Chapter 16
Pre-existing Telecommunication Optical Fiber Cables for Characterizing Bridge Modal Frequency with Temperature Variation

Jatin Aggarwal, Doyun Hwang, Jingxiao Liu, Biondo Biondi, and HaeYoung Noh

Abstract Long-term bridge health monitoring enables early damage detection, helping to prevent sudden failures. Traditionally, this is achieved by installing dedicated sensors such as accelerometers, geophones, strain gauges, and tiltmeters on bridges to collect performance data. However, this approach incurs high installation and maintenance costs and requires sensors to be physically installed on every bridge of interest, making it difficult to scale. To overcome these challenges, we introduce a new long-term bridge health monitoring approach that leverages pre-existing telecommunication optical fiber cables coupled to the bridge for continuous monitoring. These optical fiber cables were originally installed for communication purposes. We turn these cables into virtual strain sensors by sending light pulses into them, which backscatter from naturally occurring impurities based on the principle of DAS. These backscattered light pulses are phase-shifted by the strains in the optical fiber cables induced by bridge vibration. This method significantly reduces costs by using pre-existing infrastructure. However, since these fibers are placed in conduits and measure bridge vibrations indirectly through fiber-bridge interaction, accurately extracting bridge information becomes challenging. To tackle this challenge, we formulate dynamic interaction between bridge, conduit, and fiber systems which enables us to consistently identify bridge frequency under the influence of changing temperatures. Specifically, we show that the DAS response of the fiber can be decoupled into bridge harmonic motion and conduit harmonic motion, resulting in separate peaks in the frequency domain corresponding to bridge modal frequency and conduit modal frequency. Based on this insight, we can track changes in peaks corresponding to the bridge modal frequency due to temperature variations, separately from those corresponding to the conduit modal frequency. To evaluate our approach, we continuously monitored a 28m-steel composite bridge over Sand Hill Road in Palo Alto, CA, over eight months (Dec 2022 to July 2023). Our approach successfully identified the bridge's first three modal frequencies with 0.36%, 0.25%, and 0.13% errors, respectively, as compared to the conventional accelerometers installed on the bridge. Further, we observe a negative correlation between bridge modal frequencies with seasonal temperature variations due to a decrease in elastic modulus of the bridge with an increase in temperature.

Keywords Bridge health monitoring · Distributed acoustic sensing · Modal testing · Natural frequency · System identification

Introduction

Bridges are critical infrastructure for a country's economic development, facilitating connections between people, roadways, businesses, and more. However, continuous deterioration of bridges due to operational use and environmental conditions throughout their service life poses a risk of sudden failure. Such failures can lead to loss of connectivity, increased traffic

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congestion, longer travel times, and business disruptions, along with significant economic burdens from repair costs or the need for new bridge construction. According to the recent ASCE 2021 report card for infrastructure, 7.5% of bridges in the USA (around 46,500) are in poor condition, while 47% (around 291,000) are in fair condition. These bridges require more frequent monitoring compared to the current standard of inspections once every two years [1]. Given these challenges, there is a growing need for a scalable and ubiquitous bridge health monitoring (BHM) technique that can continuously track bridge deterioration across multiple structures in a city. Continuous monitoring enables early damage detection, helping to prevent sudden failures. Traditionally, dedicated sensors such as accelerometers, geophones, strain gauges, tiltmeters, and velocimeters have been installed on bridges to collect performance data [2, 3, 4]. While these sensors provide detailed and continuous data, they are associated with high installation and maintenance costs, as well as traffic interruptions. Furthermore, the physical installation of these sensors on every bridge makes scalability difficult. To improve scalability and cost efficiency, many researchers have explored drive-by vehicle-based sensing methods for bridge health monitoring [5, 6, 7]. While these methods offer the potential to monitor numerous bridges, they do not provide continuous bridge health monitoring data.

To address the need for scalable and continuous bridge health monitoring techniques, we introduce a new long-term bridge health monitoring approach that leverages pre-existing telecommunication optical fiber cables coupled to the bridge for continuous monitoring. Telecommunication optical fibers are typically bundled together and laid underground across modern cities for communication purposes. These bundled optical fiber cables, inserted into conduits and attached to bridges, often include unused cables—referred to as ”dark fiber”—that do not carry telecommunication signals. We transform these dark fibers into virtual strain sensors by sending light pulses using the principle of Distributed Acoustic Sensing (DAS). When a coherent laser pulse is injected into one end of the fiber using an instrument called an interrogator, Rayleigh backscattering occurs from the naturally occurring impurities in the optical fiber and are collected back into the interrogator [8]. When a section of the fiber is strained, the optical phase of the backscattered light changes as it returns to the interrogator. This optical phase change is quasi-linearly proportional to the strain in the fiber, allowing the system to function as a virtual strain sensor. Since the speed of light within the optical fiber remains constant, the location of the backscattering along the fiber can be determined based on the time it takes for the light to return to the interrogator. By collecting backscattered light from multiple locations along the fiber, we convert them into an array of virtual strain sensors. A single interrogator can monitor up to 100 kilometers of fiber, with a virtual strain sensor positioned every meter—effectively providing up to 100,000 sensors along the fiber length. This method is highly cost-efficient as it leverages existing optical fiber infrastructure to monitor strain across multiple bridges [9, 10]. However, since the fiber cables housed in the conduits are not directly coupled to the bridges due to the existing telecommunication infrastructure, it becomes challenging to accurately infer bridge-specific information.

To address this challenge, we first formulated the dynamic interaction of the bridge-conduit-fiber system to gain insights into identifying bridge frequencies and characterizing the influence of temperature variations on the estimated bridge parameters. Specifically, we demonstrated that the total strain response of the fiber can be decoupled into two components: bridge harmonic motion and conduit harmonic motion. This decoupling results in distinct peaks in the frequency domain that correspond to the bridge's modal frequency and the conduit's modal frequency. With this insight, we are able to track changes in the peaks associated with the bridge's modal frequencies, even in the presence of temperature variations, separately from those corresponding to the conduit.

To validate our approach, we conducted a field test involving the continuous monitoring of the Sand Hill Bridge in Palo Alto, CA, over an eight-month period from December 2022 to July 2023. Our system successfully identified the first three bridge modal frequencies with errors of 0.36%, 0.25%, and 0.13% respectively, compared to the conventional accelerometers installed on the bridge. Furthermore, we demonstrated the seasonal variation in the bridge modal frequencies and observed that all three modal frequencies exhibited a negative correlation with the average daily temperature, which is due to a decrease in the elastic modulus of the bridge with the increase in the temperature.

Pre-existing Telecommunication Optical Fiber Cables as Distributed Acoustic Sensing Systems

Telecommunication optical fiber cables are often bundled and laid underground across modern cities for communication purposes. These bundled cables are also inserted into conduits and coupled with bridges. However, many of these bundled fibers do not carry telecommunication signals and are referred to as ”dark fiber” cables.

We repurpose these dark fiber cables into DAS systems by sending light pulses through them using a device called an interrogator, as illustrated in Figure 1. When a coherent laser pulse is injected into one end of the fiber via the interrogator, Rayleigh backscattering occurs due to naturally occurring impurities in the optical fiber [8]. When a section of the fiber experiences strain, the optical phase of the backscattered light from that section changes. This phase change is quasi-linearly proportional to the strain in the fiber, thus acting as a virtual strain sensor. The location of the backscattered light can be determined based on its time of arrival back into the interrogator, as the speed of light remains constant within the fiber. By collecting backscattered light from various locations, the system effectively creates an array of virtual strain sensors.

This approach has gained popularity for urban monitoring, such as traffic monitoring [11], as well as for geophysical applications like subsurface characterization [12, 13, 14]. Modern interrogators can sense up to 100 kilometers of fiber, creating a virtual strain sensor every meter. These systems can continuously collect strain data over the years without interfering with regular telecommunication signals and without requiring the on-site maintenance or installation typical of conventional sensors like accelerometers, geophones, or strain gauges on bridges. Furthermore, these telecommunication optical fibers are inserted into conduits that are coupled to bridges. This coupling enables the fibers to capture bridge vibrations [9].

By leveraging the existing infrastructure of telecommunication optical fibers, this sensing method offers a scalable, low-cost solution for continuous bridge health monitoring, allowing multiple bridges to be monitored simultaneously without sensor installation or maintenance on every bridge of interest. However, because the conduits are not directly attached to the bridges, accurately extracting bridge dynamic information becomes challenging under changing environmental conditions, such as temperature fluctuations. To address this, we formulate the dynamic interaction between the bridge, conduit, and fiber, which provides insights into consistent monitoring of bridge frequencies, even in varying temperature conditions.

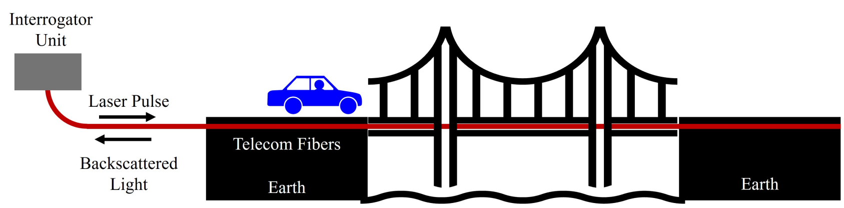

Fig. 1 Representation of pre-existing telecommunication optical fiber cable buried to the ground and coupled to the bridges.

Theoretical Formulation of Dynamic Interaction between Bridge Conduit Fiber System

The fiber conduits are not directly connected to the bridge due to the existing telecommunication infrastructure which makes it hard to infer bridge information consistently. Figure 2 shows examples of pre-existing telecommunication optical fiber cables coupled to the bridge where fiber conduits are coupled to the bridge in several ways. To address this, we formulate the dynamic interaction between the bridge, conduit, and fiber which provides insights into consistent monitoring of bridge frequencies, even in varying temperature conditions. It is shown that the total fiber strain response can be separated into two parts: the harmonic motion of the bridge and the harmonic motion of the conduit. This separation results in distinct peaks in the frequency domain, representing the modal frequencies of the bridge and conduit.

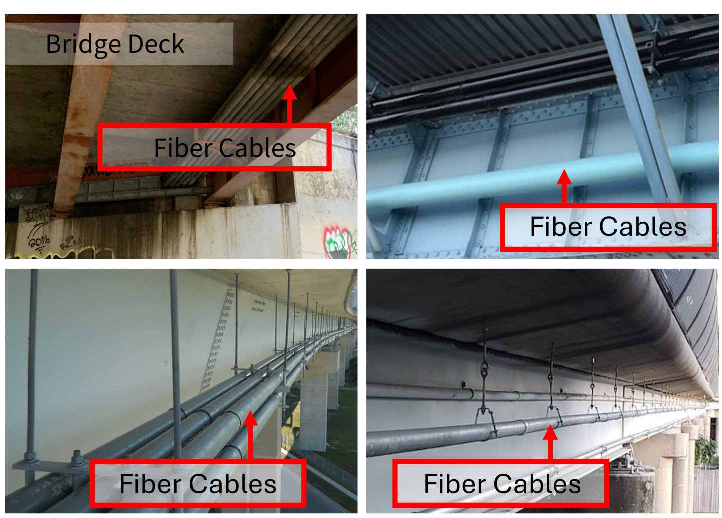

Fig. 2 Examples of pre-existing telecommunication optical fiber cable conduit coupled to the bridges.

Figure 3 shows the pre-installed optical fiber conduit coupled to a simply supported beam of length L with points of attachment at x_A and x_B from one end. To formulate the dynamic interaction between bridge fiber conduit system, We have made some simplified assumptions, as listed below.

- The bridge is assumed to be an Euler beam with a constant cross-section.
- Damping of the beam and conduit is not considered.
- The n^{th} mode shape of the beam is considered to be $sin(n\pi x/L)$

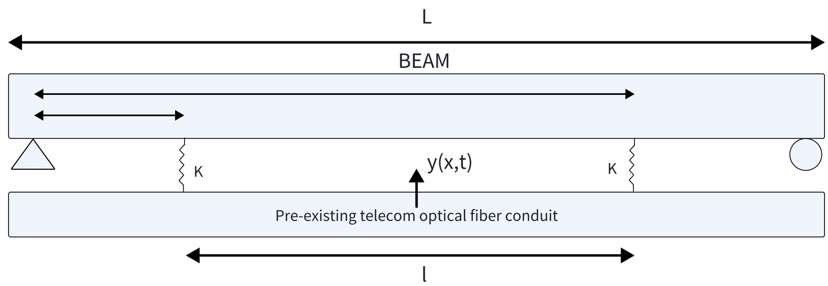

Fig. 3 Pre-existing telecommunication optical fiber cable conduit coupled to the simply supported beam of length L at locations x_A and x_B away from one end of the beam.

By solving the equation of the motion of the beam, the dynamic response of the beam at the location x_A and x_B can be resolved into:

$$u_A(t) = \Sigma_{n=1}^{\infty} A_n \sin\left(\frac{\pi x_A}{L}\right) \sin(w_{bn} t) \quad and \quad u_B(t) = \Sigma_{n=1}^{\infty} A_n \sin\left(\frac{\pi x_B}{L}\right) \sin(w_{bn} t) \tag{1}$$

where, w_{bn} is the bridge modal frequency for the n^{th} mode and A_n is the amplitude for the n^{th} mode harmonic motion of the beam. Now, the equation of the motion for the conduit can be resolved into:

$$EIy''''(x,t) + \rho A_n[(\frac{x}{l})\ddot{u}_A(t) + (1-\frac{x}{l})\ddot{u}_B(t) + \ddot{y}(x,t)] = f(x,t) \tag{2}$$

where, E, I, ρ, and A are elastic modulus, moment of inertia, density, and area of the fiber conduit. y(x,t) is the vertical displacement at location x at time t, and f(x,t) is the external forcing function applied to the conduit.

$$f(x,t) = K[u_A - y(0,t)]\delta(x) + K[u_B - y(l,t)]\delta(x-l) \tag{3}$$

where K is the connection stiffness between the beam and conduit fiber. $\delta(x)$ is the Dirac delta function. Assuming Y_i is the mode shape for the conduit and G_i is the harmonic function for the conduit for the i_{th} fundamental mode, we can solve the Eq. 2 to obtain:

$$\ddot{G}_i + \omega_{ci} G_i = \frac{1}{l}(\ddot{u}_A - \ddot{u}_B) + \frac{a_1}{a_2}\ddot{u}_B \tag{4}$$

where, $\int_0^l Y_i^2\, dx = a_1$ and $\int_0^l xY_i^2\, dx = a_2$. Solving for n_{th} mode of the bridge acceleration using the Duhamel's integral, G is solved to obtain with $Aw_{bn}^2(\frac{1}{l}(sin\pi x_A/L - sin\pi x_B/L) + \frac{a_1}{a_2} sin\pi x_B/L) = C$

$$G_i = \frac{1}{\omega_{ci}} \int_0^t C \sin(\omega_{bn}\theta) \sin\left(\omega_{ci}(t-\theta)\right)\, d\theta \tag{5}$$

$$G_i = \frac{C}{\omega_{ci}^2 - \omega_{bn}^2}\left(\sin(\omega_{bn}t) - \frac{\omega_{bn}}{\omega_{ci}}\sin(\omega_{ci}t)\right) \tag{6}$$

From the derivation, we draw the following conclusions.

- The DAS response is decoupled into the bridge harmonic motion and conduit harmonic motion.
- The frequency and amplitude of the bridge vibrations in DAS responses, which are separated from conduit vibration, vary with changes in bridge conditions and environmental factors such as temperature.

This formulation provides us insight into the decoupling of the bridge and conduit vibration, which leads to the bridge and conduit having distinct peaks in the frequency domain. Therefore, any shifts in the bridge frequency peak due to temperature are due to changes in the bridge properties.

Furthermore, bridge parameters such as fundamental frequency are estimated from the optical fiber cable strain responses through the Stochastic Subspace Identification Algorithm (SSI-data) [6]. This SSI-data method allows for the identification of system parameters from strain data (output-only) without requiring input data that works for operational system identification. It assumes the input load to be stochastic which is valid for bridges as traffic load. This is because traffic load is highly variable and unpredictable which makes it stochastic in nature. In addition, this method is based on reliable numerical algorithms that involve QR decomposition and SVD to process large data sets and don't need complex optimization techniques.

Field Evaluation: Long-term Evaluation of a Steel Composite Bridge

This section presents the field evaluation of our system, conducted through an experiment on a 28-meter steel composite bridge in Palo Alto, CA. We begin by detailing the field setup, followed by a presentation of the results and a discussion of the findings.

Field Setup

The field experiment was conducted on a 28-meter steel composite bridge with a 30° skew angle located on Sand Hill Road in Palo Alto, CA. This bridge supports both roadway traffic and a pedestrian walkway over San Francisquito Creek, as shown in 4a. Telecommunication fiber cables, housed in conduits beneath the bridge deck and coupled to the structure, are depicted in Figure 4b. To monitor the bridge, we utilized an Optasense ODH-3 interrogator installed approximately 4 kilometers away from the bridge. The system operated with a gauge length of 16.3 meters, channel spacing of 8 meters, and a sampling rate of 250 Hz. Additionally, conventional accelerometers (PCB 354C03) were deployed along the bridge for one hour on two separate days to validate the accuracy of our proposed bridge monitoring method. These validation tests were performed on the afternoon of August 11, 2022, and the morning of August 23, 2022. We continuously collected and analyzed data from the telecommunication optical fiber cables for a period of 8 months, from December 2022 to July 2023, to monitor the bridge over time. The SSI-data algorithm was employed to estimate the bridge frequencies, with hourly optical fiber strain data used to derive these estimates.

(a)

(b)

Fig. 4 Experimental setup showing (a) composite steel bridge and (b) bridge deck and optical fiber cables inside the conduit over SanFrancisquito Creek, Palo Alto, CA.

Results and Discussion

This subsection presents the evaluation results and discussion of our system's performance in continuous bridge health monitoring using pre-existing telecommunication optical fiber cables. We first validate the modal parameter estimates derived from the optical fiber cables by comparing them with results obtained from conventional accelerometers. Following this validation, we present the long-term monitoring results, which track the seasonal changes in the bridge's first three modal frequencies. Additionally, we characterize estimated frequencies with varying average daily temperatures.

Table 1 presents a comparison of the modal frequencies estimated from the telecommunication optical fiber cables and conventional accelerometers. For afternoon testing on 11th August, the bridge frequencies were estimated with errors of 0.18%, 0.31%, and 0.14% for the first three modes, respectively. In the morning testing on 23rd August, the errors were 0.54%, 0.19%, and 0.12% for the same modes. These results demonstrate that the telecommunication optical fiber cables accurately capture the bridge frequencies, closely aligning with the measurements from conventional accelerometers.

Table 1 Estimated modal frequency from conventional accelerometer and telecommunication optical fiber cables data collected for two days.

Day	Day 1 (08/11/22)		Day 1 (08/23/22)	
	Acc	Telecom Fiber (Error %)	Acc	Telecom Fiber (Error %)
Modal Parameter	Frequency, Hz			
1st Mode	4.338	4.33(0.18%)	3.956	3.935(0.54%)
2^{dr} Mode	6.103	6.122(0.31%)	5.868	5.879(0.19%)
3rd Mode	7.855	7.866(0.14%)	7.654	7.663(0.12%)

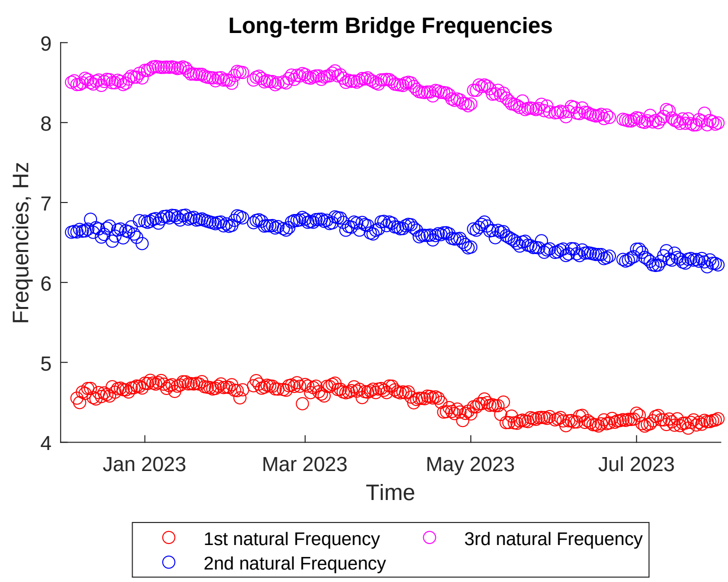

Fig. 5 Scatterplot of estimated bridge modal frequencies for the period of 8 months through telecommunication optical fiber cable strains.

Figure 5 presents a scatter plot showing the variations in the first three fundamental bridge frequencies, estimated daily using telecommunication optical fiber data over an 8-month period (from December 2022 to July 2023). The plot reveals seasonal trends in the frequencies of all three modes, with frequencies increasing during the winter months up until February due to the decrease in temperature, and then decreasing as the temperature rises toward summer. Figure 6 the scatter plot shows the relationship between the estimated bridge frequencies and the average daily temperature, with each point representing a daily estimated frequency. The first three fundamental frequencies display a negative correlation with temperature, with coefficients of determination (r^2) of 0.66, 0.55, and 0.63 for the first, second, and third modes, respectively. The negative correlation arises because as the temperature increases, the elastic modulus of the bridge material tends to decrease, leading to a reduction in the fundamental frequencies.

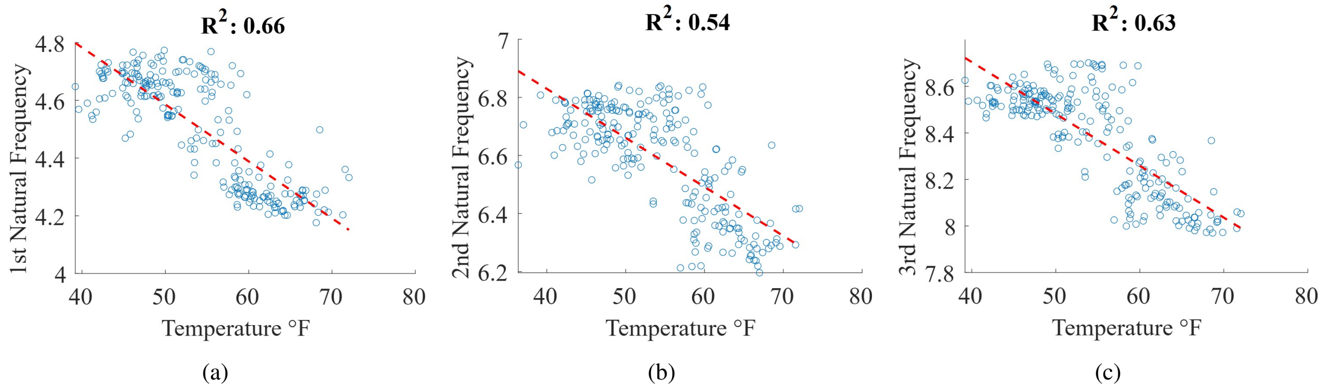

Fig. 6 Scatterplot of the estimated a) first, b) second, and c) third natural frequencies with daily average temperature variation for period of 8 months. The frequencies have a negative correlation with average daily temperature with r^2 as 0.66, 0.55, and 0.63 respectively.

Conclusion

In summary, we introduced a method for continuous bridge monitoring using pre-existing telecommunication optical fiber cables. Due to the pre-existing infrastructure, the conduits carrying the optical fiber cables are not directly attached to the bridges, making it challenging to consistently infer bridge frequencies. To address this, we formulated dynamic interaction of the bridge conduit fiber system which revealed that the total strain in the fiber can be decoupled into components representing the harmonic motion of both the bridge and the conduit. This separation allows us to track changes in the bridge frequencies caused by environmental variations by distinguishing between the frequency peaks from bridge and conduit vibrations. We successfully tested our system in the field by continuously monitoring a 28-meter steel composite bridge in Palo Alto for 8 months. The system captured seasonal changes in the bridge's modal frequencies and found that all frequencies exhibit a negative correlation with temperature, which can be attributed to the decrease in the elastic modulus of the bridge materials as the temperature rises.

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