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Dynamic characteristics of a curved cable-stayed bridge identified from strong motion records

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Abstract

An assessment of dynamic characteristics of the 455 m Katsushika–Harp curved cable-stayed bridge is presented. Dynamics characteristics such as natural frequencies, mode shapes and modal damping ratios are obtained from seismic response of the bridge by employing a time-domain multi-input multi-output (MIMO) system identification (SI) technique. The technique makes use of base motions and superstructure accelerations as pairs of inputs–outputs to realize the coefficients of state-space system matrices. The SI results indicate the occurrence of many closely spaced modal frequencies with spatially complicated mode shapes. Fourteen global modes in the ranges of 0.45–2.5 Hz were identified, in which the girder motion dominated most of the modes. The tower modes were associated with girder modes and were characterized by the lowly-damped motion. Using identification results from six earthquakes, the effects of earthquake amplitude on modal damping ratios were observed.

Keywords: Curved cable-stayed bridge; Instrumented bridge; Seismic response; MIMO system identification; Katsushika–Harp bridge

1. Introduction

The availability of multi-channel permanent sensors allows regular full-scale dynamic tests that are essential for continuous monitoring of a bridge. In a seismically active region, such as Japan, this instrumentation provides an opportunity to use system identification (SI) techniques to explain bridge performance during earthquakes. By employing the SI technique, it is also possible to monitor any changes in the bridge behavior without the presence of visually observable damage. In the context of bridge monitoring, this excellent opportunity is beneficial to evaluate the adequacy of bridge seismic design code [1].

The general approach of an earthquake-induced SI is to use the input–output relation to recreate structural models that are capable of reproducing the actual responses. In one early study Beck [2] employed the output-error minimization method for a linear, time-invariant structural system with classical damping. McVerry [3] proposed a frequency domain approach using transfer function to minimize the objective function of output error. Chaudhary et al. [4] improved it, for a more general problem of non-classical damping that includes the structural model in addition to the modal model. This method, while powerful and significantly insightful, requires prior information of structural properties that are typically unavailable and difficult to obtain, especially for large and complex structures such as cable-stayed bridges. Most conventional SI techniques were developed in the frequency domain due to the common practice of using frequency analyzer for data acquisition. These approaches offer advantages in incorporating soil–structure interaction into analysis, but often suffer from damping estimation especially when closely spaced modes are present.

Compared to cable-stayed bridges with straight girder, the curved cable-stayed bridges are relatively few. Examples of well-known curved cable-stayed bridges are the La Arena Viaduct in Spain [5], the Safti Link Bridge in Singapore [6], the Rhine Bridge near Schahausen, Switzerland [7] and the twin curved cable-stayed bridge at the Malpensa airport in Milan, Italy [8]. In the analysis of a cable-stayed bridge under seismic action, the aspects of three dimensionality, multi-modal contribution, multiple-support excitations and modal coupling

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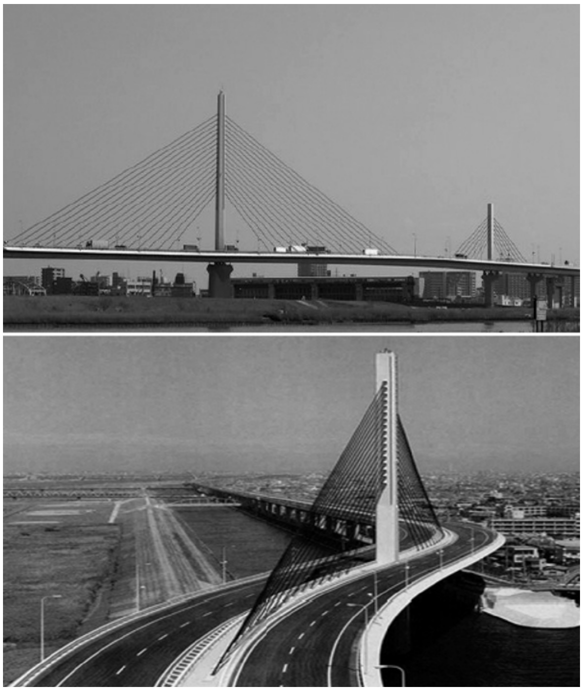

Fig. 1. View of the Katsushika–Harp bridge.

are of great importance [9]. Accordingly, the SI techniques should be developed to provide accurate information that accommodate observation of such aspects.

Challenges in the SI technique applied to a curved cable-stayed bridge come from its nature as a large and continuous structure, which makes it difficult to be represented with a lumped-mass model. Moreover, owing to its complexity, many modes are closely spaced in frequency. And due to its long span, spatial variability of ground motions may be significant. For this latter reason, the SI technique needs to employ a scheme of multiple-input excitations. More recent works on the SI of long-span bridges under seismic excitation have attempted to overcome the problems by employing time-domain algorithms that include the effect of multi-input [10–12].

The focus of the work described in this paper is twofold: (1) providing a systematic procedure for SI of the Katsushika–Harp curved cable-stayed bridge using seismic records, and (2) evaluating the dynamic characteristics of the bridge based on the SI results. The SI method adopted here is based on the input–output mapping technique of the System Realization using Information Matrix (SRIM) [13,14]. Organization of this paper is such that a brief account of the bridge is presented first, followed by explanation of the SI methodology, instrumentation and seismic records. Afterwards, the results of identification are explained, including the comparisons with an analytical finite element model, previous tests using ambient vibration, and forced vibration. Next the identification of tower modes and the observation from six earthquakes are presented. Conclusions of the study are summarized at the end.

2. Description of Katsushika–Harp bridge

The Katsushika–Harp Bridge (Fig. 1) is a curved cable-stayed bridge located in the Katsushika area of Tokyo Metropolitan city. The bridge crosses over an estuarial area between the Arakawa and Nakagawa Rivers. Its girder is made of steel with the width of 23.5 m and the total length of 455 m, consisting of 220 m main span, and three side spans of 40.5, 134 and 60.5 m (Figs. 2 and 3). The bridge's unique asymmetrical S-shaped girder is composed by two curves with a radius of 334 m and 270 m each. The bridge has two rectangular towers made of steel; the main tower (65 m in height and 3 m in width) is located in the middle of the curve and the smaller one (13.8 m in height and 2.5 m in width) is located at the end of highway approach to the Hirai Bridge. The bridge stays spring from the main tower (17 cables) and the right tower (7 cables) to support the curved girder. Construction of the bridge was completed in 1987, and since then it became the part of the Shutoo Chuo Loop line in the Tokyo Metropolitan expressway.

For the purpose of monitoring, 32 channels of sensors were permanently installed on the bridge. The sensors consist of 29 accelerometers deployed at 12 locations, (Fig. 4) and 3 displacement sensors. For system identification, only responses from accelerometers were utilized. These accelerometers have a range of frequency between 0.05 and 35 Hz with an accuracy of 15 microampere per cm/s^2. Among these accelerometers, six are located on the substructure (on the pile foundation and pile caps) and the rest were installed on the superstructure (towers, pier caps and girder). On the girder, sensors were installed at eight locations along the girder centerline. These sensors measure accelerations in vertical, transverse and longitudinal directions, at a data-sampling rate of 100 Hz. It should be mentioned that all sensors measure the motion in directions that coincide with the local coordinates of structure members (i.e. the x-direction of measurement coincides with the centerline of the bridge).

3. System identification methodology

In this study, the SRIM-based SI is employed to identify the complex modal frequencies, damping ratios and mode shapes of the bridge system. The SI consists of two steps, namely, the realization of system matrices from correlation of input and output data, and estimation of modal parameters from identified system matrices. The main advantage of this technique is its ability to provide a systematic way to identify modal parameters from multiple-input and multiple-output earthquake data without prior knowledge of structural properties or models. Moreover, it allows the identification of a classically as well as a non-classically damped structural system, and thus eliminates the need of trial and error in updating the modal parameters to achieve reasonable agreement with the recorded data.

3.1. Basic formulation of earthquake-induced vibration

The identification starts from a basic equation of motion of N degree-of-freedom (DOF) linear, time invariant, viscously damped system subjected to earthquake excitation $\ddot{u}_g(t)$, in the spatial coordinate $\{u(t)\}$ and continuous time (t). The equation is given as

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = -\mathbf{W}\ddot{\mathbf{u}}_{\mathbf{g}}(t). \tag{1}$$