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In-plane dynamic behavior of two stay cables interconnected by uniformly distributed crossties

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ABSTRACT

Over the past decade, the use of crosstie to suppress stay cable vibration has become more and more popular. Extensive research has led to a better understanding of the mechanics of cable networks, and the effects of different parameters, such as length ratio, mass-tension ratio, and segment ratio on the effectiveness of the crosstie have been investigated. However, the existing strategies for using crosstie still have drawbacks, for instance, the potential of “mode localization” and the serious effects on the aesthetics of bridge design. In this study, uniformly distributed elastic crossties serve to replace the traditional single or several crossties to overcome these drawbacks. A new numerical method is proposed to calculate the modal frequencies and mode shapes of the cable-crosstie system. The effectiveness of the new proposed method is verified by comparing the results with that from previous method. ……

1. INTRODUCTION

Large vibrations may have severe effects on stay cables. Many researchers and engineers have made great efforts to suppress the undesirable cable vibration, and several aerodynamic or mechanical methods had been proposed and successfully applied on stay cables. One of them is the use of crosstie, which has become increasingly popular over the past decade. The crosstie links the main stay cables together to form a complex cable system, which enhances in-plane stiffness, increases modal mass, and redistributes energy, and thus improves the stability of stay cables. Many researchers investigated the mechanics of crosstie through physical experiments, finite-element method simulations, and analytical methods.

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Yamaguchi (1995) experimentally investigated the modal frequency, shape, and damping of a cable network, consisting of two stay cables and two crossties, and concluded that crossties could increase the damping ratio of the network and it was more effective when more flexible and more energy-dissipative crossties were used. Sun (2007) experimentally investigated the effect of crosstie stiffness on the in-plane stiffness and damping of the network and noted that a stiffer crosstie contributed more in enhancing the in-plane stiffness, whereas a softer one was more effective increasing the damping ratio.

Caracoglia (2005a, b) developed an analytical procedure on the basis of taut cable theory to resolve the in-plane free vibration of the cable network. They derived the closed-form solutions to the in-plane free vibration of the two cables connected by single crosstie and the numerical solutions to those of multiple cables with multiple crossties. Caracoglia (2007, 2009), and Zhou (2014, 2015) investigated the hybrid method of combining crossties and dampers to suppress cable vibration through analytical methods. They pointed out that adding in-plane dampers could enhance the damping of the lower global in-plane modes of the network, whereas the localized mode vibration was still difficult to suppress.

Giaccu (2012, 2013, 2014) further developed an analytical method by considering the nonlinearity of a crosstie and simulating the imperfect transfer of a restoring force (slackening, snapping, or pre-tension loss) and the stochastic nature of the network caused by the stochastic initial condition. They concluded that the nonlinear crosstie behavior and its combination with the stochastic dynamics of the cables' initial vibration amplitude had significant effects on the free vibration dynamics of the cable network. The performance of the crosstie degraded more than 50% at several network modes, even though the equivalent frequency was reduced by only 10 to 15% in the nonlinear model. When the stochastic characteristics are considered, the mean value of the performance of the crosstie varied, even under the same level of nonlinearity, which is related to the tension in the cables and the pretension in the crosstie.

Ahmad (2013, 2014a, 2014b) extended the linear analytical procedure by considering the inherent damping of the stay cables and conducted a series of comprehensive parametric studies. The key parameters of the cable network were identified as the length ratio, mass ratio, mass-tension ratio, and frequency ratio, and the number of crossties and stay cables, and their effects on the free vibration of the cable network were investigated in detail. In addition, they proposed a new parameter, a degree of mode localization (DML) to evaluate the global nature of the cable network, and suggested to use softer crossties but a greater number of them along the entire cable to suppress localized vibration.

Through these studies, the mechanics of the cable network with single or several individual crossties were revealed, and the effects of different parameters, such as the length ratio, mass-tension ratio, and segment ratio, on the effectiveness of the crosstie have been investigated in detail. The drawbacks of the cable network with single or a few crossties (equal or less than four crossties) were also revealed, which might lead to potential deficiencies of local modal vibration. In addition, bridge aesthetics are seriously affected by crossties (Macdonald 2016, Raftoyiannis 2016), which, because of their large size required by the high stiffness, are obviously visible, even from far distances.

To overcome these drawbacks, this study proposes to replace the single or several individual big-size crossties with numerous small elastic crossties, distributed uniformly along the longitudinal direction. A new numerical method has been proposed to solve the free vibration of the cable-network system. The effectiveness of the proposed method is verified by comparing with the results by previous method proposed by Caracoglia (2005a, 2005b).

2. General problem formulations

Two stay cables linked by a plenty of uniformly distributed small elastic crossties (UDSEC) are simplified as two horizontally laid taut cables segmentally connected by continuously distributed springs, as shown in Fig. 1. The upper cable is assumed to be the target cable (Cable 1), which is prone to vibration under the external loads, whereas the lower one is regarded as its neighbor cable (Cable 2). They have different lengths, L_1 and L_2; mass-per-unit lengths, m_1 and m_2, and pre-tension in horizontal directions, T_1 and T_2, respectively. ΔL is the horizontal offset between the target cable and its neighbor. Both cables are fixed at both ends, and four nodes ($\mathbf{P}_{\mathrm{I}},\ \mathrm{I}=1,2,3,4$) separate the two stay cables into six segments. The segments are referred as the Element *j-p*; where *j* is the *j*th cable; and *p* is the *p*th segment of each cable. The *x* origin of the right element of each cable is defined at the right end to eliminate the unknown parameter in modal equation. The length of the Element *j-p* is denoted by $L_{j,p}$. The displacement of Element *j-p* is defined as $v_{j,p}$ according to the sub-coordinate $x_{j,p}$ (Fig. 1). The two central segments, $\mathbf{P}_1$ to $\mathbf{P}_3$ and $\mathbf{P}_2$ to $\mathbf{P}_4$, are orthogonally connected by J elastic crossties with intervals of l. The stiffness of the each elastic crosstie is k_e.....

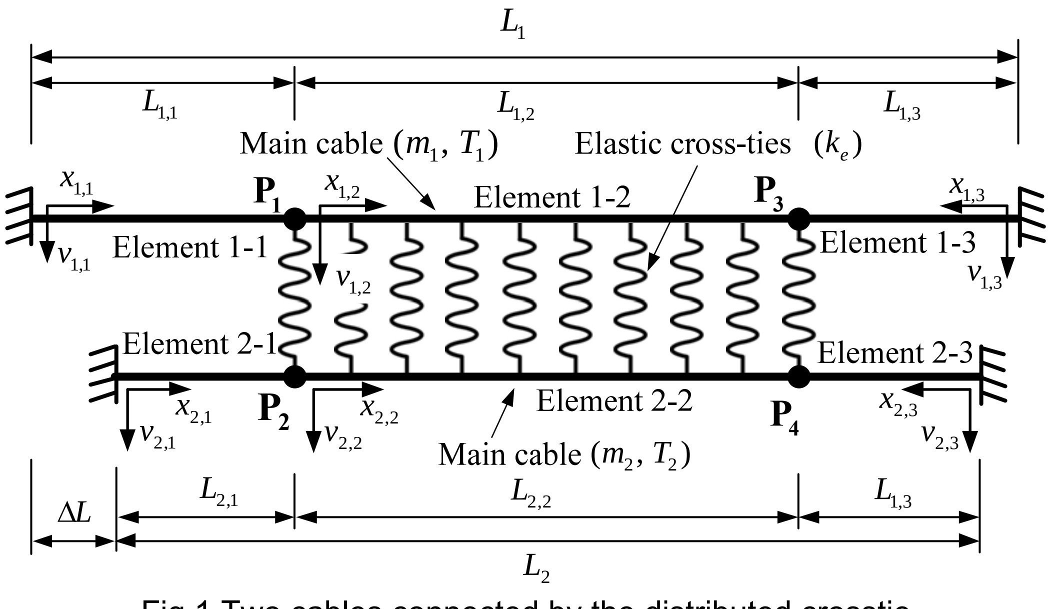


Fig.1 Two cables connected by the distributed crosstie

The stay cables are idealized as two taut cables because on the real cable-stayed bridges the stay cables are highly pre-stressed compared with their mass and elastic stiffness (Irvine 1971). They are extensible in the longitudinal direction, but the additional dynamic tension caused by the tension is neglected because it is of second order in the additional deflection. The vibrational amplitude of the stay cables is assumed to be small compared with their length; consequently, the linear theory is used when calculating the cable dynamic responses (Irvine 1971). Because the most dominant vibration of the stay cables has been observed in the in-plane transverse direction (He 2012), in this study only the vertical transverse vibration is considered in the mathematical model, and both the horizontal transvers vibration and the longitudinal vibration are not considered.

Since the number of the crossties is large, it is reasonable to simplify the UDSECs into a continuously distributed crosstie (CDC) to derive the solutions to the free vibration of this system, which is referred to CDC method hereinafter. The stiffness of the equivalent CDC is calculated as $k = k_e / l$ per unit length, in which, k_e is the stiffness of each elastic crosstie. The mathematical model of the cable-crosstie system is established as

$$m_j \ddot{v}_{j,p} - T_j v''_{j,p} = 0 \quad (j = 1,2;\ p = 1,3) \tag{1a}$$

$$\begin{cases} m_1 \ddot{v}_{1,2} - T_1 v''_{1,2} + k(v_{1,2} - v_{2,2}) = 0 & \text{(1b)} \\ s_m m_1 \ddot{v}_{2,2} - s_T T_1 v''_{2,2} + k(v_{2,2} - v_{1,2}) = 0 & \text{(1c)} \end{cases}$$

where $v_{j,p}$ is the vertical displacement of the Element *j-p*; the dimensionless parameter $s_m = m_2 / m_1$ is the mass ratio; and $s_T = T_2 / T_1$ is the tension ratio.

For the elements without UDSECs [Eq. (1a)], the cable displacement is expressed as Caracoglia (2005a, 2005b)

$$v_{j,p} = V_{j,p}(x_{j,p}) e^{i\omega t} \qquad (j = 1,2; \quad p = 1,3) \tag{2}$$

in which

$$V_{j,p}(x_{j,p}) = A_{j,p} \sin\left(\frac{\alpha\pi}{L_j} f_j x_{j,p}\right) \tag{3}$$

where $A_{j,p}$ is the unknown mode-shape coefficients determined by the boundary conditions, $\alpha = \omega / \omega_{01} = \omega \dfrac{L_1}{\pi}\sqrt{\dfrac{m_1}{T_1}}$ is the reduced frequency of the system, and $f_j = \sqrt{\dfrac{T_1}{T_j}\dfrac{m_j}{m_1}}$ is the ratio of the fundamental frequency of the 1st to the *j*th cable. Eq. (3) satisfies the boundary conditions of $V_{1,1}(0) = V_{1,3}(0) = V_{2,1}(0) = V_{2,3}(0) = 0$.

For the elements with UDSECs [Eq. (1b)], by using the Bernoulli-Fourier method, the cable displacement can be expressed as

$$\begin{cases} v_{1,2}(x,t) = V_{1,2}(x)e^{i\omega t} \\ v_{2,2}(x,t) = V_{2,2}(x)e^{i\omega t} \end{cases} \tag{4}$$

where $V_{1,2}, V_{2,2}$ are the mode shape of Element 1-2 and 2-2, respectively, and ω is the corresponding natural circular frequency.

By substituting Eq. (4) into (1b), the relationship between $V_{1,2}(x)$ and $V_{2,2}(x)$ is obtained as

$$\begin{aligned} a &= s_T T_1^2 \\ b &= (s_m \omega^2 m_1 - k)T_1 + (\omega^2 m_1 - k)s_T T_1 \\ c &= s_m m_1^2 \omega^4 - (1+s_m)m_1 k\omega^2 \end{aligned}$$

The general solutions of Eq. (6) is

$$V_{1,2}(x) = C_1 e^{r_1 x} + C_2 e^{r_2 x} + C_3 e^{r_3 x} + C_4 e^{r_4 x} \tag{7}$$

where $C_i \quad (i = 1,2,3,4)$ are unknown parameters determined by the boundary conditions, and $r_i \quad (i = 1,2,3,4)$ are the four roots of the characteristic equation of Eq. (6), which satisfy the following equation

$$ar^4 + br^2 + c = 0 \tag{8}$$

The four roots $r_i \quad (i = 1,2,3,4)$ are the function of ω.

The unknown parameters $A_{j,p}$ and C_i in Eqs. (3) and (7) are determined by the following boundary conditions:

$$\begin{cases} V_{1,1}(L_{1,1}) = V_{1,2}(0) \\ V'_{1,1}(L_{1,1}) = V'_{1,2}(0) \end{cases} \qquad 9(a)$$

$$\begin{cases} V_{1,2}(L_{1,2}) = V_{1,3}(L_{1,3}) \\ V'_{1,2}(L_{1,2}) = -V'_{1,3}(L_{1,3}) \end{cases} \qquad 9(b)$$

$$\begin{cases} V_{2,1}(L_{2,1}) = V_{2,2}(0) \\ V'_{2,1}(L_{2,1}) = V'_{2,2}(0) \end{cases} \qquad 9(c)$$

$$\begin{cases} V_{2,2}(L_{2,2}) = V_{2,3}(L_{2,3}) \\ V'_{2,2}(L_{2,2}) = -V'_{2,3}(L_{2,3}) \end{cases} \qquad 9(d)$$

Substituting Eqs. (3), (5), and (7) into (9) and rewriting it in matrix form gives

$$\mathbf{\Phi X} = \mathbf{0} \tag{10}$$

where

$$\mathbf{X} = \begin{pmatrix} A_{1,1} & A_{1,3} & A_{2,1} & A_{2,3} & C_1 & C_2 & C_3 & C_4 \end{pmatrix}^T \tag{11}$$

$$\mathbf{\Phi}=\begin{pmatrix} \sin(\phi_1 L_{1,1}) & 0 & 0 & 0 & -1 & -1 & -1 & -1 \\ 0 & \sin(\phi_{11} L_{1,3}) & 0 & 0 & -e^{r_1 L_{1,2}} & -e^{r_2 L_{1,2}} & -e^{r_3 L_{1,2}} & -e^{r_4 L_{1,2}} \\ 0 & 0 & \sin(\phi_2 L_{2,1}) & 0 & -K_1 & -K_2 & -K_3 & -K_4 \\ 0 & 0 & 0 & \sin(\phi_2 L_{2,3}) & -K_1 e^{r_1 L_{2,2}} & -K_2 e^{r_2 L_{2,2}} & -K_3 e^{r_3 L_{2,2}} & -K_4 e^{r_4 L_{2,2}} \\ \phi_1 \cos(\phi_1 L_{1,1}) & 0 & 0 & 0 & -r_1 & -r_2 & -r_3 & -r_4 \\ 0 & \phi_1 \cos(\phi_1 L_{1,3}) & 0 & 0 & r_1 e^{r_1 L_{1,2}} & r_2 e^{r_2 L_{1,2}} & r_3 e^{r_3 L_{1,2}} & r_4 e^{r_4 L_{1,2}} \\ 0 & 0 & \phi_2 \cos(\phi_2 L_{2,1}) & 0 & -r_1 K_1 & -r_2 K_2 & -r_3 K_3 & -r_4 K_4 \\ 0 & 0 & 0 & \phi_2 \cos(\phi_2 L_{2,3}) & r_1 K_1 e^{r_1 L_{2,2}} & r_2 K_2 e^{r_2 L_{2,2}} & r_3 K_3 e^{r_3 L_{2,2}} & r_4 K_4 e^{r_4 L_{2,2}} \end{pmatrix} \tag{12}$$

in which $\phi_1 = \dfrac{\alpha\pi}{L_1} f_1$, $\phi_2 = \dfrac{\alpha\pi}{L_1} f_2$ and $K_s = 1 - \dfrac{m_1\omega^2 + T_1 r_s^2}{k}$ $(s = 1,2,3,4)$.

The existence of the infinite set of nontrivial solutions ($\mathbf{X}$) to the homogeneous system (10) requires det[$\mathbf{\Phi}$]=0, through which the non-dimensional natural frequencies in terms of α are calculated. Since det[$\mathbf{\Phi}$]=0 is equivalent to det[$\mathbf{\Phi} - 0\mathbf{I}$]=0, the characteristic solutions of the homogeneous system should then be the eigenvectors with respect to the zero eigenvalues. This means that the solutions to the free vibration in the network system are transformed into the eigenvalue and eigenvector of the system $\mathbf{\Phi}$.

3 Numerical Procedure of Two General Cables with UDSECs

For two general cables with UDSECs, the closed-form solutions could not be generally identified for such a complex structure, consequently, a numerical procedure is developed and a case study is conducted in this Section.

The closed form solutions for det[$\mathbf{\Phi}$]=0 are too much complicated for two general cables with UDSECs. Therefore, a numerical procedure is developed to calculate the modal frequencies and mode shapes as follows:

Step 1: Give the desired maximum natural circular frequency ($\omega_{\max}$) and generate the vector of the circular frequency, $\boldsymbol{\omega}$, which varies from 0 to $\omega_{\max}$ with an interval of 10^{-4}, and the corresponding vector of reduced frequency, $\boldsymbol{\alpha} = \boldsymbol{\omega} / \omega_{01}$.

Step 2: Substitute $\boldsymbol{\omega}$ and $\boldsymbol{\alpha}$ into Eq. (12) and calculate the vector of det[$\mathbf{\Phi}(\omega)$].

Step 3: Define the frequency at the minimum det[$\mathbf{\Phi}(\omega)$] as the suspected natural circular frequency.

Step 4: Substitute the suspected natural circular frequencies into Eq. (12) one by one, and calculate the corresponding eigenvalues and eigenvectors of the matrix $\mathbf{\Phi}$.

Step 5: If there is a zero eigenvalue in Step 4, the suspected natural circular frequency is confirmed to be the natural circular frequency of this system and the corresponding eigenvector is determined to be the mode-shape coefficient; otherwise, go back to Step 4 and move on to the next suspected natural circular frequency.

The vector of the mode-shape coefficients ($\mathbf{X}$) is normalized such that

$$\sum_{j=1}^{2}\sum_{p=1}^{3}\int_{0}^{L_{j,p}} m_j V_{j,p}^2(x_{j,p})dx_{j,p} = 1. \tag{13}$$

4 A Case Study

An example of two stay cables [](AS20 and AS18 in Refs. Caracoglia (2005a, 2005b) of the Fred Hartman Bridge is applied to verify the effectiveness of the CDC method. The two stay cables are horizontally laid down and connected by 12 elastic crossties. The parameters of the cable-crosstie system are listed in Table 1. Cable AS20 is set as the target cable (Cable 1) with a total length of 140 m, mass of 70.1 kg/m, and horizontal extension of 3351 kN. Cable AS18 is set as the neighbor cable (Cable 2), which has a total length of 112 m, mass of 52.9 kg/m, and horizontal extension of 2732 kN. The horizontal offset between the two cables (ΔL) is set as 2.6 m. They are orthogonally connected by 12 UDSECs, with an interval (l) of 8.3 m, at the central 100 m of Cable 2. The modal frequencies and mode shapes of this system are first calculated with the multiple elastic crossties (MEC) method by Caracoglia (2005a, 2005b) and the proposed CDC method. The results are compared with each other.

Table 1. Parameters of the cable-crosstie system

m_1	70.1 kg	m_2	52.9 kg
T_1	3351 kN	T_2	2732 kN
L_1	140.0 m	L_2	112.0 m
$L_{1,1}$	8.6 m	$L_{2,1}$	6.0 m
$L_{1,2}$ $L_{2,2}$	100.0 m	$L_{2,3}$	6.0 m
$L_{1,3}$	31.4 m	ΔL	2.6 m
k_e	56.25 kN/m	k	6.75 kN/m^2

4.1 Modal frequencies and mode shapes

The natural circular frequencies are obtained as Fig. 2 shows, in which the horizontal coordinate is the circular frequency and the vertical logarithmic coordinate is det[$\mathbf{\Phi}(\omega)$]. The modal frequencies are identified at the minimum value of the curve of det[$\mathbf{\Phi}(\omega)$]. The natural circular frequencies obtained are then substituted into the matrix $\mathbf{\Phi}(\omega)$ and the eigenvalues and the corresponding eigenvectors are numerically solved by using the Matlab code “eig” (Mathworks 2009). The mode shape coefficient vector is identified as the eigenvector corresponding to the zero eigenvalue. Finally, by substituting the elements of the mode-shape coefficient vector into the mode-shape function [Eqs. (3), (5), and (7)] with additional normalizing, the mode shapes are obtained.

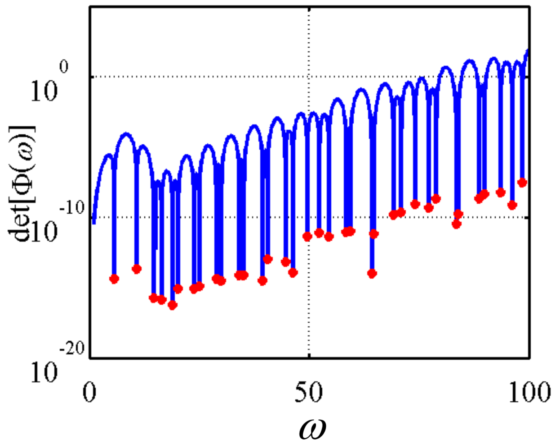


Fig. 2 Calculation of the natural circular frequency

Table 2 summarizes the first 27 modal frequencies obtained by the proposed CDC and previous MEC methods. The results show that the modal frequencies from the two methods are in good agreement; in particular, for the fourth and higher modal frequencies, the differences are less than 1.0%. For the first three modal frequencies, the results obtained by using the CDC method are higher than those of the MEC method by approximately 2.1% to 3.7%. The difference between those two methods may be caused by the gap ratio, which will be discussed later.

Table 2. Modal frequencies.

Mode	Frequency (Hz)			Mode	Frequency (Hz)		
no.	MEC	CDC	Diff. (%)	no.	MEC	CDC	Diff. (%)
1	0.8763	0.8981	2.48	15	7.0869	7.0977	0.15
2	1.6482	1.7096	3.73	16	7.3591	7.3695	0.14
3	2.2829	2.3314	2.13	17	7.8736	7.8896	0.20
4	2.5871	2.6103	0.90	18	8.3202	8.3285	0.10
5	2.9974	3.0083	0.36	19	8.6621	8.6698	0.09
6	3.2039	3.2151	0.35	20	9.2974	9.3063	0.10
7	3.7697	3.7859	0.43	21	9.4404	9.4484	0.08
8	3.9625	3.9762	0.35	22	10.2090	10.2243	0.15
9	4.5624	4.5923	0.65	23	10.2854	10.2993	0.14
10	4.7712	4.7824	0.24	24	10.9939	11.0062	0.11
11	5.4115	5.4325	0.39	25	11.2725	11.2930	0.18
12	5.5963	5.5971	0.01	26	11.7817	11.7845	0.02
13	6.2781	6.2809	0.04	27	12.2580	12.2922	0.28
14	6.4425	6.4506	0.13	--	--	--	--

Fig. 3 shows the first 27 mode shapes calculated using the CDC and MEC methods. Comparison of the results shows that the mode shapes obtained using the two methods are very close to each other. There is no local mode in the first 27 modes, which means this system successfully avoid the “mode localization” that appears in single- or multiple-cross-tie systems Caracoglia (2005b).

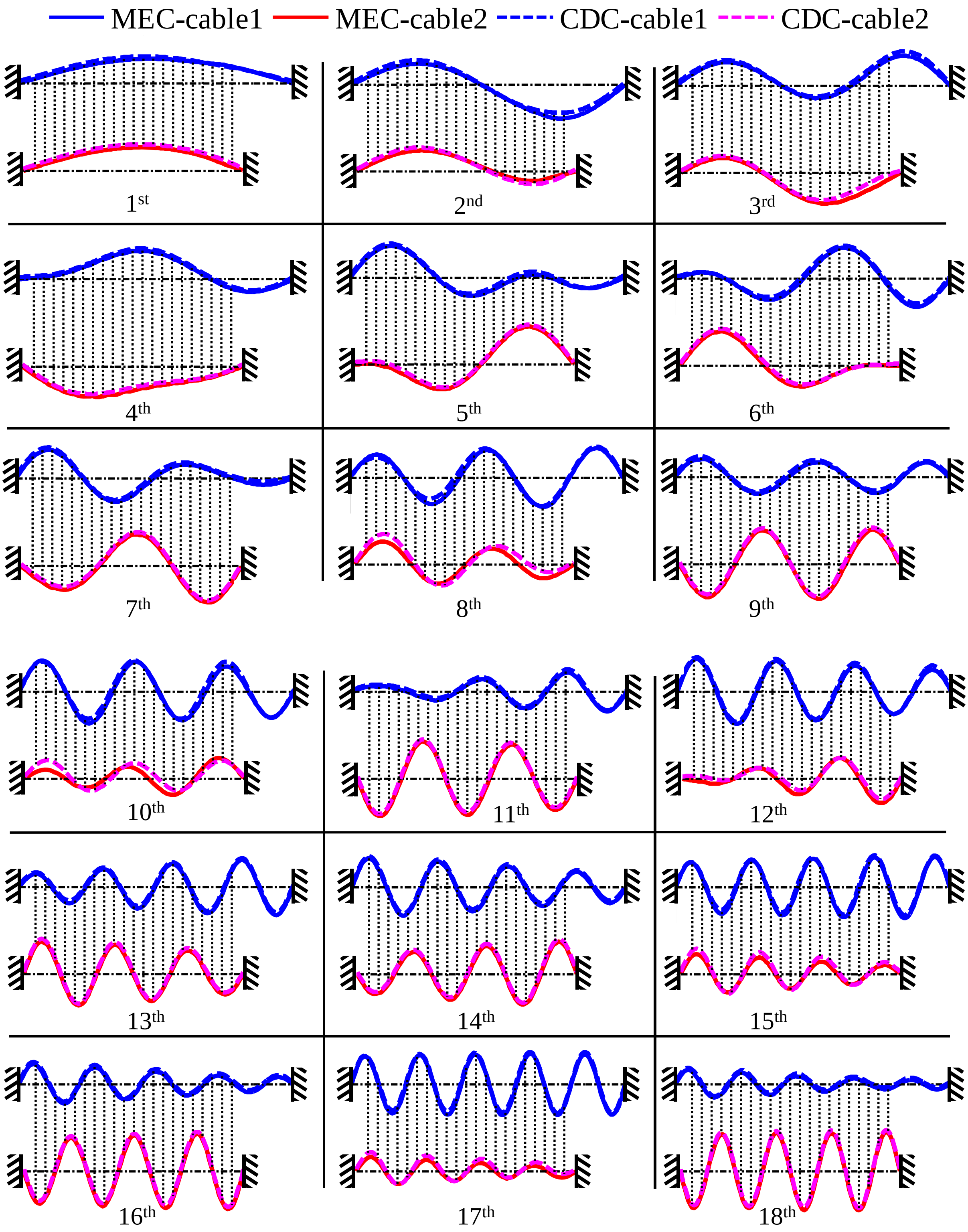
4.2 Effects of the gap ratio using the MEC method

The CDC method simplified the UDSECs into a continuously distributed crosstie, which means that the small elastic cross-ties are further divided into tiny elastic crosstie uniformly distributed along the cable axis with an interval of zero. The interval might have effect on the accuracy of the proposed CDC method. In this subsection, the interval is non-dimensionalized as gap ratio (S_r), which is defined as the length ratio between the interval distance and the total length of the segment restrained by the crossties:

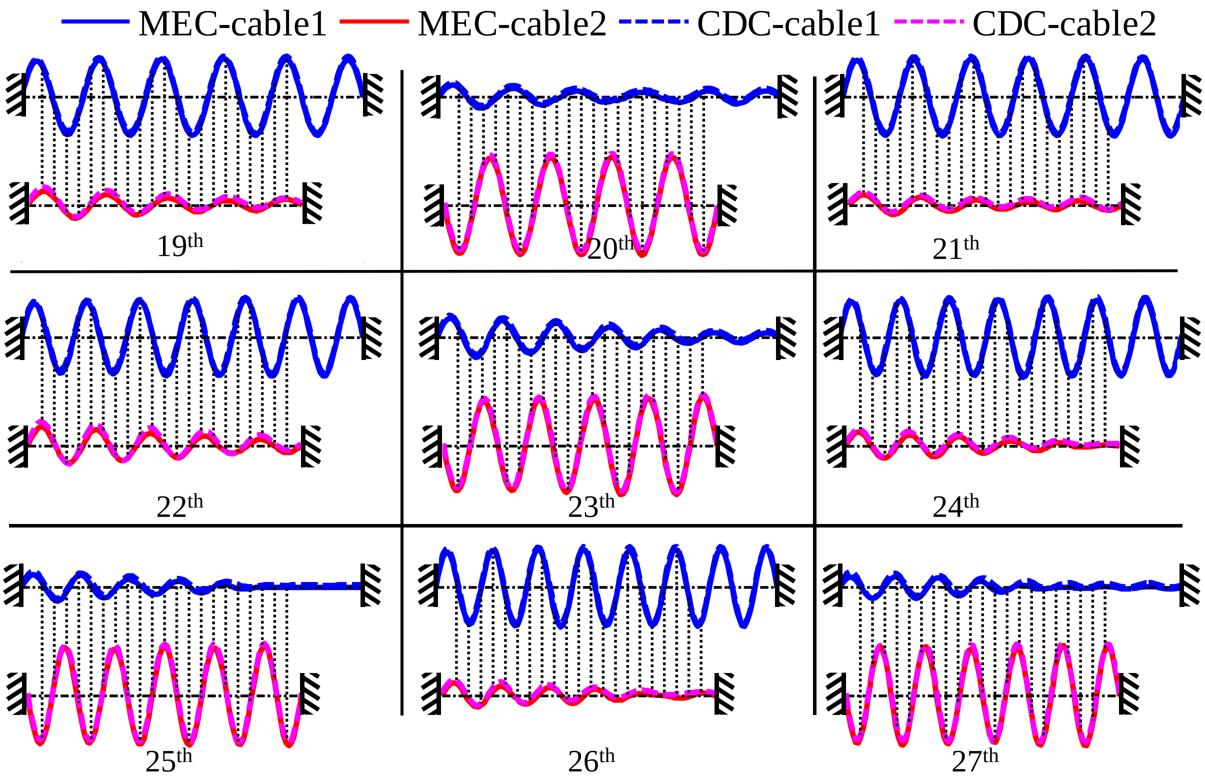
$$S_r = \frac{l}{L_{1,2}} \tag{14}$$

The effect of the gap ratio is investigated by changing the number of crossties, the interval, and the corresponding stiffness of each crosstie to check whether the gap ratio is the reason for the differences in the first three modal frequencies between the two methods or not. In this process, the total stiffness of all of the elastic crossties is ensured to be the same.

Five cases (S_r=7.1%, 8.3%, 10.0%, 12.5%, and 16.7%) are calculated using the MEC method. It is worth to note that when the gap ratio is 7.1%, only the first 12 modal frequencies are calculated because the determinant of the system's matrix exceeds the capacity of a 64-bit computer for the higher modes. Besides, if the gap ratio is smaller than 7.1%, the calculation of the determinant of the system's matrix becomes difficult because the size of the matrix is too large. The modal frequencies of the first 27 modes are shown in Fig. 4. In general, the gap ratio has very small effect on the modal frequencies, and the differences in the modal frequencies of the higher modes among these lower-gap-ratio cases are less than 1.0%. However, there are indeed small differences among the five cases in the lower modes.



(a) 1st to 18th modes



(b) 19^{th} to 27^{th} modes

Fig. 3 Mode shapes of the first 27 modes

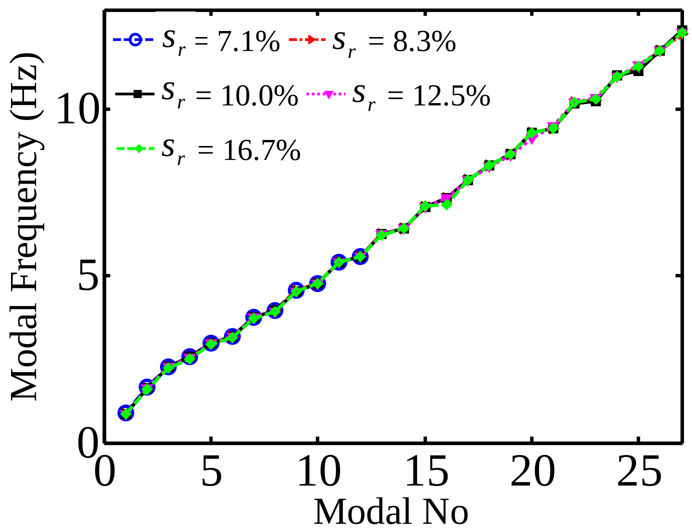
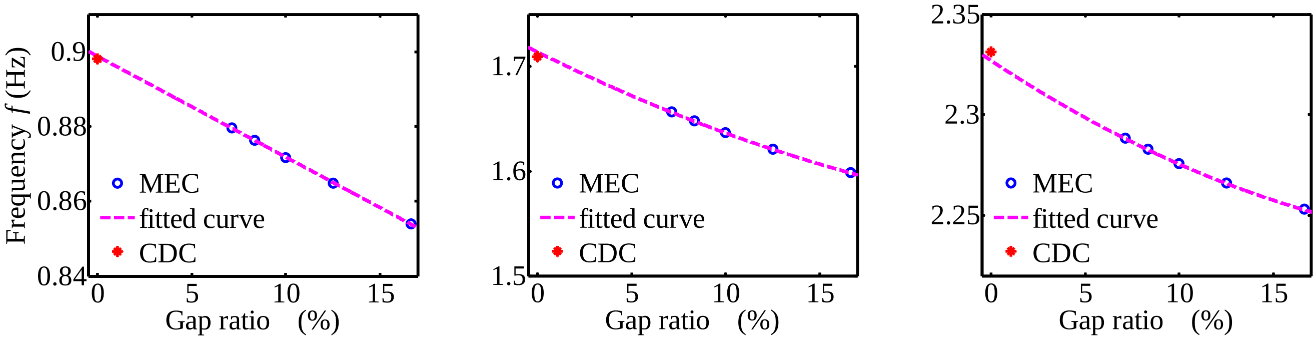


Fig. 4 Effect of gap ratio on the modal frequencies

Fig. 5 shows the calculated modal frequencies of the first three modes, which decrease by 2.9%, 3.5%, and 1.6%. For comparison, the modal frequencies calculated using the CDC method, representing the zero gap ratio, are also marked in this figure.

It is obvious that when gap ratio becomes smaller, the modal frequencies calculated using MEC method get close to that using CDC method. Besides, the calculated modal frequencies obviously decrease as the gap ratio increases. Therefore, the modal frequencies of the five MEC cases are fitted using the first- or second-order polynomial. The results show that the modal frequencies calculated with the CDC method are very close to the fitting curves. The largest difference is less than 0.3%. This result confirms that the difference between the two methods is caused by the gap ratio and the gap ratio effect can be estimated by the fitting curve. Moreover, when the gap ratio is small, the CDC method can precisely predict the modal frequencies of the cable-crosstie system.



(a) 1st Mode (b) 2nd Mode (c) 3rd Mode

Fig. 5 Modal-frequencies vary with gap ratio

5 Conclusions

In the present study, UDSECs are suggested to replace the traditional single or several crossties to avoid the “mode localization”. A new method, referred to as the CDC method, has been proposed to calculate the free vibration of the new cable-crosstie system. A numerical procedure has been developed to calculate the modal frequencies and mode shapes of two general cables with UDSECs. The effectiveness of the proposed CDC method is verified by comparing the results of the CDC method with that of the MEC method. The main conclusions are as follows:

(1) The proposed CDC method is effective in calculating the free vibration of two stay cables interconnected by UDSECs.
(2) Replacing single or several individual crossties with a numerous small elastic crossties is an effective method for preventing “mode localization”.
(3) The modal frequencies and mode shapes of two-general cable-UDSECs system are complicated, which should be studied in detail in the future.

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