Monitoring Bridge Displacement Using Pre-Existing Telecommunication Fiber

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ABSTRACT

Monitoring the condition and performance of bridges is critical for enhancing the resilience and safety of urban infrastructure. Sensor-based approaches (both mobile and in-situ) have been developed for monitoring bridges; however, such systems are limited in temporal information, or costly to install and maintain, and thus not scalable. Our previous works have demonstrated that ubiquitous pre-existing telecommunication fiber optic cables can be turned into a dense array of vibration sensors using distributed acoustic sensing (DAS). This enables scalable, high spatial resolution (meter-level) bridge health monitoring, as a single DAS interrogator can turn up to 100 km of telecommunication fiber into distributed strain sensors. While only the dynamic (1-10 Hz for short to medium-span bridges) response of the bridge using telecommunication fiber has been studied before, quasi-static (0.01 - 1 Hz) response of the bridge is critical for BHM tasks such as load rating and serviceability assessment. To this end, we aim to estimate quasi-static displacement response of bridge from telecommunication fiber response. The key challenge is the coupling between the fiber and the bridge that distorts the bridge response measurements. The telecommunication fiber optic cables are often laid inside conduits, which are attached to bridges. As the bridge vibration passes through these attachments, it gets distorted. To address this, we characterize the vehicle-induced quasi-static strain measured by telecommunication fiber, examining its response under different load positions and magnitudes. Based on this characterization, we model the transfer function as a linear relationship between DAS measurements and actual bridge response and infer the parameters using a reference sensor installed for calibration. Our evaluation results from two real-world in-service highway bridges demonstrate that DAS can serve as a displacement sensor with sub-millimeter accuracy.

INTRODUCTION

Monitoring the condition and performance of bridges is critical for enhancing the resilience and safety of urban infrastructure. The most recent ASCE report card [1] states that among the 623,218 bridges in the United States, 36% require replacement or

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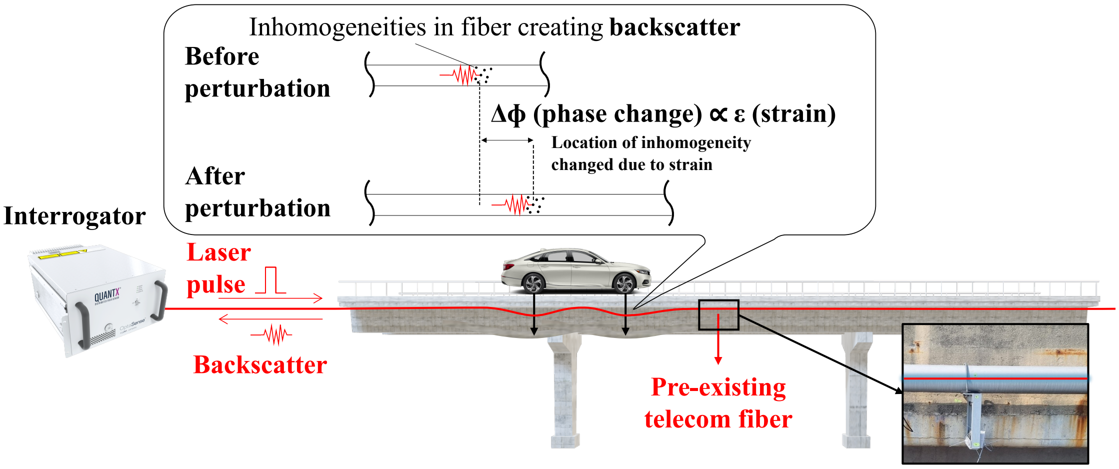


Figure 1. Measuring bridge vibration from non-dedicated pre-existing telecommunication fiber with DAS

significant rehabilitation work. Bridges in the US as of 2025 have an average age of 47 years, and with many bridges with a 50-year service life, such aging structures are at risk of further deterioration. There already exists a large funding gap ($373 billion over 10 years) to maintain this vast number of bridges. Thus, there is a need for a scalable solution to effectively prioritize the structures in need of care.

In current practice, a manual visual inspection by trained structural engineers is performed at least every 24 months and 12 months for critical bridges. While such inspections are backed by expert judgment, they involve high costs (labor, equipment, and traffic closure), and there exists the issue of the subjectivity of the experts. To address this, mobile sensing approaches [2–10], where vehicles are mounted with sensors to monitor multiple bridges, have been developed. This method is relatively low-cost, with affordable installation and maintenance costs, and achieves high spatial resolution as it passes over the entire span of the bridge. However, this requires interruptions to traffic and has low temporal resolution as the vehicle cannot remain stationary at a bridge. Thus dedicated in-situ sensing systems are deployed to monitor bridge response (e.g., acceleration, displacement, and strain). While such systems provide us with continuous, high temporal resolution bridge response, the high installation and maintenance cost limits such deployments to spatial resolution in the order of hundreds of meters [11–14], and is not a scalable solution at a city-scale.

To overcome these limitations, we convert ubiquitous pre-existing telecommunication fiber optic cables into a dense array of dynamic strain sensors using distributed acoustic sensing (DAS) [15, 16]. We measure bridge vibration using telecommunication fiber optics cables by measuring the phase change in backscatter from laser pulses injected into fiber optic cables using an interrogator. When vibration perturbs the fiber, it causes a change in the phase of the backscattered light (Figure 1). This can be converted to strain, which transforms the fiber optic cable into a continuous, distributed strain sensor array [17]. One interrogator unit can measure up to 100 km of fiber simultaneously, enabling a spatially dense, wide-scale bridge health monitoring (BHM) of bridges. This approach has shown great potential in expanding both the scalability and spatial density of bridge monitoring. Our previous works have studied using the dynamic (1 - 10 Hz) response of the bridges for modal testing. However, the quasi-static (0.01 - 1 Hz) response of the bridge has not been examined yet, which is critical for displacement. Displacement is a key parameter for BHM tasks such as load rating and serviceability assessment.

Thus, our goal is to estimate the quasi-static displacement response of bridges using telecommunication fiber optic cables. The key challenge lies in the coupling between the fiber and the bridge that distorts the bridge response measurements. The telecommunication fiber optic cables are often laid inside conduits, which are attached to bridges via channels and other auxiliary attachments. Thus, as the bridge vibration passes through these attachments, it is distorted.

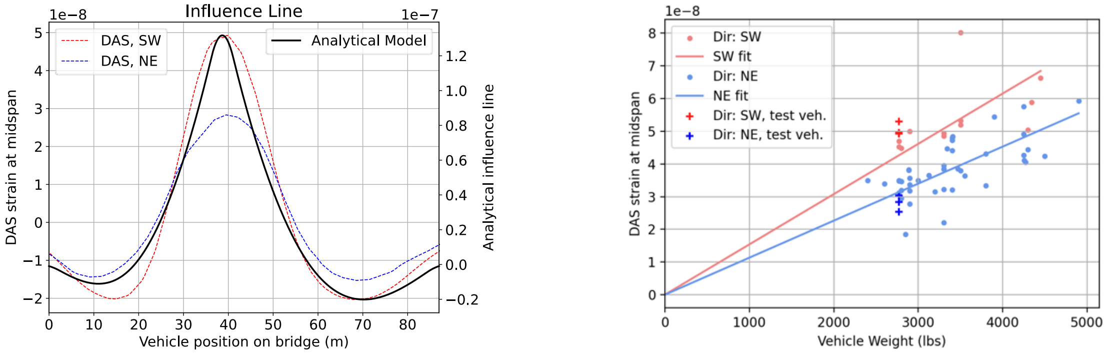
To address this, we first characterize the vehicle-induced quasi-static strain measured by telecommunication fiber, examining its response under different load positions and magnitudes. The empirical quasi-static influence line measured using telecommunication fiber is compared with an analytical influence line derived from known bridge properties. We also analyze the measured strain under ambient traffic with varying vehicle weights. Based on these characterizations, we model the transfer function as a linear relationship between telecommunication fiber measurements and actual bridge response. The transfer function parameter is estimated using a reference sensor installed for calibration. We evaluate our approach on two real-world in-service highway bridges.

CHARACTERIZATION OF TELECOMMUNICATION FIBER RESPONSE UNDER VEHICLE LOADING

Before we estimate displacement, it is important to verify the following hypothesis in order to leverage measurements from pre-existing telecommunication fiber optic cables for displacement estimation: vibration transfer from the bridge to the fiber is linear under varying load conditions. The load conditions here specifically refer to varying location and magnitude. We begin with the assumption that the bridge behaves as an Euler–Bernoulli beam and that its deformations remain within the linear elastic regime under typical vehicle loading. To verify the linearity hypothesis and characterize the bridge-fiber coupling, we conduct a two-step experimental characterization focusing on both spatial and load-dependent responses.

First, we use the quasi-static influence lines derived empirically from telecommunication fiber measurements and analytical influence lines from known bridge properties to characterize the quasi-static response. The degree of agreement between these influence lines serves as a validation of whether we can reliably capture the quasi-static deformation of a bridge under moving loads with telecommunication fiber. To construct the empirical influence line, we plot the fiber-measured strain response as a function of the vehicle's position, which is tracked using a GNSS-equipped vehicle. The analytical influence line is derived from structural models informed by available bridge drawings and known mechanical properties. We find good agreement (cosine similarity 0.89) between the empirical and analytical influence line obtained from field experiments at the Yerba Buena road bridge in San Jose, California (Figure 2a).

Second, for characterizing the coupling under varying load magnitudes, we use the existing ambient traffic on the bridge to observe the fiber-measured strain under different



(a) Good agreement between empirical and analytical influence lines (cosine similarity 0.89)

(b) Significant linear relationship between fiber response and estimated vehicle weights (p-value 0.024)

Figure 2. Characterization of telecommunication fiber response

vehicle weights. First, to identify the effects of varying load magnitudes, we limit cases to where we have a single vehicle on the bridge. From the video footage of ambient traffic, we identify the make and model of the vehicles. We compare the estimated curb vehicle weight with the fiber-measured strain and assess the statistical significance of linearity under varying load. Again, from our field experiments at San Jose, we find a very low p-value (0.024), which indicates a statistically meaningful linear relationship between the strain measured by fiber and varying load magnitudes (Figure 2b). Through this characterization process, we characterize the coupling and form the basis for modeling the transfer from bridge vibrations to strain measured by telecommunication fiber.

BRIDGE DISPLACEMENT ESTIMATION FROM TELECOMMUNICATION FIBER

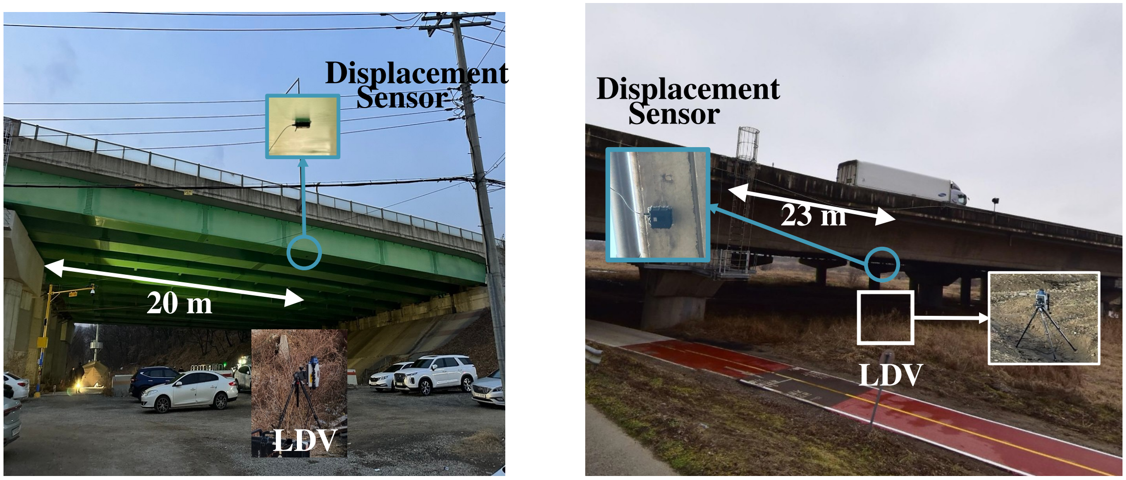
Based on the characterization, we formulate the following objective function to estimate the transfer function α:

$$\min(w_{bridge} - \alpha(w_{DAS})), \tag{1}$$

where w_{bridge} is the displacement measurement(s) of the bridge from an installed sensor and w_{DAS} is the initial displacement estimated by telecommunication fiber from spatial integration. The transfer function α can be modeled as either a scalar (for cases with low spatial heterogeneity and strong, uniform coupling— i.e., where the fiber conduit is rigidly connected to the bridge) or a matrix (for cases with high spatial heterogeneity or varying fiber geometry/configuration along the bridge span). Once α is estimated, it can be used to recover the actual bridge displacement from fiber-measured strain.

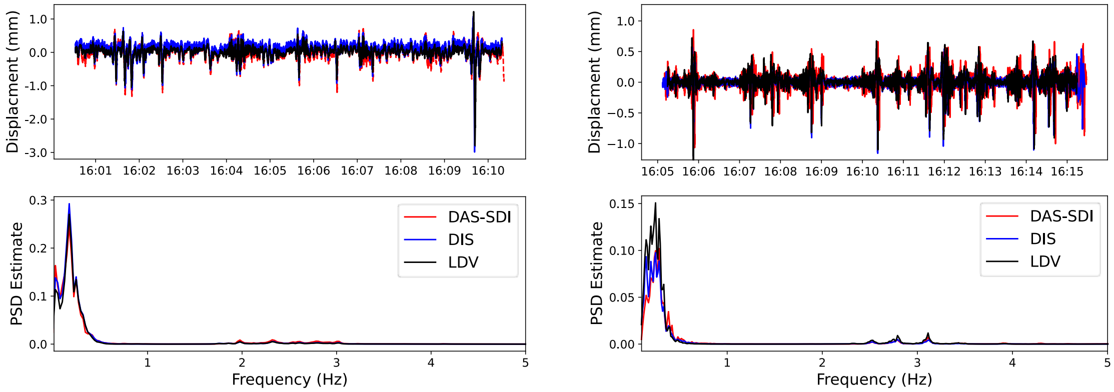
REAL-WORLD DISPLACEMENT ESTIMATION EVALUATION

We evaluate our approach on two real-world in-service bridges. The first bridge is a 50 m span steel box girder bridge located in Gwangmyung, Korea (Figure 3a), and the



(a) Steel box girder bridge, Siheung, Korea (b) PSC box girder bridge, Cheongju, Korea

Figure 3. Bridges used for real-world evaluation.



(a) Steel box girder bridge, Siheung, Korea (b) PSC box girder bridge, Cheongju, Korea

Figure 4. Sub-millimeter accurate displacement estimation through telecommunication fiber optic cables. Displacement measurements from telecommunication fiber (red), displacement sensor (blue), and LDV (black)

second bridge is a 50 m span prestressed concrete box girder bridge located in Cheongju, Korea (Figure 3b).

Here, we evaluate our results for bridges with ground truth displacement measured using a laser Doppler vibrometer (LDV) (in black) under highway traffic. A state-of-the-art displacement sensor (in blue) is also installed at the mid-span [18]. We find that the displacement estimated using telecommunication fiber (in red) achieves sub-millimeter accuracy, with the RMSE with respect to the LDV at 0.299 mm (Figure 4).

CONCLUDING REMARKS

In this paper, we estimate quasi-static bridge displacement using telecommunication fiber optic cables. Through characterization of the telecommunication fiber measurements under varying load conditions, we model the transfer function from telecommunication fiber measurements to bridge vibration. By estimating this transfer function using a low-cost displacement sensor, we were able to achieve accurate displacement estimation results (RMSE 0.299 mm).

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