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Effects of Temperature Variation on Cable Forces of an Extradosed Bridge

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ABSTRACT

In order to comprehensively realize and then filter out the temperature effect for further proposing a feasible structural health monitoring methodology mainly based on the variation of cable force, the long-term monitoring of cable frequencies and temperatures of Ai-Lan Bridge, an extradosed bridge located in central Taiwan, is conducted in this study. With the data collected on this bridge for more than one year, the variations of cable frequencies and temperatures at different structural components are examined to extract consistent tendencies. The results clearly indicate that temperature is the major environmental factor to cause the variation of cable force. A simplified model proposed in this study also demonstrates its effectiveness in correlating the variation of cable force with an effective temperature variation simultaneously considering the temperature effects from the pylon, girder, and cable.

INTRODUCTION

It is an extremely important issue to maintain the serviceability and safety of civil structures, especially for long-span bridges. Although visual inspection or some experimental methods were adopted for damage identification, their applications are generally restricted to the accessible and pre-known local portion of structure with high damage potential. Recently, more researchers have attempted to develop global damage detection methods and several studies indicated that structural health monitoring (SHM) is one of the feasible solutions to assess the structural condition of bridges. However, a crucial question immediately raised in SHM is how to decide the sufficient and effective measurements for the subsequent damage assessment.

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For cable-stayed bridges, it is obvious that the most critical structural component is the stay-cable system because it suspends most of the girder weight and is the primary path for transmitting the live loadings on girder. Consequently, it is believed that the bridges can be considered safe as long as no unusual force change is detected in the cable system. In other words, the alternation of force magnitude or distribution for the whole cable system should be evidently observed if serious damages occur on the bridge structure. Based on this concept, a strategy with continuous measurement of cable forces for SHM is proposed in this study.

In most of the vibration-based damage detection methods, the dynamic characteristics of structure such as the modal frequencies are first extracted from the measurements and their changes are then used for damage identification. Nevertheless, environmental effects are also believed to play a major role in the variation of measured cable forces in addition to damages. Under the interference of these environmental effects, the alteration of cable force due to damages would be difficult to distinguish. From the recent works by the authors and others for cable-stayed bridges, it has been shown that temperature is usually the key environmental factor to induce the variation of cable forces [1-2]. In order to comprehensively realize and then filter out the temperature effect for further proposing a feasible structural health monitoring methodology mainly based on the variation of cable force, the long-term monitoring of cable frequencies and temperatures of Ai-Lan Bridge, an extradosed bridge located in central Taiwan, is conducted in this study.

With the data collected on this bridge for more than one year, it is first confirmed that the vibration of the stay cables basically follows the string theory. Accordingly, the square of cable frequency variation can be used to represent the variation of cable force. Moreover, the variations of cable frequencies and temperatures at different structural components are examined to extract consistent tendencies. The comparison of temperature data also indicates that the temperature variations for different structural components are quite different and all with considerable time lags with the air temperature. Finally, a simple model is proposed to quantitatively construct the relationship between the variation of cable force and that of a combined temperature index contributed from temperatures at different structural components. The corresponding correlation analysis is further performed to verify this formulation.

AI-LAN BRIDGE AND ITS MONITORING SYSTEM

Ai-Lan Bridge is a thee-span symmetric concrete extradosed bridge with a main span of 120m. The cable system is arranged in a harp shape along the centreline of girder with nine pairs of stay cables on one side of each pylon. The bridge commenced its construction in 2004 and was opened for traffic in 2008. A monitoring system was established during its construction stage and an inspection management system was set up four years after its opening. The function of the monitoring system is to measure the stress and/or strain conditions of critical bridge components as well as the temperature variations of surrounding air and various structural components. The inspection management system, on the other hand, is set up to record and manage the damage and repair data of the bridge. However, both systems do not provide the important function of damage assessment. Thus, the primary objective of this study is to develop a feasible method for the damage assessment of this bridge using the existing monitoring system.

For damage assessment, extensive and continuous measurements of stay cable force are necessary. Since only four stay cables were installed with load cells to collect cable force data in the original monitoring system, it is obviously not sufficient for the purpose of damage assessment. A simple device composed of a fiber Bragg grating (FBG) sensor attached on a fishing line [3] is consequently further added in this research to adequately measure the ambient vibration signals of the cable system. These FBG sensors are installed on Cables E01 to E18, all the 9 pairs of cables on one side of a pylon. From those signals, the natural frequencies of each cable are identified and then employed to determine the corresponding cable forces with the ambient vibration method. As for the temperature measurements, a number of thermocouples were installed at six cross sections of girder and two cross sections of pylon in the original monitoring system to measure the structural temperature. In addition, several thermometers were also deployed outside and inside three selected cross sections of girder to record the air temperature. Nonetheless, no temperature sensors were aimed in the original monitoring system to directly take the cable temperature, which is no doubt most closely related to the variation of cable force. To fit this cavity, a cable specimen of 1 m long is made in this study for imitating the real cable by assembling the same number of tendons inside an HDPE tube. FBG temperature sensors are attached the surface of certain inside tendons to intimately take the temperature of the cable specimen placed on the bridge deck since the second year of measurement.

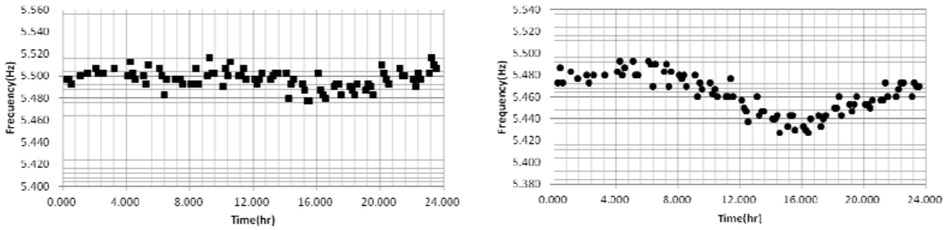
OBSERVED TENDENCIES FOR CABLE FREQUENCIES AND TEMPERATURES AT DIFFERENT LOCATIONS

In this study, the vibration signal from the FBG sensor installed on each cable is automatically collected for 300 sec every 15 minutes. The measured displacement time history of cable vibration is first transformed into the frequency domain by the discrete Fourier transform (DFT) technique. With further help from the string theory indicating that the modal frequencies of cable almost follow an arithmetic sequence, the cable frequencies can then be clearly identified without ambiguity from the corresponding Fourier amplitude spectrum (FAS). In other words, there are totally 96 identified frequency values for each cable per day. These FBG measurements have been continuously taken and processed since September of 2010 to accumulate a data base of more than one and a half years so far.

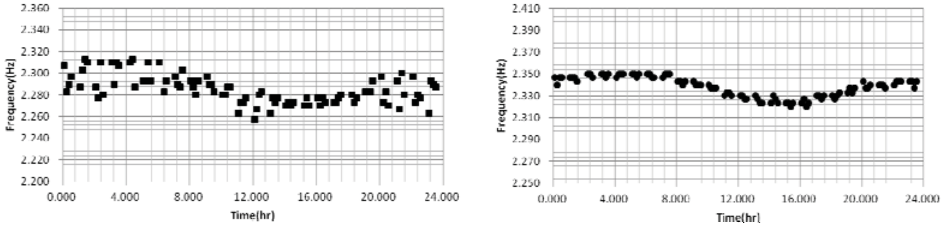
Most of the effective measurements illustrate that the first 4 modal frequencies for longer cables and only the first modal frequency for shorter cables can be typically identified. Considering the nearly equally-spaced distribution for different modal frequencies of a cable, any single cable frequency is eligible for the subsequent exploration of temperature effects in this study. A statistical analysis is performed with the collected data from the first week to determine the most significant mode usually observed for each cable. A weighting of 3 is assigned to the most dominant mode of each measurement, while the weightings of 2 and 1 are designated to the 2nd and 3rd prominent modes, respectively. The results of this analysis lead to the uniform choice of the first modal frequency for each cable in the following further investigations.

In the first phase of this study, the first-year data from September of 2010 to August of 2011 are utilized to investigate the variation trends of cable frequencies and temperatures at different locations. Due to several technical problems ever encountered in the initial year of the installed FBG system, there are totally 223 days of effective signals available for this analysis. Using the measurements taken on 2010/10/09 for example, Figure 1 depicts typical daily frequency variations for the shortest pair of cables E1 and E10 together with those for the longest pair of cables E9 and E18. The general tendency of daily frequency variation is observed to be similar for all the measured cables. The cable frequencies are usually kept steady from midnight to early morning and start to decrease after around 8:00 with a minimum value attained at approximately 14:00 to 16:00. An increasing trend then follows and continues until midnight. Examining the results for all the cables, their daily frequency variations are consistently less than 3%. Moreover, the frequency variation tendency for Cables E01 to E09 located on the east side of bridge centerline is generally not as sharp as that for Cables E10 to E18 placed on the west side. Further investigating the daily variations of cable frequencies over the whole year, it can be found that the above tendencies constantly exist in all four seasons. But more specifically speaking, the cable frequency variations in spring are relatively smaller than those in the other three seasons. Besides, the frequency variations for the longer cables are more consistent in different seasons.

As for the temperature variations, the data also collected on 2010/10/09 at the girder (top and bottom, respectively), in the air (inside and outside girder, respectively), and at the pylon are plotted in Figure 2 for illustration. It is apparently observed from this figure that the daily temperature variations at different locations share a similar fluctuation curve mainly composing of a steeper variation trend during the daytime and the other slower variation trend during the nighttime. However, closer examination reveals two major distinctions in time lags and variation magnitudes among these different temperature measurements, as listed in Table 1. Comparing the air temperatures outside and inside girder, it is clear that the former starts its increasing trend during the daytime with a variation magnitude of 5.4 °C much earlier than the latter only with a variation magnitude of 1.0 °C. Further contrasting the temperatures taken on the top and bottom of girder, the former begins its daytime rise with a variation magnitude of 2.2 °C much slower than the latter simply with a variation magnitude of 0.9 °C. Since the air temperature outside girder and the temperature at girder top are naturally more related to the variation of cable frequency, these two quantities are

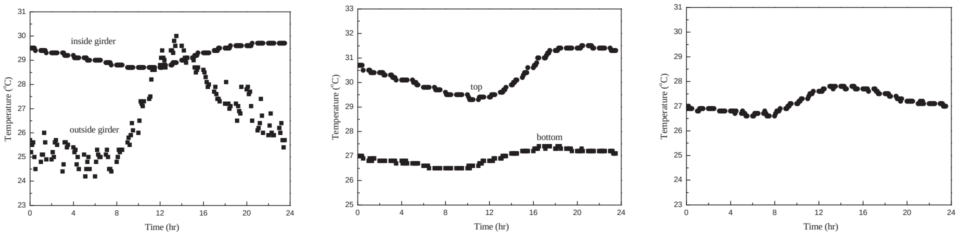


(a) Cable E01 (b) Cable E10



(c) Cable E09 (d) Cable E18

Figure 1 Daily variations of cable frequencies



(a) air (b) girder (c) pylon

Figure 2 Daily temperature variations at different locations

Table 1 Daily temperature variations at different locations

Location		Lowest Point		Highest Point		Temperature Variation (°C)
		Temp. (°C)	Time	Temp. (°C)	Time	
Air	outside girder	24.4	07:45	29.8	13:30	5.4
	inside girder	28.7	10:45	29.7	20:45	1.0
Girder	top	29.3	10:45	31.5	21:30	2.2
	bottom	26.5	9:15	27.4	18:45	0.9
Pylon		26.6	07:30	27.8	15:20	1.2

selected in this following correlation analysis for representing the air and girder temperature, respectively. Regarding the temperature of pylon, its increasing interval during the daytime is close to that of the air temperature outside girder and the variation magnitude is 1.2 °C. As far as the daily variation magnitude is concerned, the air temperature exhibits a much larger value than those for the girder and the pylon. On the other hand, the girder temperature demonstrates a considerable time lag in the daytime rising curve with respect to the corresponding air and pylon temperatures. It should be noted that the above trends are consistently held all year round from inspecting the data covering one year. The exceptions only occur in the days under cold fronts to significantly reduce the variation magnitude and spoil the daytime increasing trend. In addition, it is also observed that the daily temperature variation in winter is larger than those for the other three seasons.

CORRLEATON ANALYSIS BETWEEN CABLE FREQUENCY AND STRUCTURAL TEMPERATURE

Comparing the observed tendencies for the cable frequencies and temperatures at different locations in the previous section, the relationship between the variation of cable frequency and that of structural temperature can be qualitatively brought into sight. The monotonically decreasing trend of cable frequency and the monotonically increasing trend of structural temperature in the daytime period strongly suggest a negative correlation between them. However, it was also recognized that the temperature field of the bridge is very complicated and careful attention needs to be paid before correlating the relevant temperatures with the variation of cable frequency. Aimed to more specifically quantify the correlation between the cable frequency and structural temperature, a previously mentioned cable specimen with FBG sensors was installed on the deck of Ai-Lan Bridge to directly take the cable temperature after November of 2011.

Further including the new measurements obtained from the cable specimen, the temperature data collected on a representative day (2011/12/03) are drawn in Figure 3 together with the identified frequencies of Cables E01 (short) and E17 (long) for more comprehensive comparison. In this figure, the square of cable frequency variation with reference to the value at midnight (0:00) is adopted to indicate the variation of cable force. The results in Figure 3 disclose that the variation of air temperature seems to go a little ahead of that of cable force. On the other hand, the variations of pylon, cable, and girder temperatures all fall behind that of cable force. This phenomenon implies that the heat transfer should start from the air to different structural components and the variation of cable force cannot be exclusively attributed to that of a single structural component. Even though the cable temperature is naturally related to the variation of cable force, the temperatures of girder and pylon may also play non-negligible roles. In other words, the variation of cable force is mainly resulted from the combined temperature effect of different structural components if the variation of temperature is considered the most dominant environmental factor.

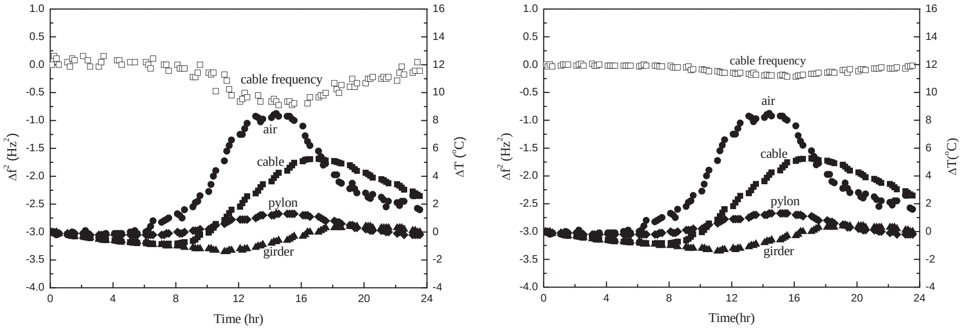
Based on the string theory, the internal force F_0 of a stay cable at a reference time t_0 can be expressed in terms of its modal frequency as

$$F_0 = 4\overline{m}L^2\left(\frac{f_{n0}}{n}\right)^2 \text{ or } \varepsilon_0 = \frac{F_0}{EA} = \frac{4\overline{m}L^2}{EA}\left(\frac{f_{n0}}{n}\right)^2 \tag{1}$$

where L, $\overline{m}$, E, and A represents the length, mass per unit length, Young's modulus, and cross-sectional area of cable, respectively, f_{n0} signifies the natural frequency of the n-th mode in Hz, and ε_0 symbolizes the axial strain, both at that reference time. Considering the corresponding quantities F_1, f_{n1}, and ε_1 at any other time instant t_1, subtraction of the two sets of quantities at different time instants directly leads to

$$\frac{\Delta F}{F_0} = \frac{F_1 - F_0}{F_0} = \frac{f_{n1}^2 - f_{n0}^2}{f_{n0}^2} = \frac{\Delta f_n^2}{f_{n0}^2} = \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_0} = \frac{\Delta\varepsilon}{\varepsilon_0} \tag{2}$$

It is well known that the change of structural temperature can directly induce the variations in internal stress and strain of a structural system. To more systematically analyze the temperature effect on the variation of cable force, a couple of engineering approximations are made in this study for simplification. First, it is assumed that the temperature of each structural component is uniform and no thermal gradient is



(a) Cable E01 (b) Cable E17

Figure 3 Daily variations of cable frequency and different temperatures considered. Moreover, the secondary effect due to structural constraints is regarded to be negligible. Under such circumstances, a stay cable with an inclination angle θ would be subjected to a variation of strain

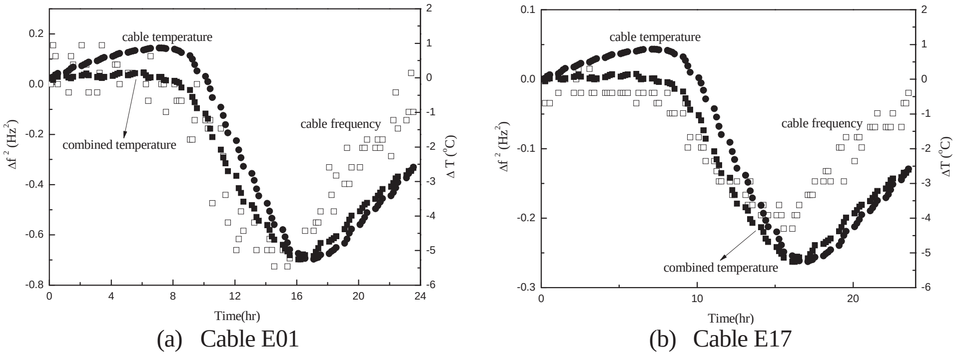
$$\begin{aligned}\Delta\varepsilon &= \varepsilon_1 - \varepsilon_0 = \alpha_G \Delta T_G \cos^2\theta + \alpha_P \Delta T_P \sin^2\theta - \alpha_C \Delta T_C \\ &\approx \alpha\left(\Delta T_G \cos^2\theta + \Delta T_P \sin^2\theta - \Delta T_C\right) = \alpha \Delta T_{eff}\end{aligned} \tag{3}$$

if the temperature variations of pylon, girder, and cable are ΔT_P, ΔT_G, and ΔT_C, respectively, between the time instants t_0 and t_1. It should be noted that α_G, α_P, and α_C in Equation (3) represent the thermal expansion coefficients of pylon, girder, and cable, respectively. For practical cases where the pylon and girder are commonly made of concrete and the steel cables are typically adopted, these thermal expansion coefficients can be approximated with the same value α. Substitution of Equation (3) into Equation (2) then gives

$$\frac{\Delta f_n^2}{f_{n0}^2} \approx \frac{\alpha}{\varepsilon_0}\left(\Delta T_G \cos^2\theta + \Delta T_P \sin^2\theta - \Delta T_C\right) = \frac{\alpha}{\varepsilon_0}\Delta T_{eff} \tag{4}$$

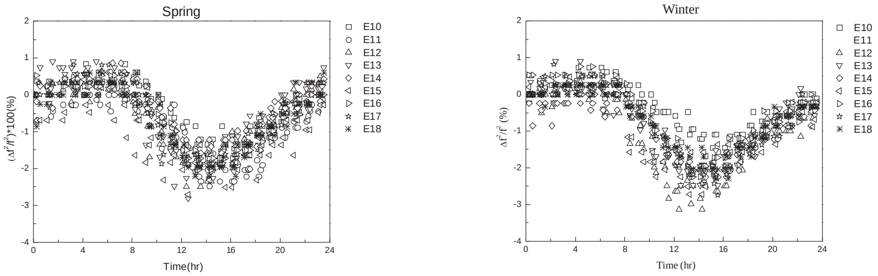
According to Equation (4), it is obvious that the square of the cable frequency variation normalized to its reference value should be proportional to the effective temperature variation ΔT_{eff} combining the temperature effects from the pylon, girder, and cable.

To investigate the effectiveness of the above analysis, the square of the cable frequency variation is plotted in Figure 4 together with the effective temperature variation ΔT_{eff} and another contrasting temperature variation of cable $-\Delta T_C$ for Cables E01 and E17. Since the stay cables of Ai-Lan Bridge are all with an identical inclination angle of $\theta = 17^\circ$ ($\sin^2\theta = 0.09$ and $\cos^2\theta = 0.91$), the contribution to the effective temperature variation from the temperature variation of pylon is trivial and can be neglected. From Figure 4, it is evident that Δf_n^2 follows a nearly perfect trend with ΔT_{eff} and its correlation with $-\Delta T_C$ deteriorates a little bit. To be more specific, the correlation coefficient between Δf_n^2 and ΔT_{eff} is found to be 0.86 for Cable E01 and 0.87 for Cable E17, whereas the corresponding values between Δf_n^2 and $-\Delta T_C$ are 0.76 for Cable E01 and 0.78 for Cable E17. Consequently, it can be verified that this simplified analysis is effective and the temperature is the major environmental factor for the variation of cable force without the occurrence of damages.



(a) Cable E01 (b) Cable E17

Figure 4 Comparison of cable frequency variation and effective temperature variation



(a) spring (b) winter

Figure 5 Normalized cable frequency variation in different seasons

In addition to being arranged in a harp shape with an identical inclination angle, all the stay cables of Ai-Lan Bridge are all made of the same number of strands and with the designed stress within a narrow range. Based on these facts and Equation (4), it can be deduced that the square of the normalized cable frequency variation $\Delta f_n^2 \big/ f_{n0}^2$ should be close for all the stay cables. To validate this deduction, the daily variation of $\Delta f_n^2 \big/ f_{n0}^2$ is shown in Figure 5 for one fan of all the 9 cables in a representative day of winter and the other of spring. With no surprise, the results for all the cables are very close as expected. It is also shown in this figure that $\Delta f_n^2 \big/ f_{n0}^2$ holds a larger daily variation magnitude in winter due to the higher daily temperature variation in this season as observed in the previous section.

CONCLUSIONS

Based on the measurements taken on Ai-Lan Bridge from September of 2010 to date, the modal frequencies of 18 cables and the temperatures of air and different structural components are analyzed and cross-examined in this paper. The results clearly indicate that temperature is the major environmental factor to cause the variation of cable force. A simplified model proposed in this study also demonstrates its effectiveness in correlating the variation of cable force with an effective temperature variation simultaneously considering the temperature effects from the pylon, girder, and cable. With this progress, a structural health monitoring methodology mainly based on the identified cable frequency from measurements will be further explored and applied to Ai-Lan Bridge in the near future.

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