Engineering Structures 172 (2018) 938–955

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Multiple internal resonances and modal interaction processes of a cable-stayed bridge physical model subjected to an invariant single-excitation

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ARTICLE INFO

Keywords:
Cable-stayed bridge
Multiple internal resonance
Interaction process
Beat vibration
Experiment
Modal analysis

ABSTRACT

There exist complex internal resonances in cable-stayed bridges. In order to study multiple internal resonances under the excitation of an invariant single-excitation and to ascertain the modal interaction processes, a nonlinear dynamic experiment of cable-stayed bridge was carried out. The modal parameters of the experimental physical model were evaluated by two finite element models (the OECS and MECS). Mode shapes were classified and compared to distinguish the in-plane and out-of-plane as well as the global, local and hybrid modes. Potential internal resonances were recognized by investigate the ratios between cable frequencies and the OECS frequencies. Then, attention was paid not only to the steady-state responses but also the coupling processes. It was observed that multiple internal resonances could induce large amplitude vibrations of the entire bridge, including the “beat vibration” of long-cables. Moreover, the sum of the two beat frequencies was equal to the excitation frequency. These phenomena were also found in transient analysis by the MECS finite element model. The interaction processes of the multi-mode resonances were revealed by separating vibration signals using the zero-phase-shift filtering technology and by precisely linking the observed modes to the MECS modes with frequency relations. Research shows that: the forced vibration, 2:1 local-local internal resonance and combined internal resonance had occurred simultaneously in the physical model.

1. Introduction

Cable-stayed bridge has became one of the most popular bridge types, especially in crossing wide rivers or valleys. According to an incomplete statistics, at present, there are over 85 cable-stayed bridges, built or under construction, whose main span are longer than 400 m in China. However, because cables are light and flexible and show significant global stiffness decreasing as spans increasing, large amplitude vibrations would be induced under ambient excitations [1,2]. Therefore, research on nonlinear dynamic behavior of cables has became an important topic. At present, many significant efforts have been carried out theoretically and experimentally to investigate the nonlinear dynamics of cables [3–8]. These studies have included large amplitude vibrations caused by parametric or external resonances [3–6], as well as internal resonances between in-plane/out-of-plane modes [7]. Modal interactions [8], especially the multi-mode nonlinear vibrations [6,9–12] have recently became the core issue of cable nonlinear dynamics. Besides single excitation, two-frequency excitation [13] as well as combination of wind flow and support motion have been considered [14]. Another aspect was the research on comparison of different analytical methods [15].

However, these studies of dynamics were focused on a single cable with ideal excitations. A single cable’s modal interaction could not exactly reflect interactions between different structural members such as the bridge deck and the pylons. Thus, the dynamics of cable-beam hybrid structures were adopted. For these structures, the single-cable-stayed beams [16–19], as well as the multi-cable-stayed beams were concerned. Lv and Kang [20] presented a cable-stayed arch model to study the cable’s primary resonance by parametric analysis. Kang et al. [21] established a nonlinear dynamic double-cable-stayed shallow arch model to investigate the in-plane 1:1:1 internal resonance. Song et al. [22,23] established a model which was consists of a simply supported four-cable-stayed deck and two rigid pylons. Besides, simplified cable-supported structures were also studied. Konstantakopoulos and Michaltsos [24] investigated the dynamic behavior of a simplified cable system bridge (combination of cable-stayed bridge and suspension

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https://doi.org/10.1016/j.engstruct.2018.06.088
Received 21 October 2017; Received in revised form 21 June 2018; Accepted 21 June 2018

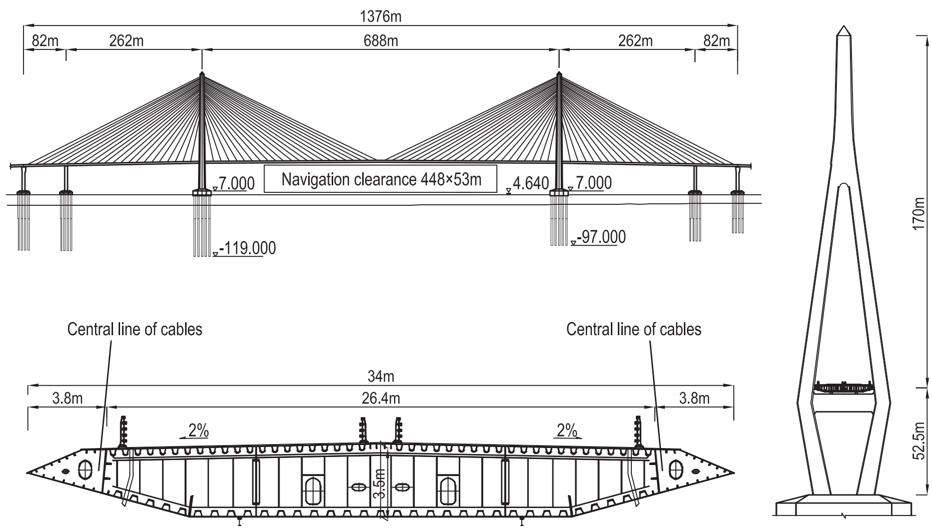

Fig. 1. General characteristics of Xiangshangang Bridge.

bridge) under moving loads. As a more general consideration, Lepidi and Gattulli [25,26] presented a multi-body section model to investigate sectional modal interactions of cable-supported bridges, which includes cable-stayed bridges, suspension bridges and (half-) through arch bridges.

As everyone knows, cable-stayed bridge is a complex composed structure that consists of deck, pylons and many cables. Any vibrations of an element would influence the others (interactions). Above simplified cable-beam structures are still insufficient in completely understanding the interactions among the cables, deck and pylons. However, it is still difficult to study nonlinear dynamics of cable-stayed bridges by theoretical modelings. Therefore, experiment and on-site measurement as well as finite element method are commonly used to study the nonlinear dynamic behaviors, especial the modal interactions. Ren et al.[27] carried out modal analysis on the Qingzhou cable-stayed bridge by finite element method and on-site measurement. Gattulli et al. [28] studied the localization and veering phenomenon by nonlinear modeling and finite element method. El Ouni et al.[29] numerical and experimental analyzed a cable-stayed bridge in construction phase under parametric excitation. Caetano et al. studied the cable-deck interaction vibrations by indoor experiment [30] and on-site measurement [31]. Wu et al. [32] studied the dynamic characteristics of Megami cable-stayed bridge via experimental and analytical results.

These researches have observed modal interactions between cables and deck/pylons. However, modal frequencies of cable-stayed bridges are extremely intensive distributed, which leads potential interactions of several cable local modes and bridge global modes. Thus, the dynamic responses of structures (especially cables) are usually the results of multiple internal resonances. It is insufficient to study how exactly the modal coupling occurs, or how one mode excites the others, only via frequency relationships or steady-state responses. Therefore, researches on the processes of modal interactions are necessary and meaningful.

The purpose of this study is to investigate the modal interaction processes under the excitation of an invariant single-excitation to ascertain how exactly the multiple internal resonances happen. A physical model of the Xiangshangang Bridge was designed according to the similarity theory. The model, manufactured and tested at Hunan University in 2014 to 2015, was a cable-stayed bridge with totally 44 cables. Modal parameters of the physical model were calculated by two types of FE model and identified by experimental tests. An electromagnetic shaker was installed in the middle of the main span to excite the deck. Attention was paid both to the transient and steady-state responses under a invariant single-excitation with 10.25 Hz frequency. It was observed that multiple internal resonances would cause large amplitude vibrations of the whole bridge. At the beginning of the resonance only a response frequency (equal to the excitation 10.25 Hz frequency) exists. Gradually, two adjacent response frequencies of the long-cable were simultaneously induced ("beat vibration"). Furthermore, the sum of these two response frequencies was exactly equal to the excitation frequency. The vibration curves of the deck/pylons of each response frequency were obtained by separating the measurement vibrations as well as MECS model calculated vibrations. The corresponding modes of each vibration curves were recognized by comparing with the frequencies and mode shapes of MECS model. Based on that, the multiple internal resonances and interaction processes were revealed by frequency relationships. Finally, the paper ends up with some conclusions and understandings.

2. Description of the prototype bridge and the physical model

The physical model was designed based on the Xiangshangang Bridge which is located at Ningbo, China. It is a three span steel cable-stayed bridge with a continuous stiffening girder. The bridge is designed as semi-floating system. The vertical and lateral supports are installed between the deck and pylons, as well as longitudinal viscous dampers. The dampers start to work when the deck longitudinal vibration exceeds the designed values. The main span of Xiangshangang Bridge is 688 m and the back spans are 344 m. The span configuration and general characteristics as shown in Fig. 1. Each cable is consists of high strength and low relaxation galvanized parallel steel wires. Its diameter is 7 mm, and the tensile strength is 1.67 GPa. The standard cable spacing on the deck is 15 m. Each pylon carries 88 stay cables. Those cables are laterally located in two spatial inclined planes. Cables in each plane are stayed on the pylon as a fan-type arrangement.

According to the size of the model storage room, the scale factor was chosen to be 250. Because the sizes and spacings of the scaled members were too small to manufacture, and some of the counterweights and stay cables were spatially conflicted, we had to make some appropriate adjustments on the bridge model. The adjustments included: (i) torsional vibration of the deck was not taken into account, the two spatial inclined cable planes were changed into a single vertical cable plane by laterally merge the two cables together; (ii) each two cables were also longitudinally merged together to enlarge the cable spacing; (iii) cable tensional forces were adjusted. The principle was to make sure the static profile of the adjusted bridge model same to that of the scaled prototype bridge. The main parameters of stay cables at one side are shown in Table 1 (the other side is the same because of symmetry). The similarity between the physical model and the prototype model is