Determining Cable Tensions of Cable Stayed Bridge Considering Viscous Damping

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***Abstract* - Determining cable tension in long-span structures as cable-stayed bridges is necessary for inspection and structural health monitoring. The one of solutions for this problem is vibration measurement. However, it may not be accurate when parameters such as the sag, damping, and bending rigidity of cable are significant. On this page, the differential equation for the cable vibration is taken into account, including damping and bending rigidity in the cables. Then, assumptions of boundary conditions are simplified and expressions showing the relationship between frequency and tension are obtained. A practically applied procedure to determine cable tension through measured frequencies is proposed. The proposed procedure is verified by some cables of the Phu My bridge in Ho Chi Minh City.**

Keywords: cables, tension, damping, flexure, natural frequency

1 INTRODUCTION

The first Tacoma Narrows Bridge was collapsed (on November 7, 1940), which had had lasting effects on applied science and engineering. Much attention has been given to the dynamic behavior of long-span bridge structures and another structure, an understanding of the damping capacity of these light and unstable structures has gained increased importance.

Over the past 50 years, construction technology of cable-stayed bridge has developed very rapidly. Due to the later development and the terrain with many large rivers, East and Southeast Asia has become the place with the largest number of cable-stayed bridges.

At the present, there are very few research projects on cable-stayed bridge cable tension based on vibration frequency. Some previous domestic studies include: Tran Ba Canh (2014) compared the effectiveness and accuracy of several methods of determining cable tension of cable-stayed bridges by indirect methods using natural vibration frequencies, and applying practically to estimate the determination of cable tension for Nguyen Van Troi and Tran Thi Ly cable-stayed bridge in Viet Nam [1]. Nguyen Thanh Chung et al (2015) surveyed practically the six cable tension determination methods using natural vibration frequency [2].

In the world, researchers have conducted more experimentally to have numerous real data, which helps them publish a variety of different reports. In 1999, Cunha, A. and Caetano, E. published Dynamic Measurements On Stay Cables Of Cable-Stayed Bridges Using An Interferometry Laser System [3]. Dynamic Analysis Of Cables With Variable Flexural Rigidity was publicized by Zhong, Min. and et al (2003) [4]. Hoang Nam and Fujino (2008) studied and analyzed the influence of flexural stiffness in cable-stayed bridge cables with joint and mount connections at both ends [5]. Hoang Nam et al (2011) considered an inclined tensioned cable connecting the clamps at both ends of the cable anchorage and took into account the simultaneous effects of cable slack and flexural stiffness of the cable with the asymptotic equations [6]. Huang, Yong-Hui, et al (2015) wrote Unified Practical Formulas for Vibration Based Method of Cable Tension Estimation [7], ect.

A cable-stayed bridge, one of the most modern bridges, consists of a continuous beam with one or more pillars in the middle of the span. From these piers, cables are attached diagonally to the girder to provide additional support. The typical cable-stayed bridges have a low center of gravity which makes them strong against earthquakes, but at the same time makes them vulnerable to the uneven sinking of the ground. Triangles are one of the shapes used for the attachment of the cables and the beams, this shape is used because of its ability to transfer the tension as the moving load goes across the bridge. In this bridge, the distance of the cable up the tower is equal to the distance from the tower to the connection point on the beam and is at a 90-degree angle. Cables are stretched diagonally between these pillars and the beam. These cables supported the beam are anchored in the pillar. Cables are extremely well suited for axial tension; however, are weak against compression and bending forces. As a result, cable-stayed bridges, though strong under normal traffic loads, are vulnerable to the forces of winds. Special methods are taken to reduce that the bridge does not vibrate or sway under heavy winds [8].

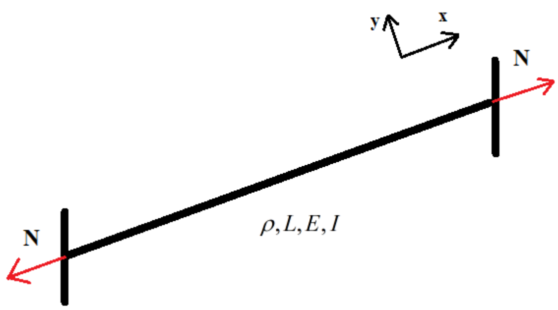

Fig. 1. A model of an inclined cable

2 General Equations of the Cables

A cable model is presented where the cable is modeled as a string or a beam with multiple boundary constraints and axial force (shown in Figure 1). The cable tension has an incorporated variety of damping mechanisms. Moreover, there is no external damper, and only energy dissipation occurs through the second order differential equation of material viscous damping. In this case, viscous damping is considered with friction forces between individual strings, which is difficult and computationally intensive. [4]

The cable is modeled as a very long beam with flexural rigidity varying with space and time. The assumptions are followed as: [4]

◦ Plane sections of each string remain plane after deformation, although the transverse section of the cable is allowed to warp as strings slip.

◦ The string material is homogeneous, isotropic, and linearly elastic.

◦ Shear deformation and Poisson's effect are neglected.

◦ Cable strain is small though the displacement and rotation can be large.

◦ No external dampers are used. Internal damping is governed by static friction only, and kinetic friction is neglected. This assumption overestimates cable damping.

◦ Two ends of the cable have the simple supports

2.1. Model string with viscous damping

To develop the cable model, a cable element is modeled as shown in Figure 1. Mechanical systems include an inclined cable under tension force N, a coordinate system is defined with the x-axis along the cable chord and the y-axis in the perpendicular direction. The cable has a mass per unit length, a length L, and viscous damping c. The dynamic equation of the cable vibration u(x, t) (in the y-direction) is expressed below: [9]

$$\rho\frac{\partial^2 u(x,t)}{\partial t^2} = N\frac{\partial^2 u(x,t)}{\partial x^2} - c\frac{\partial u(x,t)}{\partial t} \qquad (1)$$

Where: ρ is the cable length mass density, length per mass (kg/m); N is the cable tension, is constant with position (N or kN); c is the viscous damping coefficient (N.s/m) [9].

Using the classical Sturm-Liouville method to separate $u(x,t) = W(x).T(t)$ [10]

After that, the solution of the differental equations, is given as:

$$\begin{cases} W(x) = C_1 e^{\frac{\omega}{a}x} + C_2 e^{\frac{-\omega}{a}x} & \text{(a)} \\ T(t) = D_1 e^{\frac{t}{2}\left(\sqrt{k^2-4\omega^2}-k\right)} + D_2 e^{\frac{-t}{2}\left(\sqrt{k^2-4\omega^2}-k\right)} & \text{(b)} \end{cases} \qquad (2)$$

Where: the constants C_1 to C_2 are to be determined from the boundary conditions of this model; the constants D_1 to D_2 are ignored.

Solving the differential equation (2a), the boundary condition of cable is simply supported at both the ends. At each end $(x = 0, x = l)$, the deflection $W(x)$ and the curvature $W''(x)$ are zero. [10]

$$W(x) = 0;\ \frac{d^2W(x)}{dx^2} = 0 \qquad (3)$$

$$\Rightarrow N = \rho\left(\frac{2L}{n}f_n\right)^2 \qquad (4)$$

In (2b), We can survey characteristics variety of the formed vibration through time. [10]

$$\left(\frac{c_c}{\rho}\right)^2 - 4\omega_n^2 = \Delta \tag{5}$$

$$\Rightarrow c_c = 2\omega_n^2 \rho \tag{6}$$

The damping factor [10]

$$\zeta = \frac{c}{c_c} = \frac{c}{2\omega_n \rho} = \frac{c}{4\pi f_n \rho} \tag{7}$$

Because of viscous damping, measured frequency is damping frequency f_d. It's a necessary to change damping frequency to natural frequency; from vibration theory, as desired:

$$\omega_d = \omega_n \sqrt{1-\zeta^2} \tag{8}$$

$$f_d = f_n \sqrt{1-\left(\frac{c}{4\pi f_n \rho}\right)^2} \tag{9}$$

This is the tension equation through natural frequency. This calculating formula is applied to calculate the tension of cable-stayed bridge in order to inspect the working situation for structural bridge also else viscous damping cable model.

Moreover, the viscous damping coefficient can be determined as below:

$$c = (4\pi\rho)\sqrt{f_d^2 - f_n^2} \tag{10}$$

In the next subsection, a model has been expanded from string model with more material coeffect, expected to determine exactly the tension of cables than the previous model.

2.2. *Model beam with viscous damping*

To expand the string model, the beam model has been studied. The cable has a mass per unit length m, a length L, a finite flexural rigidity EI, and the sag has been ignored. The differential equation of the cable vibration u(x, t), is defined by:

$$EI\frac{\partial^4 u(x,t)}{\partial x^4} - N\frac{\partial^2 u(x,t)}{\partial x^2} + \rho\frac{\partial^2 u(x,t)}{\partial t^2} + c\frac{\partial u(x,t)}{\partial t} = 0 \tag{11}$$

Where: ρ is the cable length mass density, length per mass (kg/m); N is the cable tension (N); c is viscous damping effect (N.s/m); E is Young's modulus (N/m^2); I is inertia (m^4)

Repeat the Sturm-Liouville method of separation of variables is used to find the solution of $u(x,t) = W(x).T(t)$. After that, the answer of the differental equations, is given as: [10]

$$\begin{cases} W(x) = C_1 e^{s_1 x} + C_2 e^{-s_1 x} + C_3 e^{s_2 x} + C_4 e^{-s_2 x} & \text{(a)} \\ T(t) = D_1 e^{\frac{t}{2}\left(\sqrt{k^2-4\lambda}-k\right)} + D_2 e^{\frac{t}{2}\left(\sqrt{k^2-4\lambda}+k\right)} & \text{(b)} \end{cases} \tag{12}$$

Where: the constants C_1 to C_4 are to be determined from the boundary conditions of this model; the constants D_1 and D_2 are to be ignored. The value of s_1, s_2 can be given by:

$$s_1;\ s_2 = \sqrt{\frac{N}{2EI} \pm \sqrt{\left(\frac{N}{2EI}\right)^2 + \frac{\rho\omega_n^2}{EI}}} \tag{13}$$

Solving the differential equation (12a), the simply supported boundary condition is used. At each end , the deflection and the curvature are zero.

$$W(x) = 0;\ \frac{d^2W(x)}{dx^2} = 0 \tag{14}$$

When (6) are used in the solution,

$$\sinh s_1 L \sin s_2 L = 0 \tag{15}$$

Due to $S_1L > 0$, the equation was given by:

$$s_2 L = n\pi;\ \text{n}= 1, 2, 3, \ldots \tag{16}$$

After that, equations (13) and (16) yield the tension equation of cable through natural frequency, as shown:

$$\frac{N}{2EI} \pm \sqrt{\left(\frac{N}{2EI}\right)^2 + \frac{\rho\omega_n^2}{EI}} = \left(\frac{n\pi}{L}\right)^2 \tag{17}$$

$$N = \rho\left(\frac{2Lf_n}{n}\right)^2 - EI\left(\frac{n\pi}{L}\right)^2 \tag{18}$$

In equation (12.b), We can survey characteristics variety of the formed vibration through time.

$$\left(\frac{c_c}{\rho}\right)^2 - 4\omega_n^2 = \Delta \tag{19}$$

$$\Rightarrow c_c = 2\omega_n \rho \tag{20}$$

The critical damping factor

$$\zeta = \frac{c}{c_c} = \frac{c}{2\omega_n \rho} = \frac{c}{4\pi f_n \rho} \tag{21}$$

Because of viscous damping, measured frequency is damping frequency. It's a necessary to change damping frequency to natural frequency; vibration theory has provided the same (8), as desired: [10]

$$f_d = f_n \sqrt{1-\frac{c^2}{(4\pi f_n \rho)^2}} \tag{22}$$

Moreover, viscous damping coefficient can be determined as below: [10]

$$c = (4\pi\rho)\sqrt{f_d^2 - f_n^2} \tag{23}$$

It is necessary to apply these calculating formulas for structural health monitoring, determined cable tension and compare with designed technical standard.

3 CALCULATING APPLICATION

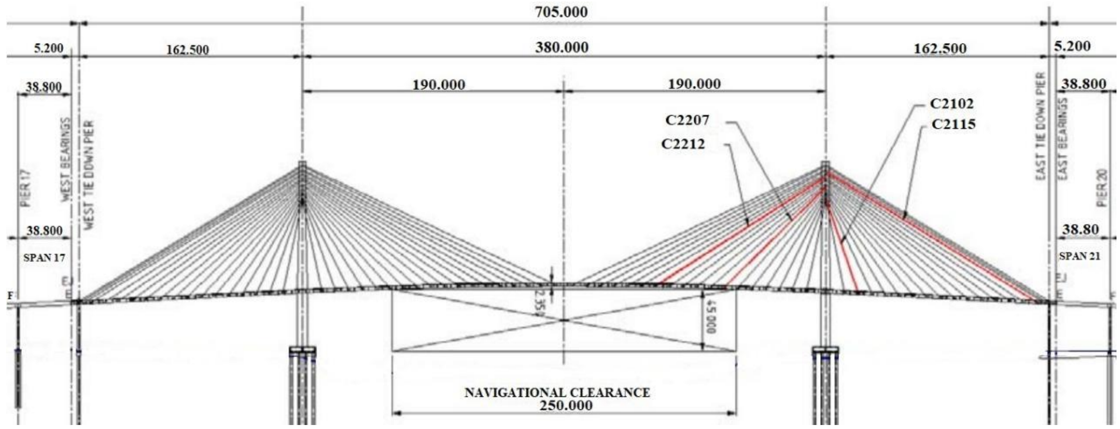

Fig. 2. The Phu My Bridge sketch [6]

For the experimental analysis, measurement data were collected from a Phu My Bridge, which is one of the cable-stayed bridges in Ho Chi Minh City. The main span of the bridge is 380 m, with 16 m deck width, 90 m pylon height. The cable system here includes 36 cables in multi-fan type. These cables are of Freyssinet mono strand which consists of a group of parallel individually protected type S15 strands by HDPE material (high density polyethylene material). The length of cables varies from 60 to 202 m. The properties of the typical 4 cables selected for this study, named C2102, C2212, C2207, and C2115, are given in table 1. Using the data in this table, the curves relating the tension and natural frequencies of cables.

In March 2022, an experimental measurement has been conducted for the stay cables of Phu My Bridge under usual weather conditions. The cables were excited by traffic conditions, then free vibration with damping string was recorded by accelerometer. The purpose of the test is to estimate the cable tension through natural vibration frequency to design the calculating tension cable procedure with viscous damping; moreover, the result can make use of a structural health monitoring of the Bridge.

For the four cables considered in this study, The modal frequencies from the measured data are presented in Figures 3 to Figure 6. Marking these measured frequencies on the corresponding curves in Figure 7, the tension which fits all considered modes can be recognized and its value is shown in Table 4 to Table 7, as below:

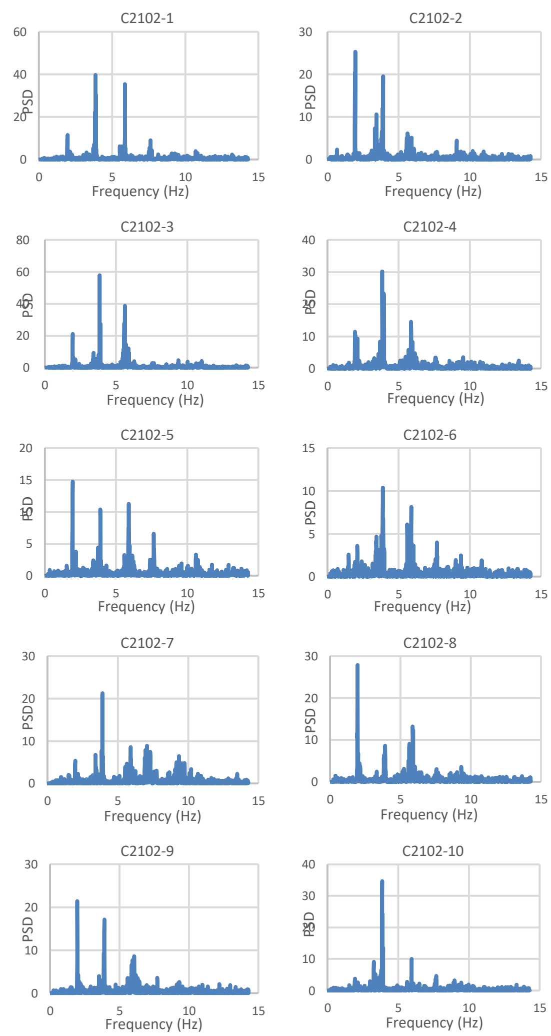

Fig. 3. Periodogram of C2102 Cable

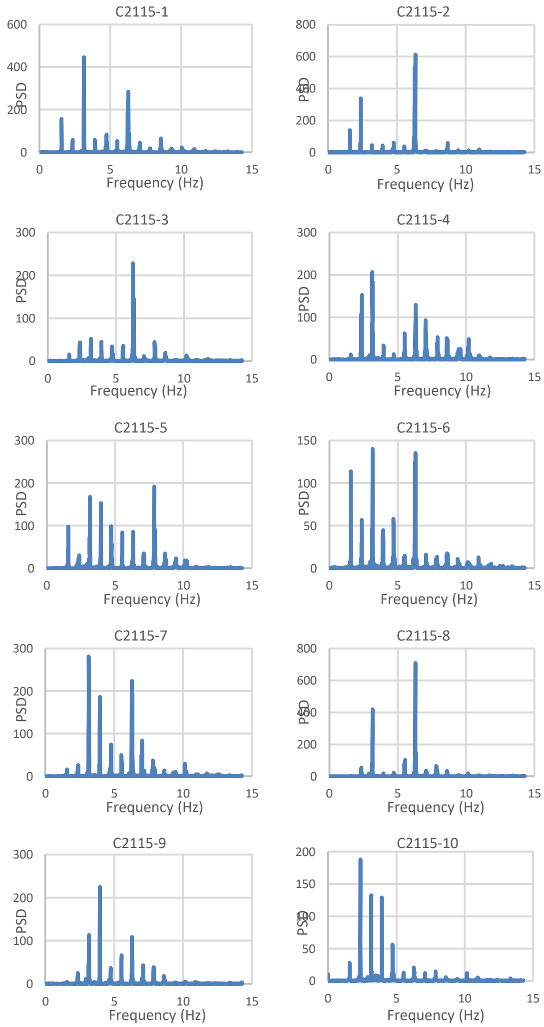

Fig. 4. Periodogram of C2115 Cable

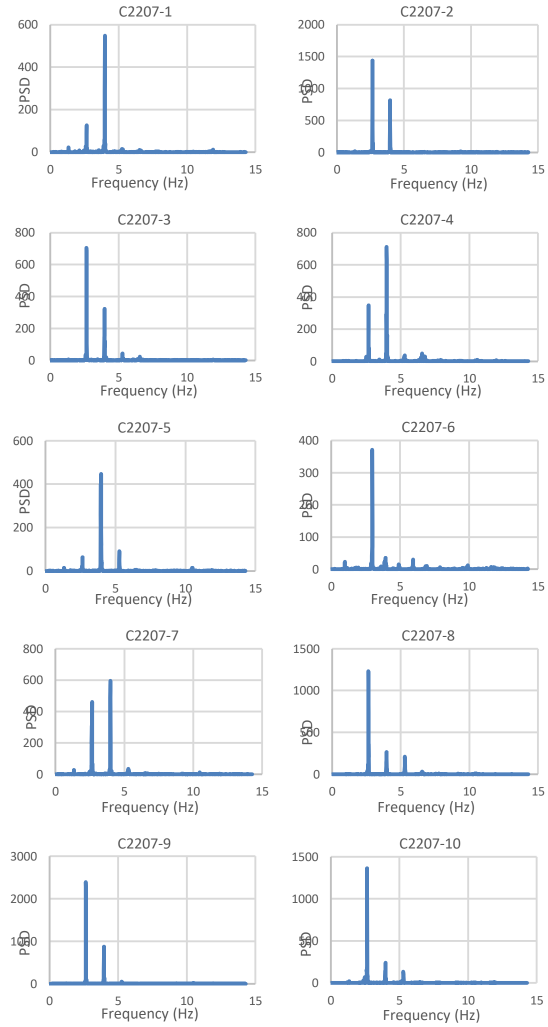

Fig. 5. Periodogram of C2207 Cable

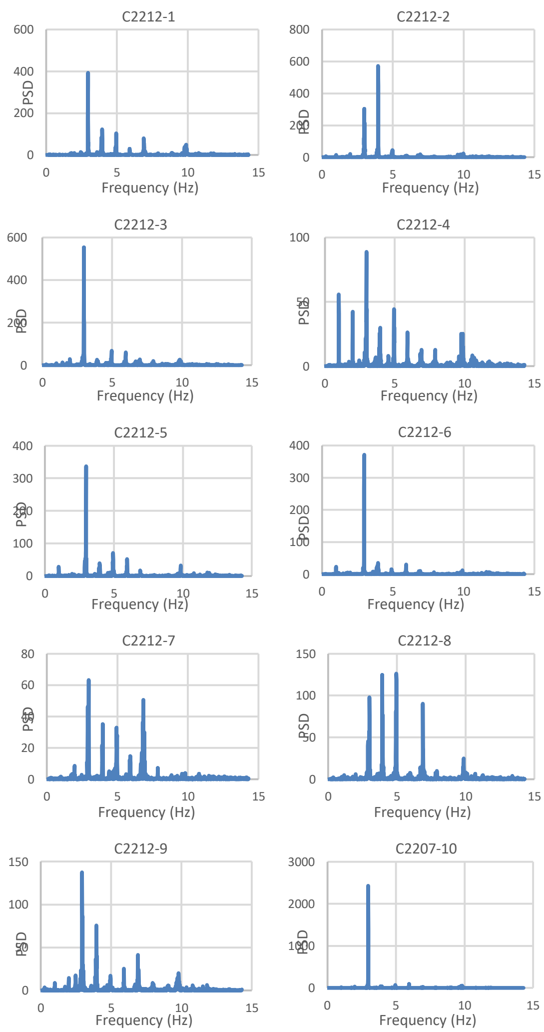

Fig. 6. Periodogram of C2212 Cable

TABLE 1 CABLES' PROPERTIES [6]

Cable No	Outer dia	Cable weight	Inertia	Length	Young Modulus
	m	kg/m	m^4	m	N/m^2
C2102	0.160	31.86	8.363×10^{-6}	68.1327	1.97×10^{11}
C2115	0.200	60.18	2.468×10^{-5}	177.1652	
C2207	0.180	41.3	1.372×10^{-5}	101.2186	
C2212	0.200	53.1	2.178×10^{-5}	148.1245	

3.1. *Determining tension cable with string model*

The first step to estimate the cable tension is using formula (9) to determine natural frequencies from measured damping frequencies by ignoring the influence of damping in vibration. Then, Equation. (4) is used to estimate cable tension . Finally, the damping coefficients are also determined in Table 2.

TABLE 2
THE VISCOUS PARAMETER FOR CABLES OF STRING MODEL (N.S/M)

Repeat	C2102	C2115	C2207	C2212
1st	3.511	141.81	154.0	668.837
2nd	0.822	142.498	89.587	140.375
3rd	4.038	246.912	89.236	139.784
4th	2.741	199.985	199.45	198.311
5th	3.977	10.988	154.067	171.480
6th	3.107	200.511	87.904	198.311
7th	1.174	320.037	154.067	197.598
8th	5.107	658.576	88.912	297.012
9th	2.633	138.798	501.814	172.004
10th	1.655	99.858	125.970	10.851

After calculating to the final result, the cable tensions have been performed in figure 7, in the follow:

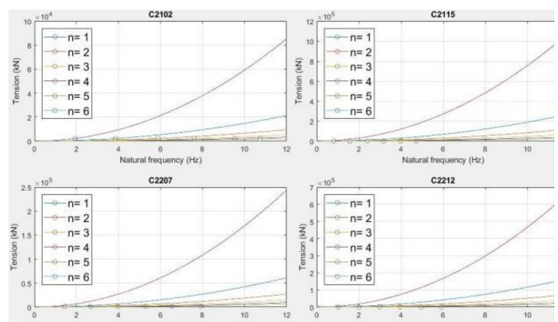

Fig. 7 Relationship between tension and natural frequencies for stay cables of the Phu My Bridge (string model)

3.2. *Determining tension cable with beam model*

Similarly, the previous step of string model has been solved, this specific model has a flexural rigidity. However, critical damping hasn't changed (as shown), the adapted frequency function has the same as its string model. The viscous effect also determines during calculating as:

TABLE 3
THE VISCOUS PARAMETER FOR CABLES OF BEAM MODEL (NS/M)

Repeat	C2102	C2115	C2207	C2212
1st	309.376	141.809	154.000	668.836
2nd	310.916	142.498	89.587	140.375
3rd	184.984	246.912	89.236	139.784
4th	285.918	199.985	199.450	198.311
5th	371.048	10.988	154.067	171.480
6th	287.615	200.511	87.904	198.311
7th	759.088	320.037	154.067	197.598
8th	468.455	658.576	88.912	297.012
9th	262.795	138.798	501.814	172.004
10th	165.530	99.858	125.970	10.851

Repeating the process to estimate the tension cable, was also given in tables. The cable tensions have been performed in figure 8, as shown:

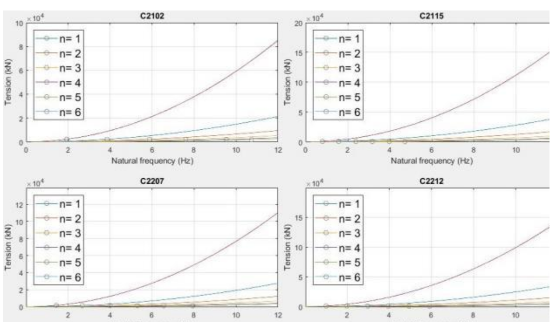

Fig. 8 Relationship between tension and natural frequencies for stay cables of the Phu My Bridge (beam model)

3.3. *Discussion*

The average tension for each cable, compared to the formula without damping (Cunha et al 1999) [3], was given in Table 4 to Table 7 below:

TABLE 4 TENSION CABLE OF C2102 (KN)

	String	Beam	By Cunha et al
1st	2114.5028	2061.3767	2136.3514
2nd	2089.1928	2036.0668	2121.3181
3rd	2111.1458	2058.0198	2126.9751
4th	2136.0897	2082.9636	2141.8908
5th	2160.0938	2106.9677	2168.8064
6th	2171.2454	2118.1193	2218.6820
7th	2084.6145	2031.4884	2106.1388
8th	2124.7597	2071.6336	2144.0607
9th	2168.2587	2115.1327	2188.3609
10th	2066.2992	2013.1731	2099.8248

TABLE 5 TENSION CABLE OF C2115 (KN)

	String	Beam	By Cunha et al
1st	5086.5516	5063.3646	4686.4236
2nd	4840.8707	48176837	4818.9164
3rd	4852.2577	4829.0707	4756.2468
4th	4774.4564	4751.2695	4742.3661
5th	4725.0613	4701.8743	4863.4096
6th	4778.8286	4755.6416	4688.6013
7th	4927.1529	4903.9659	4839.4637
8th	5280.6936	5257.5066	4960.4610
9th	4730.0680	4706.8810	4937.6832
10th	4741.0949	4717.9079	5043.4832

TABLE 6 TENSION CABLE OF C2207 (KN)

	String	Beam	By Cunha et al
1st	2948.4338	2908.9436	2953.1772
2nd	2969.6423	2930.1521	2966.5276
3rd	2946.8742	2907.3839	2953.9567
4th	2983.3817	2943.8915	3051.3292
5th	2954.6121	2915.1219	2948.6115
6th	2983.6591	2944.1689	2991.1609
7th	2972.2028	2932.7126	2972.4261
8th	2950.6443	2911.1541	3035.5841
9th	3248.0257	3208.5355	2980.5743
10th	2975.4512	2935.9610	2971.4397

TABLE 7 TENSION CABLE OF C2212 (KN)

	String	Beam	By Cunha et al
1st	4483.4200	4454.1475	4429.8888
2nd	4623.0114	4593.7389	4630.6541
3rd	4564.6531	4535.3806	4572.2474
4th	4570.1993	4540.9268	4582.1944
5th	4588.8661	4559.5935	4592.1581
6th	4570.6423	4541.3697	4582.6373
7th	4571.4001	4542.1276	4575.7851
8th	4579.8397	4550.5672	4586.3457
9th	4563.6488	4534.3763	4573.4830
10th	4589.2167	4559.9442	4595.7602

The difference between the two models, which is flexural rigidity, has been studied and calculated. The tension value conform also with the values calculated using the formula in Cunha et al. (1999), given in the last column of Table 4 to Table 7. It is necessary to study more about parameters to decrease minimized error in these models.

4 CONCLUSION

During this study, two mechanical models describing the overall damping properties of a cable, established as a one-dimensional continuum system, included the string and beam model. A simplified cable vibration model is developed to determine cable damping and tension. The equation of motion governing the cable vibration is derived from the partial differential equation concerning the cable and time. By using proper simplifying approximation model for the cable's equations of motion have been explicitly obtained and their accuracy is compared. It renders a practically applicable procedure to determine cable tension using measured frequencies. The developed procedure has been verified by realistic data of Phu My Bridge in Vietnam. (the errors do not exceed 10 % in all cases)

The results indicated that the proposed formulas can be used to determine tensions accurately for each long or short cables. From the results on this page, this method has a broad range of applications. However, the application of this study for reality needs more tests by experiment and simulation in future studies.

CONFLICT OF INTEREST

An Huynh Thai, Hung Nguyen-Quoc, Toan Pham-Bao, Luan Vuong-Cong, Cong Hoa Vu declare that they have no conflict of interest.

CONTRIBUTORS

An Huynh Thai, Hung Nguyen-Quoc, Luan Vuong-Cong and Toan Pham-Bao processed the corresponding data. An Huynh Thai wrote the first draft of the manuscript. Toan Pham-Bao designed the research and helped to organize, revise and edit the manuscript. Cong Hoa Vu is the supervisor, contributes ideas for the proposed method and also takes part in checking the data and simulation results and manuscript .

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Xác Định Lực Căng Của Cáp Cầu Dây Văng Xét Đến Giảm Chấn Nhớt

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Tóm tắt
Việc ước tính sức căng của dây cáp trong cầu dây văng hoặc các kết cấu dây cáp khác là cần thiết để kiểm tra và theo dõi sức khỏe kết cấu. Giải pháp cho vấn đề này là đo độ rung; tuy nhiên, nó có thể không chính xác trong trường hợp các thông số như độ võng, giảm chấn và độ cứng uốn của cáp là đáng kể. Trong trang này, phương trình vi phân cho trường hợp rung động phổ biến của cáp được tính đến, bao gồm giảm xóc nhớt và độ cứng uốn của cáp.
Sau đó, xem xét việc đơn giản hóa các giả định về điều kiện biên một cách thích hợp, sẽ thu được các biểu thức thể hiện mối quan hệ giữa tần số và lực căng. Nó đưa ra một quy trình được áp dụng thực tế để xác định độ căng của cáp thông qua các tần số đo được. Quy trình được xây dựng được kiểm chứng bằng dữ liệu thực tế của cầu Phú Mỹ, Thành phố Hồ Chí Minh.
Từ khóa_
Dây cáp, lực căng, giảm chấn, độ cứng chống uốn,
tần số đo