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AN EVALUATION METHOD OF MODAL DAMPLING AND ITS APPLICATION BASED ON A FVT OF CABLE STAYED BRIDGE

Masataka NAKAMURA[1], Shuji UEDA[2], Jun-ichi SUZUMURA[3], Kazufumi HANADA[4], Makoto NAKAI[5] And Mitsuhide YOSHIDA[6]

SUMMARY

Many kind of damping evaluation methods to estimate the modal damping constants of an existing structure has been proposed such as a half power method, Nyquist circle method or the curve fitting method for the frequency response function (FRF), Random Decrement Technique and Ibrahim method for the time domain data. And they lead the various modal damping constants even if they used same data set. Being based on the comparison with each data reduced from them, it is evaluated that a modified Ibrahim method lead a reasonable damping parameters and the modal shapes from MIM agree well with the bending modal shapes of numerical simulation mode and observed mode.

INTRODUCTION

It is one of the most important problems to evaluate damping characteristics of structure system for analyzing dynamic behaviors of the system during earthquakes. Usually the theoretical natural frequencies and modal shapes of constructed structures agree well with a result by the Forced Vibration Tests (FVT) for them. But we are forced to use the modal damping of similar structures or result by the FVT as them of the objected system, because of having no method to evaluate them theoretically. Moreover, it is too difficult to find the modal damping constants of higher modes, especially for a light damping system such as a cable stayed bridge (CSB) with long span. Recently FVT of long span bridges have been often carried out and those results were reported in [Davenport *etal*, 1989], [Takeda *etal*, 1999] and so on. But it is pointed out that the more experimental and theoretical methods to determine the modal damping should be needed.

The experimental determination method is divided broadly into two categories, frequency domain method and time domain method. The frequency domain method includes the half power method, Nyquist circle method and the transfer curve fitting method. These methods have been applied to a lot of FVT. But a disadvantage of these methods is essentially due to modes interference which obscures the individual modal shapes, natural frequencies and modal damping by the adjacent mode form. The time domain methods includes the Random Decrement Technique (RDT) [Tamura *etal*, 1992] and Ibrahim method [Ibrahim *etal*, 1976] and [Zaghool *etal*, 1980].

The RDT was developed at aero-space engineering field, and is applicable to determine the modal damping of constructed structures forced randomly. The RDT is required operations where the object mode is extracted used band-pass filter in frequency domain and re-transformed to time domain data set. It is pointed out that the modal damping is affected by the band width of the filter.

In comparison with the RDT, the Ibrahim methods have an advantage, which uses time response information directly without transformation to the frequency domain and re-transforms to time history, and the method does not require the assumptions where the analyst should determine the frequency range for some mode arbitrarily. The determined range affects the mode damping too much. The modal damping set is determined by solving proper value problem by the method. The method is applicable to determine the high order modal damping or closely spaced natural frequencies as against the RDT and the frequency domain methods.

[1] *Department of Civil Engineering, Nihon University, Tokyo, Japan Email: masa@civil.cst.nihon-u.ac.jp*
[2] *Department of Civil Engineering, College of Science and Technology, Nihon University, Tokyo, Japan*
[3] *Department of Civil Engineering, College of Science and Technology, Nihon University, Tokyo, Japan*
[4] *Department of Civil Engineering, College of Science and Technology, Nihon University, Tokyo, Japan*
[5] *Kozo Gijutu Kennkyujo co, Tokyo, Japan Email: nakai-1067@mth.biglobe.ne.jp*
[6] *Fuji PS CORPORATION, Tokyo, Japan Email: mitsuhid@venus.dti.ne.jp*

As the method is applicable to one point and/or multi-points observation results [Ibrahim *etal*, 1977] and [Pappa *etal*, 1981], the reduced modal constants are the system global ones and are independent from the measured location.
But its application to random response data has not be reported, because the method requires time series of unit impulse response data [Ibrahim *etal*, 1976].
Damping characteristics of structures are separated from some arguments: 1) hysteretic damping, 2) structual damping, 3) radiation damping, 4) aerodynamic damping, and 5) systemic damping such as beam-cable interaction at CSB. Because modal damping determined experimentally are composed of them, it is difficult to separate the modal damping to those arguments. For the reason that damping is defined a cycle dissipation energy against total strain energy, evaluation methods of damping which add energy dissipated in individual member were presented in [Kawashima *etal*, (1989)] and [Yamaguchi *etal*, (1996)].
This paper proposes the modified Ibrahim method (MIM) which is applicable to time series random response, and the results which is reduced from FVT results of CSB applying the technique.

EXPERIMENTAL DETERMINATED METHOD OF MODAL DAMPING

Ibrahim method reduces to the proper values of the object system from time series unit impulse response data by solving proper value problem [Ibrahim *etal*, 1976]. MIM proposed here reduces to the proper values and from time series random response data acquired at multi-points of the system. The unit impulse response of SDOF system can be written as

$$\varsigma(t) = \frac{1}{m\omega_d} e^{-\sigma t} \sin\omega_d t \qquad (1)$$

where $\omega_d = \omega\sqrt{1-h^2}$ is the damped natural circular frequency, ω is the undamped natural circular frequency, $\sigma = h\omega$, and h is the damping constant. The auto-correlation function of eq.(1) can be written as

$$R_\varsigma(\tau) = I x_0^2 e^{-\sigma\tau} \cos(\omega_d \tau + \phi) \qquad (2),$$

where, τ is time lag, and

$$I = \sqrt{I_1 + I_2}, \quad \tan\phi = \frac{I_2}{I_1}$$

$$I_1 = \lim_{T\to\infty} \frac{1}{T}\int_0^T e^{-2\sigma t}\cos^2(\omega_d t + \varphi)dt, \quad I_2 = \lim_{T\to\infty}\frac{1}{T}\int_0^T e^{-2\sigma t}\cos(\omega_d t + \varphi)\cdot\sin(\omega_d t + \varphi)dt$$

Comparing eq.(1) with eq.(2), the auto-correlation function of unit impulse response has the same period and the same envelope as unit impulse response or free vibration response.
The same SDOF system is assumed to be described by following equation during random force $f(t)$:

$$\ddot{x}(t) + 2h\omega\dot{x}(t) + \omega^2 x(t) = f(t) \qquad (3)$$

The solution of eq.(3) is

$$x(t) = x_f(t) + x_r(t) \qquad (4)$$

where, $x_f(t)$ is free vibration solution, $x_r(t)$ is forced vibration solution. The auto-correlation function of eq.(4) can be written as

$$\begin{aligned} R(\tau) &= E[x(t)\cdot x(t+\tau)] = E[\{x_f(t)+x_r(t)\}\{x_f(t+\tau)+x_r(t+\tau)\}] \\ &= R_{ff}(\tau) + R_{fr}(\tau) + R_{rf}(\tau) + R_{rr}(\tau) \end{aligned} \qquad (5),$$

where E[ ] is ensemble average, and

$$R_{ff}(\tau) = E[x_f(t)\cdot x_f(t+\tau)] \qquad (6)$$

$$R_{fr}(\tau) = E[x_f(t)\cdot x_r(t+\tau)] \qquad (7)$$

$$R_{rf}(\tau) = E[x_r(t)\cdot x_f(t+\tau)] \qquad (8)$$

$$R_{rr}(\tau) = E[x_r(t)\cdot x_r(t+\tau)] \qquad (9).$$

If expect value of $f(t)$ equals to zero then

$$E[f(t)] = 0 \qquad (10).$$

The ensemble average of random response $x_r(t)$ is written as

$$E[x_r(\tau)] = \int_0^t E[f(t)]\varsigma(t-\tau)d\tau = 0 \qquad (11),$$

As $x_f(t)$, $x_r(t)$ are independet , eqs. (7) and (8) can be rewritten as

$$R_{fr}(\tau) = E[x_f(t)\cdot x_r(t+\tau)] = E[x_f(t)]\cdot E[x_r(t+\tau)] = 0 \qquad (12)$$

$$R_{rf}(\tau) = E[x_r(t)\cdot x_f(t+\tau)] = E[x_r(t)]\cdot E[x_f(t+\tau)] = 0 \qquad (13).$$

$R_{rr}(t)$ is the auto-correlation function of forced vibration solution, and is Delta function at $\tau \neq 0$. If $E[f(t)] \approx 0$, then

$$R_x(\tau) \approx R_{ff}(\tau) \quad (14)$$

$$R_{ff}(\tau) = E[x_f(t) \cdot x(t+\tau)] = I x_0^2 e^{-\sigma t} \cos(\omega_d t + \phi) \quad (15),$$

where

$$I = \sqrt{I_1 + I_2}, \quad \tan\phi = \frac{I_2}{I_1}$$

$$I_1 = \lim_{T\to\infty} \frac{1}{T} \int_0^T e^{-2\sigma t} \cos^2(\omega_d t + \varphi) dt, \quad I_2 = \lim_{T\to\infty} \frac{1}{T} \int_0^T e^{-2\sigma t} \cos(\omega_d t + \varphi) \cdot \sin(\omega_d t + \varphi) dt$$

$$\therefore \quad R_{ff}(\tau) = R_{\varsigma}(\tau) \quad (16).$$

Eq.(16) shows that the auto-correlation function of unit impulse response is equivalent with that of random response. After all, the auto-correlation function of random response is applicable to Ibrahim method to determine experimentally proper values of the objected system.

APPLICATION OF A CABLE STAYED BRIDGE

The Object Csb Profile

Figure 1 shows the dimensions of Kakkaku-Sazanami Bridge, with 2 spans 255m length. All measured data were sampled digitally at 256Hz sampling frequency thorough A/D converter, amplifier and 30Hz low-pass filter and recorded in MO. The FVT was conducted as follows.
1) Impulse test : Rear wheals of a dump truck was dropped 10cm high and free vibration response was measured.
2) Microtremor obsevation : microtremor was measured about a half hour without forced excitation.

3.2 THE FVT RESULTS BY THE MIM

Figure 2 shows a Fourie spectrum observed by an impulse test. The natural frequency interval spaced closely around 1.5Hz or 2.7Hz. The MIM was applied to the FVT, and the reduced data of natural frequencies and the modal damping constants are shown in Table 1. Figure 3 shows the observed time history comparing with identified one by the MIM. The observed behavior agrees well with the identified one. In comparison the impulse test with the microtremor observation, natural frequencies resulted by the microtremor observation are a little higher than those reduced from the impulse test, and the modal damping constants resulted by the impulse test are a little larger than those of the microtremor observation. The analyzed frequencies are shown in Table 1. The 3-dimensional frame model is adopted to numerical model. Figure 4 shows the FVT and numerical analyzed modal shapes. The natural frequencies calculated and the modal shapes from MIM agree well with the natural frequencies and the bending modal shapes by a numerical simulation model.

CONCLUSIONS

The values are roughly coincident with the experimental values lead by MIM.
Being based on the comparison with each data, it is evaluated that a modified MIM lead a reasonable damping parameters set and the modal shapes from MIM agree well with the bending mode shape of a numerical simulation model

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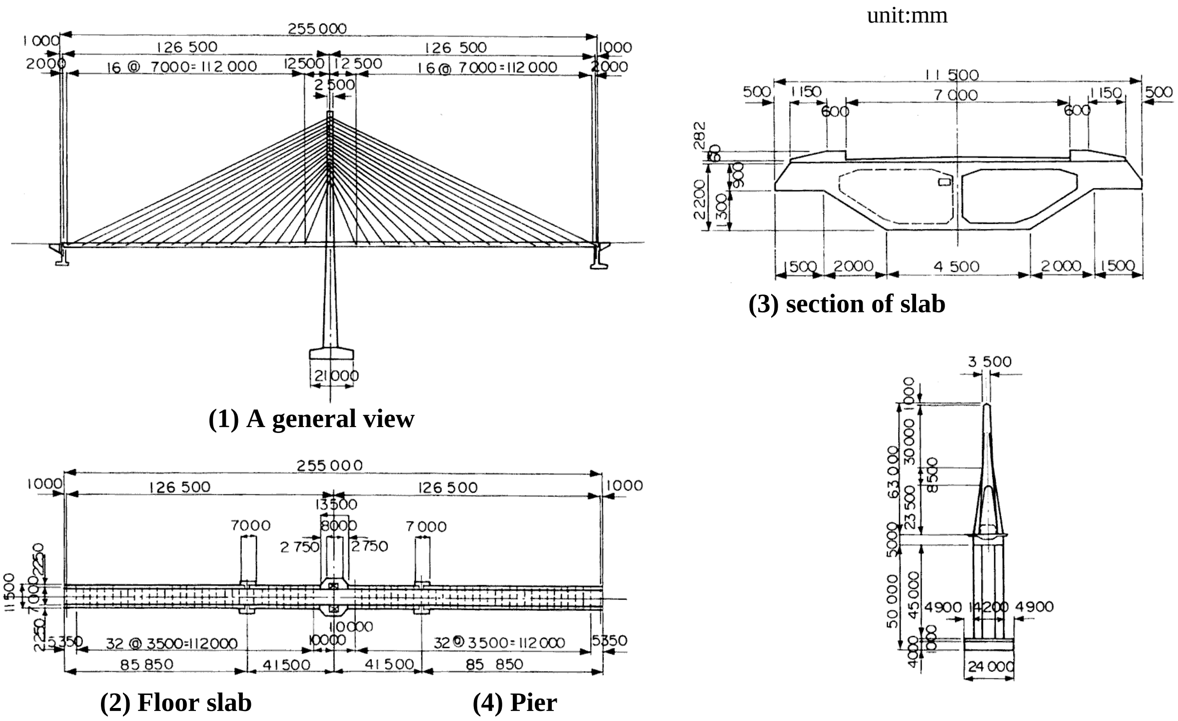


Figure 1: Parameter of the object CSB

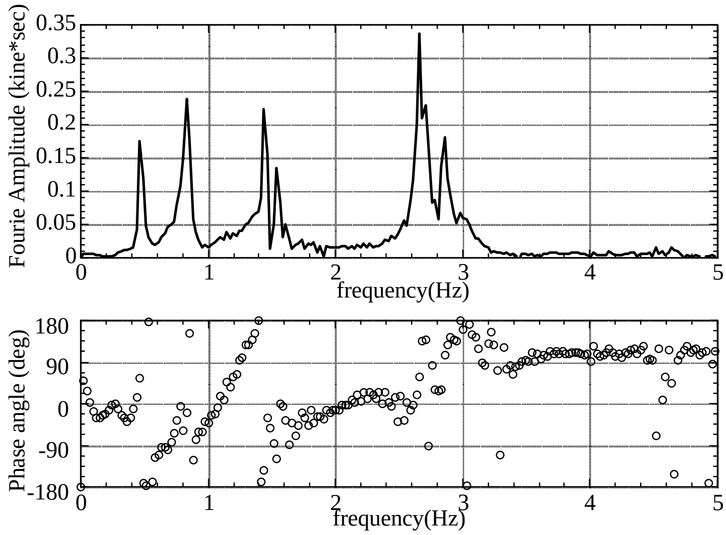


Figure 2: A fourie spectrum

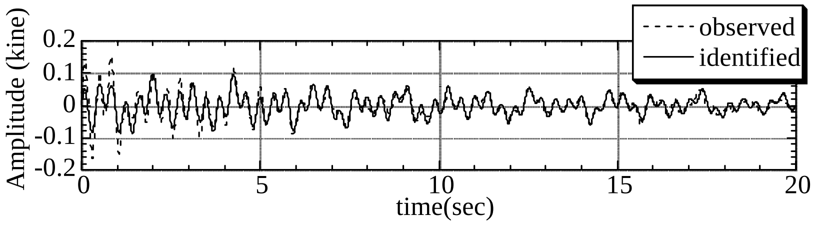
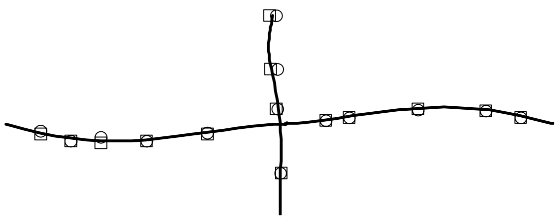


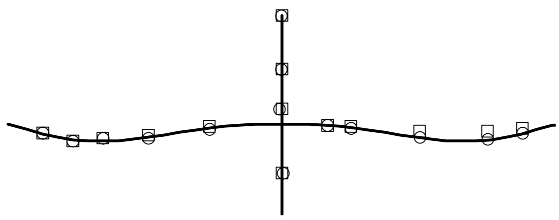
Figure 3: Curve fitting at time domain

Table 1: Comparison the FVT results with calculated frequencies, and the modal damping constants

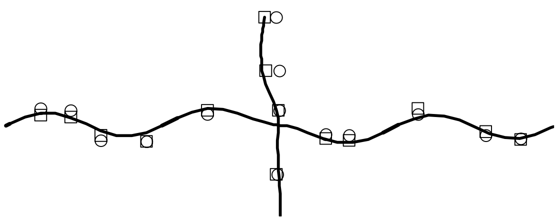
natural frequency(Hz)					damping constant (%)		
the FVT results				calculated	the FVT results		
modal order	impulse test	microtremer observation	average		impulse test	microtremer observation	average
1st	0.469	0.492	0.481	0.467	1.20	0.97	1.09
2nd	0.846	0.860	0.853	0.879	0.77	0.75	0.76
3rd	1.44	1.47	1.46	1.29	0.17	0.43	0.30
4th	1.56	1.57	1.57	1.57	0.59	0.22	0.41
5th	2.66	2.71	2.69	2.73	0.40	0.32	0.36
6th	2.82	2.83	2.83	2.81	0.24	0.49	0.37
7th	4.57	4.57	4.57	4.42	0.31	0.33	0.32
8th	4.64	4.64	4.64	4.46	0.41	0.38	0.40



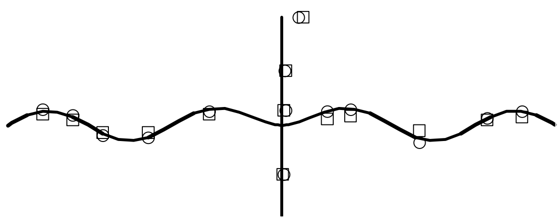
(1) 1st mode



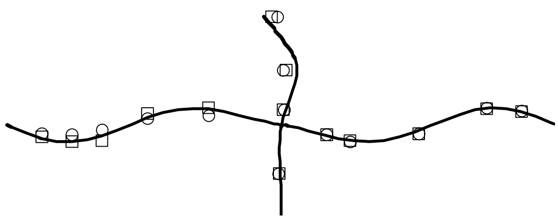
(2) 2nd mode

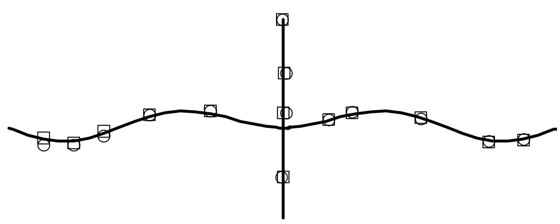


(3) 3rd mode



(4) 4th mode





(5) 5th mode **(6) 6th mode**

□ *microtremor observation*

▬ *numerical simulation*

Figure 4: The modal shapes