Engineering Structures 75 (2014) 225–236

Contents lists available at ScienceDirect

Engineering Structures

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

An analytical approach to evaluate damping property of orthogonal cable networks

Javaid Ahmad, Shaohong Cheng *, Faouzi Ghrib

Department of Civil and Environmental Engineering, University of Windsor, 401 Sunset Ave., Windsor, Ontario N9B 3P4, Canada

ARTICLE INFO

Article history:
Received 30 August 2013
Revised 16 May 2014
Accepted 1 June 2014
Available online 25 June 2014

Keywords:
Cable network
Cross-tie
Cable-stayed bridge
Modal damping
Optimum cross-tie position
Vibration control

ABSTRACT

Cross-tie solution is becoming more popular for mitigating unfavorable cable vibrations on cable-stayed bridges. Connecting a vulnerable cable with its neighbours using cross-ties to form a cable network would not only enhance its in-plane stiffness, but also affect its damping property. While the majority of existing studies focused on the enhancement of the in-plane stiffness, of which the mechanisms are better understood now, the research on the damping effect remain scarce. However, an effective cross-tie design should consider both factors. An analytical model of a two-cable network consisting of two horizontally laid main cables interconnected by a transverse orthogonal rigid cross-tie will be proposed in the current paper to study the damping property of the system. The inherent structural damping of the two main cables will be considered in the formulation, and an equivalent modal damping of the cable network is proposed. The developed analytical model and approach will be applied to a number of two-cable networks with various configurations, and validated by independent finite element simulations. Based on the impact of cross-tie design on the in-plane stiffness and damping of the network, a range of optimum cross-tie position will be defined.

1. Introduction

Over the past few decades, rapid development in material and construction technology as well as analysis and design techniques constantly sets new span length record for cable-stayed bridges. Consequently, the length of stay cables grew continuously. The longest cable on the current record keeping Russky Bridge in Russia has a length of 579.83 m. However, these encouraging breakthroughs come at price and present new challenges to engineers. A typical problem of concerns is the excessive vibrations of bridge stay cables. Under the combined effects of low inherent structural damping and long flexible feature, stay cables are prone to dynamic excitations due to various environmental factors, such as rain combined with wind and nonlinear coupling between motions of cables, deck and/or pylon [1]. Numerous cable vibration control solutions have been proposed and implemented in field with various levels of success. Installing helical wires on the cable surface, which proves to be an effective aerodynamic countermeasure to suppress rain–wind-induced vibrations [2], has now become a standard requirement of manufacturing stay cables. External dampers and cross-ties are capable to "calm down" cables excited by different mechanisms. While the former has been widely used on site and the design tools are more matured [3]; the mechanics of the latter is still not completely apprehended despite its increasing popularity on new bridges [4] and in the rehabilitation of existing ones [5].

In the case of cross-tie solution, a cable which has exhibited or is expected to experience large amplitude vibrations (referred to as the "target cable" in the rest of the paper) is inter-connected with its neighbouring cable(s) through transverse secondary cables, i.e. cross-ties, and thus forms a cable network. It was understood from the past studies that the performance of a target cable could be enhanced by the application of cross-ties through ways of increasing the in-plane stiffness [6–8], introducing additional structural damping to the system [9–11], and allowing the energy accumulated in the oscillating target cable being redistributed to more "calm" neighbouring cables [12]. However, some literature reported that the variation of one specific physical and/or geometrical parameter of a cable network would generally result in conflicting effects by enhancing one advantage but sacrificing the other. For example, the experimental studies by Yamaguchi and Nagahawatta [10] and Sun et al. [11] both indicated that stiff type cross-tie would have more considerable effect on increasing the network in-plane stiffness, whereas soft type cross-tie would lead to higher raise of structural damping. A proper understanding of how changes in certain system parameters would affect the gain

* Corresponding author.
E-mail addresses: ahmad1d@uwindsor.ca (J. Ahmad), shaohong@uwindsor.ca (S. Cheng), fghrib@uwindsor.ca (F. Ghrib).

http://dx.doi.org/10.1016/j.engstruct.2014.06.001
0141-0296/

Nomenclature

A, B	shape function constants of cable transverse displacement
B_{2j-1}, B_{2j}	shape function constants of left and right cable segments of the jth cable
c	damping coefficient per unit cable length
f	frequency of a cable network
f_1	fundamental frequency of the target cable
f_j	fundamental frequency of the jth cable
H_j	pretension in jth cable
L_j	length of jth cable
l_{2j-1}	length of the left segment of jth cable
l_{2j}	length of the right segment of jth cable
m_j	mass per unit length of the jth cable
n	mode number
n_G	mode number of the global mode
n_{LS}	mode number of the local left segment mode
n_{RS}	mode number of the local right segment mode
O_L	horizontal offset of the second cable on the left end
O_R	horizontal offset of the second cable on the right end
R_j	complex parameter of the jth cable, $R_j = \sqrt{[(\Omega\eta_j)^2 - i\cdot 2\pi\xi_j\Omega\eta_j]}$
[S]	coefficient matrix
$v(x,t)$	transverse displacement of a cable
$\bar{v}(x)$	shape function of the cable transverse displacement
$\bar{v}_{2j-1}(x)$	transverse displacement shape function of the left segment of the jth cable
$\bar{v}_{2j}(x)$	transverse displacement shape function of the right segment of the jth cable
{X}	vector containing all four unknown shape function constants
α_j	complex wave number of the jth cable, $\alpha_j = \sqrt{\frac{m_j\omega^2 - i\cdot 2m_j\xi_j\omega\omega_{0j}}{H_j}}$
χ	non-dimensional damping relation parameter, $\chi = \xi_2/\xi_1$
ε_{2j-1}	segment ratio of the jth cable left segment, $\varepsilon_{2j-1} = l_{2j-1}/L_j$
ε_{2j}	segment ratio of the jth cable right segment, $\varepsilon_{2j} = l_{2j}/L_j$
$\emptyset_{2j-1}$	product of system parameters of the jth cable left segment, $\emptyset_{2j-1} = \Omega\eta_j\varepsilon_{2j-1}$
$\emptyset_{2j}$	product of system parameters of the jth cable right segment, $\emptyset_{2j} = \Omega\eta_j\varepsilon_{2j}$
γ_j	complex mass–tension ratio parameter of the jth cable, $\gamma_j = \frac{H_jR_j/L_j}{H_1R_1/L_1}$
η_j	frequency ratio of the jth cable, $\eta_j = f_1/f_j$
λ_j	length ratio parameter of jth cable, $\lambda_j = L_1/L_j$
Ξ	non-dimensional network modal damping ratio, $\Xi = \xi_{eq}/\xi_1$
ξ_{eq}	equivalent structural damping ratio of the cable network
ξ_j	structural damping ratio of the jth cable
Ω	complex non-dimensional cable network frequency, $\Omega = \pi f/f_1 = \Omega_{re} + i\cdot\Omega_{im}$
Ω_0	non-dimensional undamped cable network frequency
Ω_{im}	imaginary part of complex frequency Ω of the cable network
Ω_{re}	real part of complex frequency Ω of the cable network
ω_o	undamped circular frequency of the cable
ω	complex circular frequency of the cable network

and loss of these benefits and thus the overall effectiveness of cable network is imperative to an efficient cross-tie design. The accurate quantification of these impacts would be possible through the analytical approach.

Due to the complexity of cable network behaviour, only a few analytical studies have been conducted so far. Caracoglia and Jones were perhaps the first who attempted the analytical approach. They proposed models of a basic two-cable network and a more general non-orthogonal network system in two companion papers [6,7]. In both models, the main cables were assumed to be taut cables, and cross-ties were assumed to be rigid rods or linear elastic springs. The modal solutions were obtained either analytically in the case of simple configuration [6] or numerically for more complex layouts [7]. Ahmad and Cheng [8] developed an analytical model of a general cable network consisting of n horizontally laid main taut cables interconnected by a single line of transverse rigid cross-ties. The modal solutions were derived analytically. The key system parameters were identified from the system characteristic equation and their respective impact on the system modal response were analytically studied [13]. In a subsequent work [14], the effect of cross-tie stiffness on the modal response of a cable network was investigated. In the proposed analytical model, the taut cable assumption was applied to the main cables whereas the behaviour of flexible cross-tie was modelled as reversible tension/compression linear spring connector. The role of cross-tie stiffness was explored and the results showed that when a more flexible cross-tie was used, a "modal evolution" phenomenon would occur, of which the local modes observed in a corresponding cable network with stiffer cross-tie would evolve into global modes. Giaccu and Caracoglia [15] investigated the nonlinear interaction between main cables and cross-ties by employing a generalized power-law stiffness model for the cross-ties. An equivalent linearization method was used to find the approximate modal response. It is worth pointing out that all of the above analytical studies focused on the in-plane stiffness and modal frequency of cable networks. The structural damping property of the main cables and cross-ties are neglected in the analysis. Thus, these analytical models are not capable of predicting how the structural damping of a target cable would be affected after it is connected to its neighbours, neither can they adequately infer the optimal cross-tie location. Needless to affirm that for an optimal design of cross-tie, the combined effects on the network frequency and the damping property should be considered.

In view of the above mentioned research needs, the current paper aims at extending the cable network analytical model developed earlier by the authors [8] by including the damping property of main cables in the formulation. The network system characteristic equation will be derived analytically. The equivalent modal damping ratio of the cable network will be determined by solving the associated complex eigenvalue problem. The in-plane modal behaviour, including the modal frequency, the mode shape and the modal damping property will be examined. The results will be compared and verified with those yielded from independent finite element simulations. The recommended range of optimum cross-tie installation location will be proposed, within which both the in-plane stiffness and the damping level of the target cable will be increased to a certain required level.

2. In-plane free vibration of orthogonal two-cable networks

In a real cable network system, structural damping exists in both main cables and cross-ties. The role of a cross-tie in the