_k \mathbf{v}_l^T] = \mathbf{R}_k \delta_{kl}$; and δ_{kl} = Kronecker delta function. The extended Kalman filter can estimate the optimal values $\hat{\mathbf{X}}_k$ of the state vector $\mathbf{X}_k$ ('^' means an estimated value) sequentially from the observation vector $\mathbf{Y}_k$ if the initial state vector $\mathbf{X}_0$ and the initial error covariance matrix $\mathbf{P}_0$ are given.

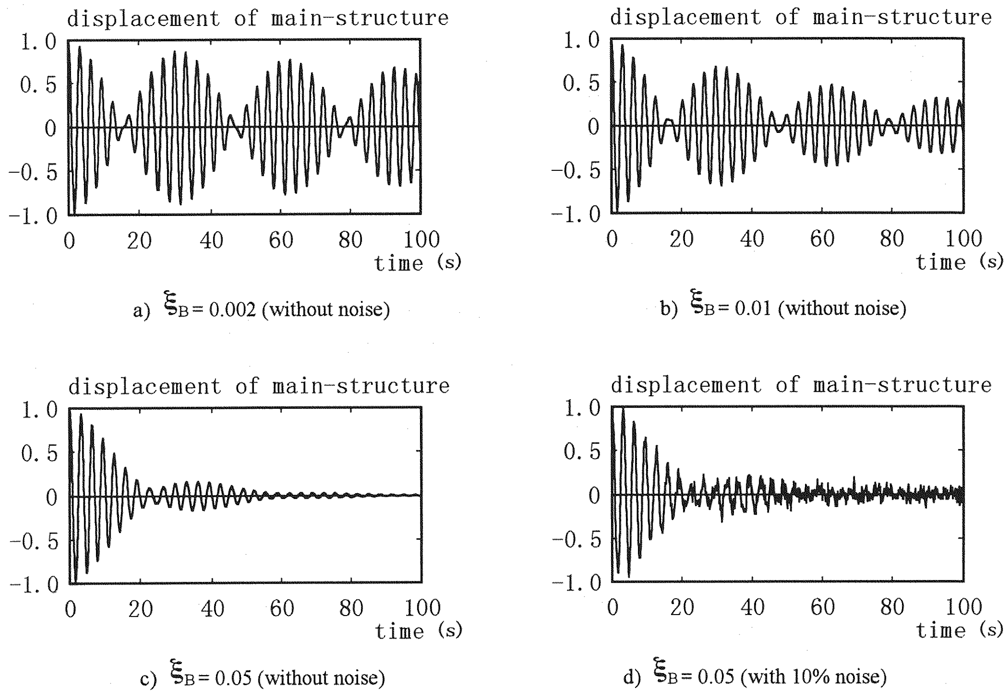
The weighted global iteration method is an algorithm for processing finite time histories of responses. The first procedure starts with the initial values $\mathbf{X}_0$ and $\mathbf{P}_0$ which are assumed from the structural information and the extended Kalman filter is used until the end of the data. The same procedures so-called global iterations are repeated using the final values of the preceding procedure as the initial values until the estimated state vector converges. In the beginning of each iteration, the matrix $\mathbf{P}$ is multiplied by a weight coefficient $\mathbf{W}$ for activating the estimated state vector and accelerating the convergence. We modified the algorithm for treating free-vibration data which has a finite duration. Additionally, the U-D factorization filter algorithm [8] was used for the computational stability.

Table 1 Parameters estimated from displacement record of SDOF system

ξ	$\hat{\xi}$	$\hat{\omega}_0$
0.002	0.00187 (7%)	2.00 (0%)
0.01	0.00989 (1%)	2.00 (0%)
0.05	0.0500 (0%)	2.00 (0%)

4. IDENTIFICATION OF SDOF LINEAR SYSTEM

Before the identification of 2DOF systems, the identification of SDOF linear systems from free-vibration data were carried out. The numerical simulation models are three types: the natural circular frequency ω_0 = 2rad/s, the damping ratio ξ = 0.002, 0.001 and 0.05. The sampling conditions are as follows: the sampling interval Δt = 0.01s and the duration time T = 10s (the number of data $N_d = T / \Delta t$ = 1000). The initial conditions of free-vibration data are the displacement = 1 and the velocity = 0. Observation noises are modeled as white noises with the intensity 10% of root mean square values of response waves.



a) $\xi_B = 0.002$ (without noise)

b) $\xi_B = 0.01$ (without noise)

c) $\xi_B = 0.05$ (without noise)

d) $\xi_B = 0.05$ (with 10% noise)

Fig.3 Free-vibration waves of main-structure simulated numerically

Table 1 shows the parameters estimated from the displacement record. The SDOF system is so simple that the parameters are estimated accurately even in the presence of 10% noise in the record. It is found that the accuracy of the estimation of ξ is better as ξ is larger. When the decay of response is small, data with a large T are needed for an accurate estimation. The estimated parameters converge within about 5 global iterations in all cases.

5. IDENTIFICATION OF 2DOF LINEAR SYSTEM

(1) Formulation of state and observation equations

The equation of motion of a 2DOF linear system as shown in **Fig.1** can be obtained as follows.

$$\left.\begin{aligned} &\ddot{z}_A + (2\xi_A\omega_A + 2\mu\xi_B\omega_B)\dot{z}_A \\ &\quad - 2\mu\xi_B\omega_B\dot{z}_B + (\omega_A^2 + \mu\omega_B^2)z_A \\ &\quad - \mu\omega_B^2 z_B = 0 \\ &\ddot{z}_B - 2\xi_B\omega_B\dot{z}_A + 2\xi_B\omega_B\dot{z}_B \\ &\quad - \omega_A^2 z_A + \omega_B^2 z_B = 0 \end{aligned}\right\} \quad (3)$$

in which z = a displacement; μ = a mass ratio = m_B/m_A; m = a mass; ω = a natural circular frequency; ξ = a damping ratio; and the subscripts A and B mean main- and sub-structure, respectively. Here, unknown parameters to identify are ξ_A, ξ_B, ω_A and ω_B. State variables are introduced to the state vector $\mathbf{X}$: $x_1 = z_A$, $x_2 = z_B$, $x_3 = \dot{z}_A$ and $x_4 = \dot{z}_B$. Unknown parameters are also put in $\mathbf{X}$: $x_5 = \xi_A$, $x_6 = \xi_B$, $x_7 = \omega_A$ and $x_8 = \omega_B$. Then the state equation is written from Eqs.3 as follows.

$$\left.\begin{aligned} &\dot{x}_1 = x_3, \quad \dot{x}_2 = x_4 \\ &\dot{x}_3 = -\{(2x_5x_7 + 2\mu x_6x_8)x_3 - 2\mu x_6x_8x_4 \\ &\qquad + (x_6^2 + \mu x_8^2)x_1 - \mu x_8^2 x_2\} \\ &\dot{x}_4 = -\{-2x_6x_8x_3 + 2x_6x_8x_4 \\ &\qquad - x_8^2x_1 + x_8^2x_2\} \\ &\dot{x}_5 = \dot{x}_6 = \dot{x}_7 = \dot{x}_8 = 0 \end{aligned}\right\} \quad (4)$$

Mass ratio μ has to be also identified in some cases because m_A and m_B are often modal masses of continuous structures and modal masses of complex structures, such as a long-span suspension bridge,

Table 2 Dynamic parameters for simulation models

Model	ξ_A	ξ_B	ω_A	ω_B	μ
I (girder-cable)		0.002			
II	0.002	0.01	2.0	2.0	0.01
III (structure-TMD)		0.05			

Table 3 Initial conditions for identification from displacement records of main- and sub-structure

$\hat{\xi}_A$	$\hat{\xi}_B$	$\hat{\omega}_A$	$\hat{\omega}_B$	$\hat{\mu}$	p_z, $p_{\dot{z}}$	p_ξ	p_ω	p_μ
0.0	0.01	1.0	1.0	0.0	0.01	1.0×10^{-8}	0.01	1.0×10^{-8}

Note: $R = 0.01$; $W = 100.0$.

Table 4 An example of parameters estimated from displacement records of main- and sub-structure (the influence of observation noise level); μ is known; $\Delta t = 0.01$s, $T = 10$s

ξ_B	Noise (%)	$\hat{\xi}_A$	$\hat{\xi}_B$	$\hat{\omega}_A$	$\hat{\omega}_B$
	1	0.00193 (4%)	0.00196 (2%)	2.00 (0%)	2.00 (0%)
0.002	5	0.00166 (17%)	0.00183 (9%)	2.00 (0%)	2.00 (0%)
	10	0.00132 (34%)	0.00169 (16%)	2.00 (0%)	2.00 (0%)
	1	0.00193 (4%)	0.00998 (0%)	2.00 (0%)	2.00 (0%)
0.01	5	0.00165 (18%)	0.00989 (1%)	2.00 (0%)	2.00 (0%)
	10	0.00131 (35%)	0.00981 (2%)	2.00 (0%)	2.00 (0%)
	1	0.00194 (3%)	0.0500 (0%)	2.00 (0%)	2.00 (0%)
0.05	5	0.00168 (16%)	0.0502 (0%)	2.00 (0%)	2.00 (0%)
	10	0.00137 (32%)	0.0504 (1%)	2.00 (0%)	2.00 (0%)

Note: $\xi_A = 0.002$, $\omega_A = \omega_B = 2.0$.

calculated analytically from the design dimensions may be uncertain. Additionally, μ of the structure-TLD (Tuned Liquid Damper) [16] system is unknown when the effective mass of the TLD is difficult to estimate. Then in the case when μ is unknown, μ is added to a state vector $\mathbf{X}$: $x_9 = \mu$. Therefore μ in Eqs.4 is replaced by x_9 and the equation, $\dot{x}_9 = 0$ is added to Eqs.4.

When displacement and velocity responses of main-structure are obtained for example, observation equations Eqs.2 are written as follows.

$$\begin{Bmatrix} y_{1k} \\ y_{2k} \end{Bmatrix} = \begin{bmatrix} 1, 0, 0, \cdots, 0 \\ 0, 1, 0, \cdots, 0 \end{bmatrix} \mathbf{X}_k + \begin{Bmatrix} v_{1k} \\ v_{2k} \end{Bmatrix} \tag{5}$$

(2) Simulation of free-vibration data

We chose three types of the models which possess closely-spaced modes as shown in **Table 2**; model I is a deck-cable system of a cable-stayed bridge and model III the structure-TMD system. The values of the damping ratios of sub-structure ξ_B, 0.002 and 0.05 in **Table 2** correspond to those of a cable and a TMD, respectively. The initial conditions of free-vibration data are $z_A = z_B = 1$ and $\dot{z}_A = \dot{z}_B = 0$. Observation noises are modeled as white noises with the intensity 1, 5 and 10% of root mean square values of response waves of the first 10 seconds. **Fig.3** shows free-vibration time histories simulated numerically. The accuracy of the identification is

Table 5 An example of parameters estimated from displacement records of main- and sub-structure (the influence of observation condition); μ is known; noise level = 10%

ξ_B	Δt (s)	T (s)	$\hat{\xi}_A$	$\hat{\xi}_B$	$\hat{\omega}_A$	$\hat{\omega}_B$
0.002	0.01	10	0.00132 (34%)	0.00169 (16%)	2.00 (0%)	2.00 (0%)
	0.02	20	0.00176 (12%)	0.00182 (9%)	2.00 (0%)	2.00 (0%)
	0.05	50	0.00202 (1%)	0.00222 (11%)	2.00 (0%)	2.00 (0%)
	0.1	100	0.00200 (0%)	0.00187 (7%)	2.00 (0%)	2.00 (0%)
0.01	0.01	10	0.00131 (35%)	0.00981 (2%)	2.00 (0%)	2.00 (0%)
	0.02	20	0.00148 (26%)	0.00957 (3%)	2.00 (0%)	2.00 (0%)
	0.05	50	0.00184 (8%)	0.0104 (4%)	2.00 (0%)	2.00 (0%)
	0.1	100	0.00228 (14%)	0.00930 (7%)	2.00 (0%)	2.00 (0%)
0.05	0.01	10	0.00137 (32%)	0.0504 (1%)	2.00 (0%)	2.00 (0%)
	0.02	20	0.00119 (41%)	0.0495 (1%)	2.00 (0%)	2.00 (0%)
	0.05	50	0.00152 (24%)	0.0507 (1%)	2.00 (0%)	2.00 (0%)
	0.1	100	0.00007 (97%)	0.0475 (5%)	2.01 (1%)	2.00 (0%)

Note: $\xi_A = 0.002$, $\omega_A = \omega_B = 2.0$.

Table 6 An example of parameters estimated from displacement records of main- and sub-structure (the influence of observation noise level); μ is unknown; Δt = 0.05s; T = 50s

ξ_B	Noise (%)	$\hat{\xi}_A$	$\hat{\xi}_B$	$\hat{\omega}_A$	$\hat{\omega}_B$	$\hat{\mu}$
0.002	1	0.00200 (0%)	0.00202 (1%)	2.00 (0%)	2.00 (0%)	0.00999 (0%)
	5	0.00200 (0%)	0.00210 (5%)	2.00 (0%)	2.00 (0%)	0.00997 (0%)
	10	0.00202 (1%)	0.00219 (10%)	2.00 (0%)	2.00 (0%)	0.00993 (1%)
0.01	1	0.00199 (1%)	0.0100 (0%)	2.00 (0%)	2.00 (0%)	0.0100 (0%)
	5	0.00197 (2%)	0.0101 (1%)	2.00 (0%)	2.00 (0%)	0.00998 (0%)
	10	0.00194 (3%)	0.0103 (3%)	2.00 (0%)	2.00 (0%)	0.00996 (0%)
0.05	1	0.00189 (6%)	0.0501 (0%)	2.00 (0%)	2.00 (0%)	0.0100 (0%)
	5	0.00147 (27%)	0.0503 (1%)	2.00 (0%)	2.00 (0%)	0.0101 (1%)
	10	0.00100 (50%)	0.0506 (1%)	2.00 (0%)	2.00 (0%)	0.0102 (2%)

Note: $\xi_A = 0.002$, $\omega_A = \omega_B = 2.0$.

influenced by sampling conditions of responses i.e. the sampling interval Δt and the duration time T (or the number of data $N_d = T / \Delta t$). Here we examine the effect of sampling intervals on the identification: Δt = 0.01, 0.02, 0.05 and 0.10s with a fixed duration N_d are selected.

6. RESULTS OF IDENTIFICATIONS

(1) When displacement records of main- and sub-structures are available

The number of a data record N_d is fixed at 1000 and the initial conditions for the identification as shown in **Table 3** are used.

Assuming that the mass ratio μ is known, the parameters are estimated and the results are shown in **Table 4** and **5**. Natural circular frequencies ω_A and ω_B are estimated very accurately, while the estimation errors of damping ratios ξ_A and ξ_B due to observation noises are relatively large. **Table 5** shows that the observation conditions (Δt and T) affect the accuracy of estimations; the tendency of

Table 7 Initial conditions for identification from displacement record of main-structure and its differential wave

$\hat{\xi}_A$	$\hat{\xi}_B$	$\hat{\omega}_A$	$\hat{\omega}_B$	$\hat{\mu}$	p_z, $p_{\dot{z}}$	p_ξ	p_ω	p_μ
0.0	0.01	1.0	1.0	0.0	0.01	1.0×10^{-10}	0.01	1.0×10^{-10}

Note: $R = 0.01$; $W = 100.0$.

Table 8 An example of parameters estimated from displacement record of main-structure and its differential wave (the influence of observation noise level); μ is known; $\Delta t = 0.01$s; $T = 10$s

ξ_B	Noise (%)	$\hat{\xi}_A$	$\hat{\xi}_B$	$\hat{\omega}_A$	$\hat{\omega}_B$
0.002	1	0.00519 (160%)	-0.00159 (180%)	2.00 (0%)	2.00 (0%)
	5	0.00350 (75%)	0.00366 (83%)	2.04 (2%)	1.96 (2%)
	10	0.00568 (184%)	0.00500 (150%)	2.06 (3%)	1.95 (3%)
0.01	1	0.00543 (172%)	0.00741 (26%)	2.02 (1%)	1.98 (1%)
	5	0.00980 (390%)	0.00258 (74%)	2.02 (1%)	1.98 (1%)
	10	0.0171 (755%)	0.00420 (58%)	2.06 (3%)	1.94 (3%)
0.05	1	0.00151 (25%)	0.0493 (5%)	2.01 (1%)	2.00 (0%)
	5	-0.00054 (127%)	0.0496 (1%)	2.01 (1%)	2.00 (0%)
	10	-0.0270 (1350%)	0.0437 (13%)	2.07 (4%)	2.00 (0%)

Note: $\xi_A = 0.002$, $\omega_A = \omega_B = 2.0$.

the variations about ξ_A and ξ_B is different according to ξ_B. When ξ_B is small ($\xi_B = 0.002$) and the decay of response is 0.0101 (1%) small , the accuracy of estimations is better as Δt is larger (T is larger). On the other hand, the opposite tendency is shown when ξ_B is large ($\xi_B = 0.05$). Generally speaking the identification accuracy is better as a sampling interval Δt is smaller and a sampling duration time T is larger. But in this analysis a number of data record N_d is fixed, so that T is smaller as Δt is smaller. When the decay of response is small, data with a large T are needed for an accurate estimation even if Δt becomes large.

Assuming that the mass ratio μ is also unknown, identification is made and the result is given in **Table 6**. The accuracy of estimations is similar to the case when μ is known. But when Δt is small ($\Delta t = 0.01$s, $T = 10$s), the estimation errors of ξ_A, ξ_B and μ are relatively large. A long duration T is necessary for a good estimation when μ is unknown.

The stability of the identification is good and the estimated parameters converge within about 10 global iterations in all cases.

(2) When only displacement record of main-structure is available

When a free-vibration test of the structure-TMD system is made, either displacement or velocity wave of the structure is only measured. The similar situations are observed in many field tests of closely-spaced modes systems. Considering these situations, we tried to identify dynamic parameters of 2DOF linear system models from the displacement record of the main-structure only. It was found that parameters could not be estimated even if responses without noises were used. Therefore we identify the parameters from displacement and velocity waves of main-structure, the latter of which is computed from the displacement record with a digital differential filter [17]. The number of a data record N_d is fixed at 2000 and the initial conditions for the identification are given as shown in **Table 7**.

In the case when the mass ratio μ is known, an example of estimated parameters is given in **Table 8**. The accuracy and stability of the estimation are much lower than the case when displacements of main- and sub-structure are available. Another

Table 9 An example of parameters estimated with 2-stage estimation method from displacement record of main-structure and its differential wave (the influence of observation noise level); μ is known; Δt = 0.01s; T = 10s

ξ_B	Noise (%)	ξ_A	$\hat{\xi}_B$	ω_A	$\hat{\omega}_B$
	1		0.00196 (2%)		2.00 (0%)
0.002	5	0.002	0.00179 (11%)	2.00	2.00 (0%)
	10		0.00157 (22%)		2.00 (0%)
	1		0.00996 (0%)		2.00 (0%)
0.01	5	0.002	0.00978 (2%)	2.00	2.00 (0%)
	10		0.00955 (5%)		2.00 (0%)
	1		0.0500 (0%)		2.00 (0%)
0.05	5	0.002	0.0498 (0%)	2.00	2.00 (0%)
	10		0.0495 (1%)		2.01 (1%)

Table 10 An example of parameters estimated with 2-stage estimation method from displacement record of main-structure and its differential wave (the influence of observation noise level); μ is unknown; Δt = 0.01s; T = 10s

ξ_B	Noise (%)	ξ_A	$\hat{\xi}_B$	ω_A	$\hat{\omega}_B$	$\hat{\mu}$
	1		0.00131 (35%)		2.00 (0%)	0.00981 (2%)
0.002	5	0.002	-0.00356 (278%)	2.00	2.00 (0%)	0.00797 (20%)
	10		-0.0302 (1510%)		2.01 (1%)	0.00001 (100%)
	1		0.00911 (9%)		2.00 (0%)	0.00979 (2%)
0.01	5	0.002	-0.00059 (106%)	2.00	2.00 (0%)	0.00734 (27%)
	10		0.0273 (173%)		2.01 (1%)	0.00001 (100%)
	1		0.0465 (7%)		2.00 (0%)	0.00950 (5%)
0.05	5	0.002	-0.0148 (130%)	2.00	2.00 (0%)	0.00001 (100%)
	10			diverged		

problem is that parameters cannot be uniquely estimated from one displacement record of 2DOF system because the displacement record is just the sum of responses of two modes and is determined only by modal frequencies and modal damping ratios. When the mass ratio μ is unknown, estimated values cannot be obtained even if response waves without noises are used.

(3) 2-stage estimation method

In order to avoid these troubles, we suggest the 2-stage estimation method. This method is applicable to the system in which the sub-structure can be temporarily fixed relative to the main-structure e.g. a TMD. When the sub-structure is fixed, the system can be treated as a SDOF system. Then as the first stage, dynamic parameters of the main-structure ξ_A and ω_A are estimated from free-vibration test records. As mentioned above, parameters of a SDOF system can be easily and accurately estimated. Next as the second stage, a free-vibration test is carried out with the sub-structure unfixed, and parameters of sub-structure ξ_B and ω_B are estimated from displacement record of main-structure and its differential (velocity) wave obtained with the differential filter. Dynamic parameters of the main-structure ξ_A and ω_A can be treated as known in this stage. The 2-stage procedure makes an unique estimation possible.

The number of a data record N_d is fixed at 2000 and the initial conditions for the identification are given as shown in **Table 7**. In this analysis, in order to examine the accuracy of the second stage, no error is assumed to be made in the first stage.

Assuming that μ is known, parameters are estimated and are shown in **Table 9**. The reduction of the number of unknown parameters improves the identification accuracy in the second stage. The stability of the identification is good and the estimated parameters converge within about 10 global iterations. Using the 2-stage estimation method, estimated parameters converge as shown in **Table 10** even when μ is unknown. But in this case, estimation errors are large due to observation noises.

7. CONCLUSIONS

Dynamic parameters of a 2DOF linear system with closely-spaced natural frequencies are identified from free-vibration data. The extended Kalman filter (EK-WGI method) is utilized and its applicability is examined through the numerical simulations. It is found that accurate and stable estimation is possible when displacement records of both degrees of the model are available, even in the presence of 5% noise in the record. Results show that the identification from data of only one degree response is difficult, while the 2-stage estimation method suggested in this paper is effective in the structure-TMD system.

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Papers

Ultimate Strength of Stiffened Plates Subjected to Biaxial Forces

Yoji KUMAGAI and Masashi IURA 29~42

Tests of stiffened steel plates subjected to biaxial compressive forces have been performed to obtain the ultimate strength of the plates. A plate test rig has been modified to apply compressive forces to rectangular stiffened plates. A new approach is presented for predicting the ultimate strength of plates under biaxial loadings. The experimental results are used to show the validity of the new approach. The existing numerical and experimental results are also used to examine the applicability of the present approach to the plates under biaxially applied in-plane compressive and tensile forces. Although the present approach is easier to apply than other available approaches, it provides consistently good predictions.

Wave Propagation Analysis for Layered Solid-Fluid Media in a Gravity Field Using a Thin-Layered Element and Discrete Wave Number Method

Terumi TOUHEI 43~52

Layered solid-fluid media in a gravity field were analyzed by a thin-layered element and discrete wave number method. The gravity effects were incorporated to the governing equation for fluid and solid-fluid interaction equations. Green's function for layered solid-fluid media in a gravity field was represented in terms of the normal modes, which were obtained from the thin-layered element matrices. Several investigations were applied to the differences between the Rayleigh wave mode and the gravity wave mode. Numerical calculations showed that the gravity waves, in which the phase velocity and frequency is very low, were caused as a reult of the propagtion of the body waves and the Rayleigh wave.