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WAVELET-BASED VIBRATION ANALYSIS OF AKASHI KAIKYO BRIDGE

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Abstract

The wind-resistant design of the Akashi Kaikyo Bridge was the most difficult part in the bridge design work. In order to confirm the design parameters of the bridge vibration such as natural frequency and structural damping, bridge monitoring has been conducted since the bridge was completed in 1998. In addition, the monitoring is used for the health monitoring and bridge maintenance.

Since then, monitoring data has been accumulated, including data at typhoons. Some typical data was analyzed with random decrement method and eigensystem realization algorithm method. The first report on the vibration parameters showed a stable and reliable identification result for natural frequencies, while relatively large variation in damping identification. Because structural damping is one of the most important parameters in wind-resistant design, a more accurate and reliable result for damping identification is desirable.

This study focuses on accurate damping identification using the combination of wavelet analysis and ERA method. The result showed significant improvement in damping identification. In addition, it is shown that natural frequency can be identified with high accuracy and it can be a health index of the bridge condition.

INTRODUCTION

The wind-resistant design of the Akashi Kaikyo Bridge, which is the current world's longest span suspension bridge, was the most difficult part in the bridge design work. Exhaustive investigations by wind-tunnel testing and analysis were carried out and realized the bridge construction. However, those results are closely depending on design parameters assumed such as natural frequency and structural damping.

Field vibration tests were carried out with big exciters for some long-span bridges in Japan in order to confirm the design parameters. However, in the case of the Akashi Kaikyo Bridge, a field vibration test was not carried out due to non-availability of a capable big exciter. Instead of this, monitoring sensors were installed on the bridge for the purposes of daily traffic control, design parameter verification and health monitoring.

Based on this fact, the authors have been trying to identify the design parameters with monitoring data. Some typical data including that at typhoons was analyzed with random decrement method[1), 2)] and eigensystem realization algorithm method[3), 4)]. The first report on the vibration parameters showed a stable and reliable identification result for natural frequencies with relatively large variation in damping identification. Because structural damping is one of the most important parameters in the wind-resistant design, a more accurate and reliable result for damping identification is desirable.

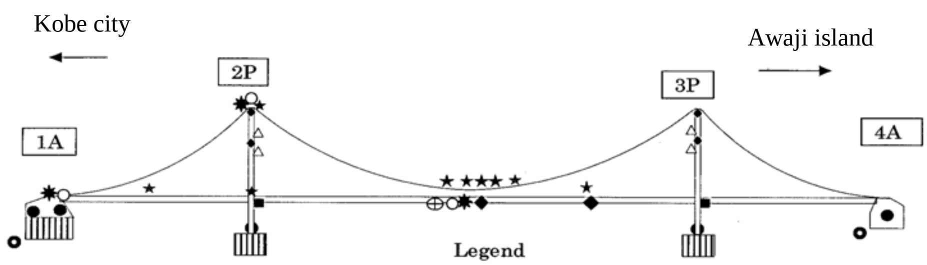
The past results showed that bridge response contained non-stationary characteristics and therefore damping identification yielded large variation. This study first examines characteristics of the bridge response and tries to realize accurate damping identification with combination of wavelet analysis and ERA method. The paper also presents that natural frequency can be identified accurately with a normal identification process and it can be a health index of the bridge condition.

MONITORING SYSTEM AND DATA

About 100 channel sensors are installed on the bridge to monitor wind speeds, ground acceleration, bridge responses (acceleration, velocity and GPS-based deflection) during strong winds and earthquakes, as shown in Figure 1.

In this study, identification of natural frequencies and damping as a function of a wind speed was done. Vertical and torsional components of velocity data of the bridge deck at the span center and a quarter point of the span were used. Wind-speed data at the span center was referred. The data was recorded at 20Hz sampling frequency.

Table 1 shows a list of data used in this study in which each data is 10 minutes long. In order to analyze effects of aerodynamic damping, different wind-speed data was used. It was confirmed that there was not large increasing/decreasing trend in the wind speed nor large change in the wind direction during each data.



Legend

Symbol	Sensor
★	Anemometer
◆	Velocity Gauge(Girder)
◆ (small)	Velocity Gauge(Tower)
■	Displacement Gauge(Girder Edge)
●	Accelerometer
o	Seismometer
✱	GPS
○	Thermometer(Cable)
⊕	Thermometer(Air)
△	Displacement Gauge for T.M.D

Figure 1. Layout of monitoring sensors on Akashi Kaikyo Bridge

Table 1. List of observations

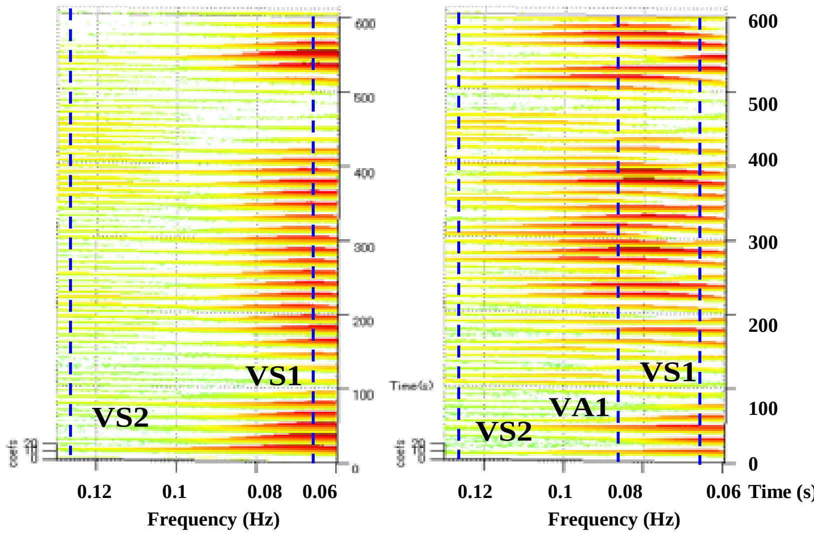
No.	Mean wind speed (m/s)	yyyy,mm/dd	Time	Note
1	1.8	2002,1/26	9:06-9:16	
2	4.3	2002,1/26	4:26-4:36	
3	4.6	2002,1/26	4:36-4:46	
4	5.1	2002,1/25	9:26-9:36	
5	5.4	2002,1/26	4:46-4:56	
6	5.5	2002,1/25	8:56-9:06	
7	5.5	2002,1/25	9:06-9:16	
8	6.3	2002,1/25	9:36-9:46	
9	6.4	2002,1/25	9:46-9:56	
10	6.7	2002,1/25	10:26-10:36	
11	6.8	2002,1/25	11:16-11:26	
12	7.3	2002,1/25	10:16-10:26	
13	15.0	1999,2/3	7:50-8:00	
14	16.6	1999,1/29	1:50-2:00	
15	18.1	1999,2/3	6:50-7:00	
16	20.1	1999,12/7	0:00-0:10	
17	26.2	1998,9/22	13:53-14:03	Typhoon
18	28.4	1998,9/22	14:33-14:43	Typhoon
19	32.0	1998,9/22	14:03-14:13	Typhoon
20	33.1	1998,9/22	14:13-14:23	Typhoon

VIBRATION ANALYSIS

As described, this study aims at stable and accurate damping identification. Firstly, characteristics of bridge response were examined by wavelet analysis, that is, what happened in time domain. Figure 2 shows the result of the wavelet analysis of the vertical velocity of the deck at a wind speed of 5.3 m/s and recorded over a 10 minute period. Broken lines in the figures show the design values of natural frequencies.

Time sections where a particular mode is strongly excited (darker portions) can be recognized. During this 10-minute period, wind speed and direction did not change so much. Based on the result shown in Figure 2, a stable and accurate identification result was expected, if only those time sections were analyzed. In order to realize this, only those time sections were extracted and connected to one continuous signal as shown in Figure 3, and those screened data was applied to the ERA method[5), 6)], called the wavelet screening ERA method.

In this study, five modes were analyzed: 1st symmetric vertical (VS1), 1st anti-symmetric vertical (VA1), 2nd symmetric vertical (VS2), 1st symmetric torsion (TS1) and 1st anti-symmetric torsion (VA1). Free vibration signal, which is the input data of ERA method, was generated by correlation functions. Since velocity data of the deck at the span center and quarter point was used, auto-correlation of each data and their cross-correlation functions were used as shown in Figure 4. In addition, as described later, previous analysis results were compared with this study. Those previous analyses used random decrement method, simple ERA method and ERA method with RD method. The ERA method with RD method generated a free-vibration signal by RD method.



(1) Mid-span (2) Quarter point

Figure 2. Wavelet analysis of monitored data (vertical velocity at 5.5 m/s)

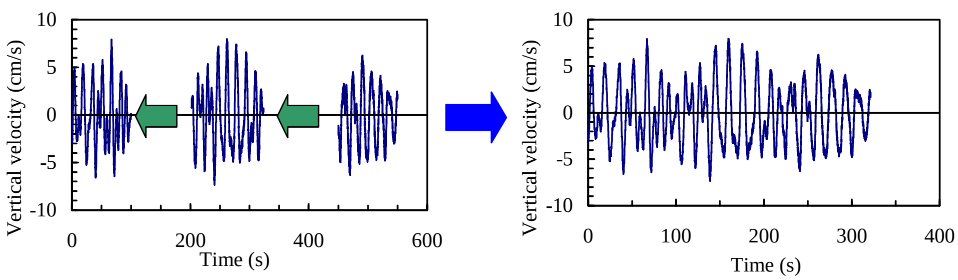


Figure 3. Data extraction and connection of screened data

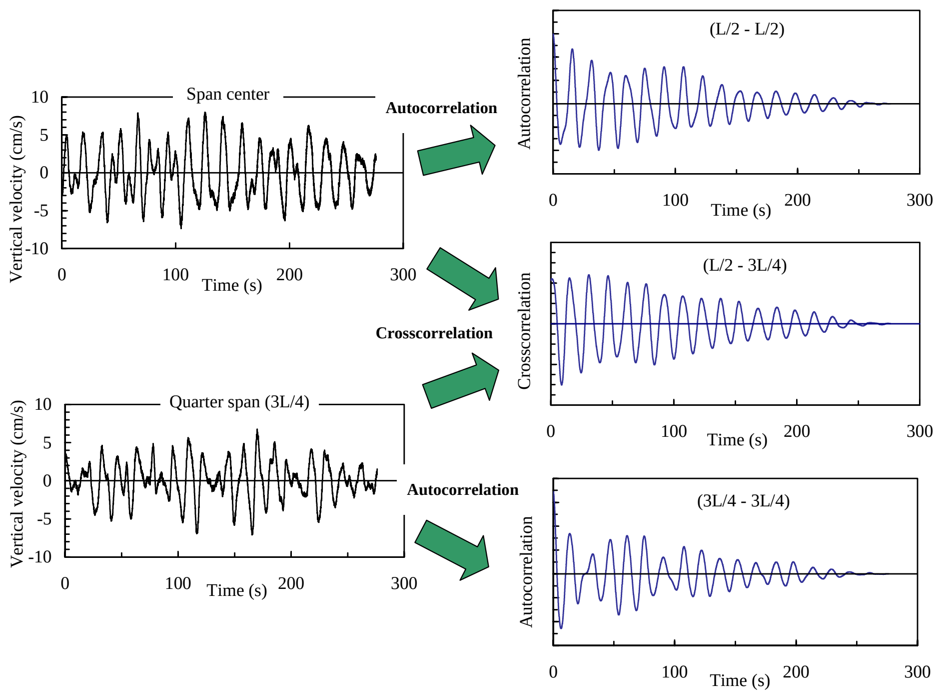


Figure 4. Free vibration signals by National Excitation Technique

VIBRATION CHARACTERISTICS

Natural frequencies identified by the wavelet screening ERA method are shown in Figure 5. Corresponding design values are also shown in the figure with broken lines. Good agreement can be seen between the identified natural frequencies and the design values in the first three modes, while those of torsional modes are by about 10% higher than the design values. The possible reason is that the steel road deck stiffness affects the torsional stiffness of the truss stiffening girder, because the eigenvalue analysis of natural frequency in the design calculation assumed a non-composite action between the steel road deck and the truss girder.

Modal damping identified by the wavelet screening ERA method (WS+ERA) as a function of a 10-minute average wind speed is shown in Figure 6. Modal damping at different wind speeds includes aerodynamic damping. Modal damping by a simple ERA method (ERA) not using the wavelet screening and the RD method (RD) are also shown in the figure. In addition, changes of modal damping in the aeroelastic model wind-tunnel test of the Akashi Kaikyo Bridge are shown by dotted lines (WT) and that by the quasi-steady theory are shown by solid lines (QS) in the vertical modes.

Generally, there is not so much difference between the wavelet screening ERA method and the simple ERA method. However, significant improvement can be seen in the wavelet screening ERA method with smaller variation, comparing with the wind-tunnel test result and quasi-steady theory. The RD method also showed large variation around the ERA method result. One of the reasons for the difference of the torsional damping in a high wind speed region between the identified values and the wind-tunnel test might be the difference in the amplitude of damping calculation. Damping of the wind-tunnel test was calculated at the amplitude of 1 degree in torsion. On the other hand, torsional amplitude of the monitoring data is far below the wind-tunnel test level.

The lowest wind speed at which damping was identified is 1.8 m/s for the 1st symmetric torsional mode. Modal damping at a low wind speed region (<10 m/s) closely follows the trends of the wind-tunnel test and quasi-steady theory. Therefore, judging from the results in this study, the structural damping of the Akashi Kaikyo Bridge will be 0.04-0.05 of logarithmic decrement for the 1st symmetric vertical mode and 0.02-0.025 of logarithmic decrement for the 1st symmetric torsional mode. They are both higher than the design values of 0.03 for vertical and 0.02 for torsional modes.

As described, vibration analysis of monitoring data of the Akashi Kaikyo Bridge was conducted several times for different time data and with different identification methods, as shown in Table 2. Identification cases are basically classified into low wind-speed (10-minute average wind speed < 10 m/s), middle wind-speed (14-20 m/s) and high wind-speed (> 25 m/s, typhoon) conditions. Identification methods used are RD method, ERA method and wavelet screening ERA method.

Natural frequencies of the 5 modes identified for the cases in Table 2 are shown in Figure 7. Except torsional modes at high wind-speed data, natural frequencies are identified with very small variation, even for different data and with different identification methods. For example, coefficients of a variation (standard deviation / mean) are about less than 1%. Slight decrease of torsional frequencies at high wind speed is due to an aeroelastic force effect. Based on this fact, natural frequency can be identified accurately with a normal identification process from monitoring data and it can be used as a health index of the bridge condition if bridge monitoring is continued for a long time.

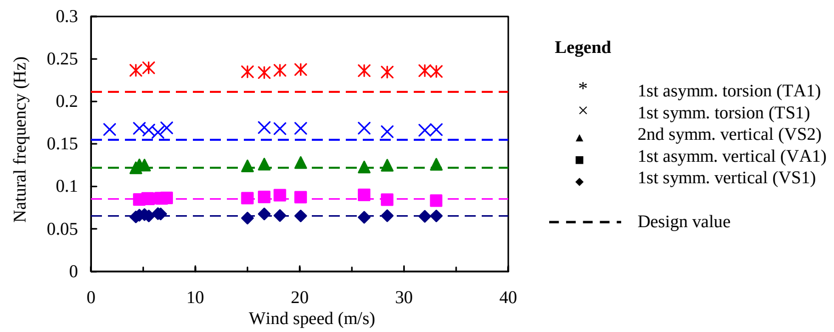
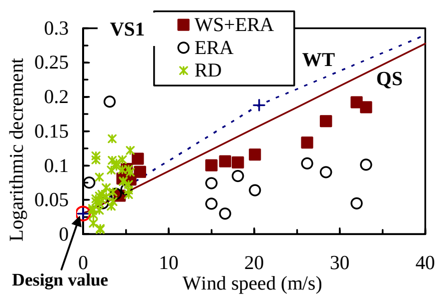
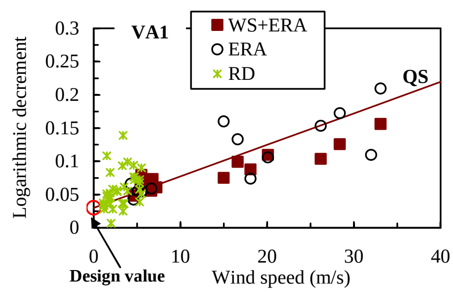


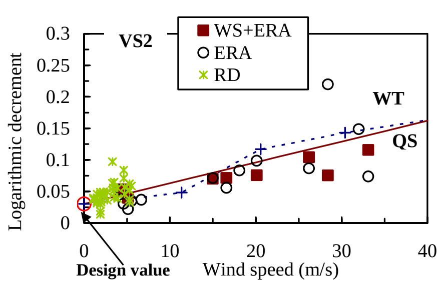
Figure 5. Natural frequencies by wavelet screening ERA method



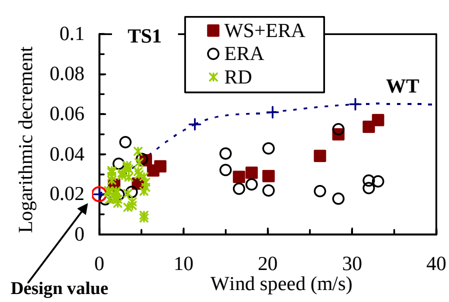
(1) 1st symmetric vertical



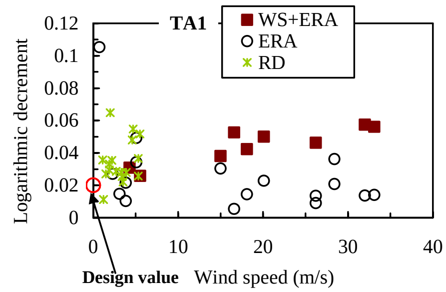
(2) 1st anti-symmetric vertical



(3) 2nd symmetric vertical



(4) 1st symmetric torsion

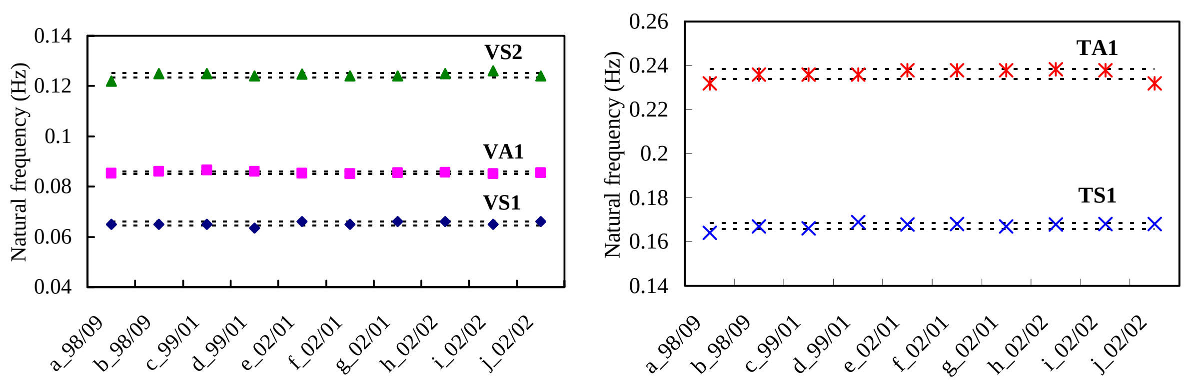


(5) 1st anti-symmetric torsion

Figure 6. Modal damping by wavelet screening ERA method

Table 2. List of monitoring data analyzed

Case	yy/mm	Wind speed	No. of data sets	Identificatoin method	Note
a	98/09	26-33m/s	4 × 10min	ERA	Typhoon #7
b	98/09	26-33m/s	4 × 10min	WS+ERA	Typhoon #7, This study
c	99/01	14-20m/s	6 × 10min	ERA	
d	99/01	15-20m/s	4 × 10min	WS+ERA	This study
e	02/01	< 10m/s	12 × 100min	RD	
f	02/01	< 10m/s	12 × 100min	ERA	
g	02/01	< 7m/s	12 × 10min	WS+ERA	This study
h	02/02	< 8m/s	18 × 100min	RD	
i	02/02	< 5m/s	5 × 10min	ERA	
j	02/02	< 5m/s	5 × 10min	RD+ERA	



(1) Natural frequencies of vertical modes

(2) Natural frequencies of torsional modes

Figure 7. Natural frequencies by different data and different method

CONCLUSIONS

Natural frequencies and structural damping of the Akashi Kaikyo Bridge were identified from the bridge monitoring data with the wavelet screening ERA method. Significant improvement, that is, reduction in variation in the modal damping identification was realized, comparing with the previous identification with RD method and simple ERA method.

Structural damping of the Akashi Kaikyo Bridge was estimated by damping identification result at low wind-speed data, the aeroelastic model wind-tunnel test and quasi-steady theory. The result showed that it will be 0.04-0.05 of logarithmic decrement for the 1st symmetric vertical mode and 0.02-0.025 of logarithmic decrement for the 1st symmetric torsional mode.

Natural frequencies of the 5 lower modes were identified with very small variations, even for different data and with different identification methods. Therefore, natural frequency can be identified accurately with a normal identification process from monitoring data and it can be used as a health index of the bridge condition if bridge monitoring is continued for a long time.

REFERENCES

1. Katsuchi, H., Miyata, T., Yamada, H. and Hata, K., Full-scale measurement of the Akashi-Kaikyo Bridge, *Proc. of 11th International Conference on Wind Engineering, Lubbock*, USA, 2003, 1431-1438.
2. Katsuchi, H., Yamada, H., Hata, K. and Kusuhara, S., Full-scale Monitoring of Akashi-Kaikyo Bridge, *Proc. of the 3rd China-Japan-US Symposium on Health Monitoring and Control of Structures*, Dalian, China, 2004.
3. Katsuchi, H., Miyata, T., Yamada, H. and Kusuhara, S., Improved Identification of Modal Parameters of Akashi Kaikyo Bridge, *Proc. of IABSE Conference*, Denmark, 2006.
4. Yamada, H., Katsuchi, H. and Kusuhara, S., Wavelet-based Identification of Modal Parameters of Akashi Kaikyo Bridge, *Proc. of Int. Nat. Conf. on Bridge Engineering –Challenges in the 21st Century (CD-ROM)*, Hong-Kong, 2006.
5. Juan, J.N., Pappa, R.S., An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction, *J. of Guidance, Control and Dynamics*, Vol.8, No.5, 1985, 620-627.
6. Nagayama, T., Abe, M., Fujino, Y. and Ikeda, K., Mon-Iterative Identification of Non-Proportionally Damped System from Ambient Vibration Measurement and Analysis of Dynamic Properties of a Long Span Suspension Bridge, *J. of Structural Mechanics and Earthquake Engineering*, JSCE, No.745, I-65, 2003, 155-169.