Hybrid cross-tie system with passive dampers study

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Abstract. The authors have investigated the use of passive vibration dampers through the implementation of concentrated masses in the hybrid cross-tie system of a cable-stayed bridge. A 3D model of a cable-stayed bridge was built in ANSYS suite. The authors have studied the stress-strain behavior and dynamic characteristics of the model under the gravity load. The study has shown that the most effective model appears to be the one with passive dampers implemented by means of six concentrated masses. The increased stiffness of links of the concentrated masses had stronger effect on the model with passive dampers implemented by means of ten concentrated masses, however the model where passive dampers were implemented by six concentrated masses displayed comparable values of natural vibration frequencies with deflections in the spans being 3% lower, deflections of the towers being 8% lower, and longitudinal forces in the main cable being 6% lower. The results obtained by the authors allow for the conclusion that all models of a hybrid cross-tie system with passive dampers reviewed have high aerodynamic stability.

1. Introduction
Hybrid systems in which the roadway comprises a girder with tower supports and staying system are widely used in bridge engineering. This kind of structures provide high load-bearing capacity to cable-stayed bridges, are lightweight, and allow for covering long bridge spans without having to install additional supports. Yet, such systems are sensitive to dynamic loading. Different dampening devices are used for the prevention of wind-induced vibrations in bridge structures. This study is intended as the study of stress-strain behavior, evaluation of wind-induced vibration critical velocities and aerodynamic stability of the structures when passive dampers are used in the form of additional concentrated masses attached by elastic constraint. To that end, a 3D model of a cable-stayed bridge was built in ANSYS suite. The dimensions of the model were assigned as per the contemplated design of a bridge across the Kuznechikha River in Arkhangelsk [1].

The influence of passive vibration dampers on the strain-stress behavior and dynamic characteristics of the structure were studied for a cable-stayed bridge with the end spans each 200 m long and 450 m central span, 90 m high towers, and the bridge height of 30 m. Stiffeners, dimensions and configuration of a hybrid system meets the model described in ref. [2].

2. Stress-Strain Analysis and Modal Analysis
Three cases of passive vibration dampers modeling were analyzed: ten, six and two concentrated masses fixed at the ends of the stiffening truss in the central span on elastic elements by means of constraint $EI = 2.46 \cdot 10^{11}$ Nm², $EA = 2.51 \cdot 10^8$ N. Passive dampers implemented by means of ten concentrated masses are shown on figure 1. The distance from the tower to the nearest concentrated mass is 80 meters; the
distance between the masses along the stiffening truss is 60 meters, while the distance between the masses across the stiffening truss is 30 meters.

![Figure 1. Passive dampers implemented by means of concentrated masses.](image)

Initially, the effect of the weight of concentrated masses on the stress-strain behavior of the model was analyzed. The variation was between 0 and 8% of the bridge structure weight without dampers. The calculations showed that increase of the weight of 10 passive dampers to 8% of the weight of the original bridge structure will increase the deflections at midspan by 35%. A 40% increase was noted in the displacement of the tops of towers.

The modal analysis of a cable-stayed bridge model with different concentrated masses has shown that the use of passive dampers has no significant effect on the variation of natural torsional frequencies and natural transverse frequencies of a cable-stayed bridge. The transverse frequency has changed by 1.25%, and the torsional frequency has changed by 2.9%. The frequency of vertical motions has decreased by 6%. The relationships between the variation of natural frequencies and the value of additional masses are shown on figure 2. The mod spacing is not consistent with the original model in which the first harmonic vibrational modes were located in the 3rd, 4th and 5th positions in the spectrum. Transverse, torsional and vertical vibrations of the model with dampers are located respectively in the 3rd, 24th and 35th positions in the spectrum (figure 3). Intermediate positions in the spectrum are occupied by vibrations of additional masses.

![Figure 2. The Relationship of Natural Vibrations and the Weight of Additional Masses.](image)
Figure 3. The first harmonic vibrational modes with passive dampers: transverse, vertical and torsional.

At the next phase of the study, the value of additional concentrated masses was assumed to be constant and equal to 8% of the original weight of the bridge structure. The modal analysis of a cable-stayed bridge with varying stiffness of links of the concentrated masses has shown that the increased stiffness of links of additional masses has resulted in 60% increase of transverse vibrational frequency. The changes in the stiffness of links of the concentrated masses have no effect on the frequencies of vertical and torsional vibrations (figure 4).

Figure 4. The Effect of Additional Masses Link Stiffness on the Natural Frequency.

Next, the study focused on the influence caused by the number of concentrated masses used in the cable-stayed bridge structure on its stress-strain behavior and dynamic characteristics. In all cases, the
displacements and internal forces in the structural elements were confirmed to be tending to increase as an effect of the increased load by means of additional concentrated masses. In contrast, the frequencies of natural vibrations of the structure showed very small change. In all cases reviewed using 2, 6 and 10 additional concentrated masses, considerable effect on transverse frequency of the structure was caused only by the increase in the stiffness of links that attached these masses to the structure (Figure 4).

On the basis of the analysis completed on the models, the most efficient model appears to be the model with passive dampers implemented by means of six concentrated masses. As compared to the models having passive dampers implemented by two and ten concentrated masses, the model with dampers represented by six concentrated masses has lower deflections in the spans, lower displacements of the towers, lower stress in the stiffening truss, and lower longitudinal forces in the main cable (Table 1).

Table 1. Characteristics of a Cable-Stayed Bridge with Passive Vibration Dampers.

| Parameter                                                                 | The Number of Concentrated Masses With the Total Weight Equal to 8% of the Bridge Weight |
|--------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Maximal stress in the stiffening truss at midspan, MPa                   | 100.1 135 133.17 133.2                                                               |
| Maximal stress in the stiffening truss at the end span, MPa              | 67.34 125 111.4 115.5                                                                |
| Longitudinal forces in the main cable, ×10^7, N                           | 9.17 11.5 10.5 11.2                                                                   |
| Deflection in the middle of the central span, m                          | 1.819 2.725 2.46 2.548                                                                |
| Deflection in the middle of the end span, m                              | 0.68 1.16 1.08 1.113                                                                  |
| Displacement of the tower top, m                                        | 0.443 0.646 0.607 0.621                                                                |

3. Aerodynamic Stability

The change of aerodynamic characteristics of the structure has an effect on its aerodynamic stability [3]. Aerodynamic stability condition is written as [4, 5]

\[ v_{cr} >> v_{WND} \quad \text{or} \quad v_{cr} > 1.5 v_{WND} \]  

where \( v_{WN} \) is the design wind speed, i.e. the maximum wind speed that can be expected in this bridge construction area (normally, \( v_{WND} = 25\ldots35 \text{ m/s} \)); 1.5 is specific safety factor [6, para. 2.24].

In the practice of cable-stayed bridges structural analysis, aerodynamic stability is evaluated using various methods and criteria that are based on the natural vibrational frequency of the bridge structures. A.A. Petropavlovskij states the relationship between the flow velocity \( v \), characteristic effective size \( h \) of the structure towards the cross flow, and Karman vortex shedding frequency \( \Theta_w \) [6, p.183]

\[ S_h = \Theta_w h v^{-1} \]  

where \( \Theta_w \) is the circular frequency of Karman vortex generation; \( S_h \) is the Strouhal number, dependent on the shape of the structure; for bridges, \( S_h = 0.12 \ldots 0.18 \), \( S_h = 0.15 \) is assumed. Wind-induced vibrations are understood to be the build-up of amplitudes of self-exited vibrations directed across the air flow that occurs when the Karman vortex shedding frequency coincides with one of the natural vibrational frequencies of the structure. For the estimation of aerodynamic stability by criterion of critical velocity for wind-induced vibrations the following formula is used:

\[ v_{cr} = \sqrt{2\pi \cdot (h_y \cdot B)^{1/2} \cdot S_h \cdot v_{WN}^{-1}} \]
where $h_B$ is the stiffening truss height, (m); $B$ is the bridge breadth, (m); $\omega$ is the natural vibrational frequency of the structure, (Hz). Table 2 is the summary of results obtained by the calculation of wind-induced vibrations critical velocities using the formula (3) for the models reviewed in this study.

| Vibration frequency, $\omega$, Hz | Critical velocity, $v_{cr}$, m/s |
|----------------------------------|----------------------------------|
| Cable-stayed bridge model without passive vibration dampers | Model with passive vibration dampers which total weight is 8% of the bridge weight |
| | The number of concentrated masses |
| | 2 | 6 | 10 |
| transverse | 0.162 | 0.158 | 0.161 | 0.160 |
| | 74.3 | 72.5 | 73.8 | 73.4 |
| vertical | 0.282 | 0.261 | 0.269 | 0.266 |
| | 129.3 | 119.7 | 123.3 | 122.0 |
| torsional | 0.171 | 0.165 | 0.167 | 0.166 |
| | 78.4 | 75.7 | 76.6 | 76.1 |

3. Conclusions
In contrast to the models of passive dampers implemented by means of two and ten concentrated masses, the model of passive dampers implemented by six concentrated masses has less deflection in the spans, lower displacements of the towers, lower stress in the stiffening truss, and lower longitudinal forces in the main cable (see table 1). However, the greatest effect on the frequencies of natural vibrations was seen in the model with passive dampers implemented by means of two concentrated masses (table 2). The increased stiffness of links of the concentrated masses had stronger effect on the model with passive dampers implemented by ten concentrated masses, but the model where passive dampers are represented by six concentrated masses also displays comparable values of natural vibration frequencies with deflections in the spans being 3% lower, displacements of the towers being 8% lower, and longitudinal forces in the main cable being 6% lower. Aerodynamic stability conditions are met for all modeled cases. Based on the analysis of the models described above, the model with passive dampers represented by six concentrated masses can be considered as the most efficient model.

References
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