Conference materials
UDC 681.7.068:681.2.08:624.21
DOI: https://doi.org/10.18721/JPM.183.227

Remote transport infrastructure monitoring system based on fiber-optic sensors

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Abstract. We present a low-power autonomous system for remote structural health monitoring of bridges and similar assets in rural/hard-to-reach areas. The method uses distributed macro-bending sections of standard fiber; load-induced loss is measured by optical time-domain reflectometry. The architecture minimizes components and transmits only incremental data via low-power radio or short satellite links, reducing cost and energy use. Laboratory tests detected 0.4 mm displacement; base spatial resolution was ≈1.5 m (0.5 m by interpolation) and dynamic range reached 67 dB. Field trials on a rural reinforced-concrete bridge confirmed autonomous logging of load-induced attenuation. Active-mode power ≤ 2 W enables long-term operation and cost-effective scaling to many sensing points.

Keywords: fiber-optic sensors, monitoring, transport infrastructure, LPWAN, autonomous system

Citation: Petrov P.S., Kolybelnikov N.Yu., Davydov V.V., Remote transport infrastructure monitoring system based on fiberoptic sensors, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.2) (2025) 138–142. DOI: https://doi.org/10.18721/JPM.183.227

Материалы конференции
УДК 681.7.068:681.2.08:624.21
DOI: https://doi.org/10.18721/JPM.183.227

Система мониторинга удалённой транспортной инфраструктуры на основе волоконно-оптических датчиков

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Аннотация. Представлена автономная система дистанционного мониторинга технического состояния мостов в сельских и труднодоступных районах. Метод основан на фиксировании потерь на макроизгибных участках волокна, измеряемых оптической рефлектометрией во временной области. Минимально обнаруживаемое перемещение в лабораторных условиях составляет 0,4 мм; базовое разрешение 1,5 м, динамический диапазон 67 дБ.

Ключевые слова: волоконно-оптические датчики, мониторинг, транспортная инфраструктура, LPWAN, автономная система

Ссылка при цитировании: Петров П.С., Колыбельников Н.Ю., Давыдов В.В. Система мониторинга удалённой транспортной инфраструктуры на основе волоконно-оптических датчиков // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 138–142. DOI: https://doi.org/10.18721/JPM..183.227

Introduction

In this work, increased attention is given to monitoring transportation infrastructure systems (bridges, tunnels, and others) using various technical means [1–3]. One of the key elements of any transportation infrastructure system (e.g., road or railway) is the bridge. Many sensors and instruments have been developed for real-time monitoring of its condition [4–6].

However, in rural and hard-to-reach areas continuous power and reliable communications are often unavailable, so inspections remain episodic; this motivates low-power, low-cost remote structural health monitoring. For such sites, traditional electrical sensors and high-end distributed optical systems (e.g., Brillouin/Raman) are constrained by reliability, cost, and maintenance complexity.

Optical measurements offer high accuracy [7–10], and optical fiber is immune to electromagnetic interference and resistant to corrosion [11–13]. Therefore, we consider macro-bending fiber sensors combined with OTDR as an economical, low-power solution applicable to rural bridges and similar assets.

Materials and Methods

Fiber-optic deformation monitoring follows two main approaches: point FBG sensors that read spectral shifts [14] and distributed Raman/Brillouin systems for continuous stress profiling over tens of kilometers [15]. Both are accurate but costly and power-hungry, limiting use in low-budget, power-constrained projects.

As a low-cost alternative, we use macro-bending fiber sensors measured by optical time-domain reflectometry (OTDR), which provides distributed readings with adequate sensitivity and spatial resolution at minimal hardware cost. A macro-bending sensor is a standard single-mode fiber fixed at designated bends; loading increases bend-induced attenuation recorded by OTDR. Geometry is application-specific (e.g., U-loops), chosen by required sensitivity and robustness.

Although less sensitive than classical approaches (≈0.1–0.2 mm vs micron-level for FBG), this is adequate for bridges and overpasses where displacements of engineering interest are centimeter-scale. Differential measurement between idle and loaded states reduces temperature influence and avoids complex compensation, which is crucial for wide outdoor temperature ranges.

Bending the optical fiber causes light to leak from the core, resulting in additional attenuation. For single-mode fiber, this process is well described by an exponential dependence.

$$\alpha_b(R) = \alpha_0 \exp\left(-\frac{R}{R_C}\right), \tag{1}$$

where α_b is the specific bend loss; R is the bend radius; α_0, R_C are the parameters determined using a calibration sample.

During OTDR operation, a short light pulse with a duration of τ_p is injected into the fiber, after which the device records the backscattered power as a function of time.

$$z = \frac{\nu_g t}{2}, \tag{2}$$

where ν_g is the group velocity of signal propagation.

One of the key metrological characteristics of an OTDR is its spatial resolution. It is limited, first, by the duration of the probing pulse τ_p (determined similarly to formula 2, where τ_p is substituted instead of *t*). And second, by the spatial sampling step, which is determined by the clock frequency of the analog-to-digital converter f_s:

$$\Delta z_{adc} = \frac{\nu_g}{2f_s}, \tag{3}$$

The actual limit is determined by the greater of the two values.

In the implementation, the probing pulse is generated by a Fabry–Perot laser diode at a wavelength of 1550 nm, producing peaks of 8–10 mW; the 5 ns pulse duration is set by a driver based on an AD8009 and a BFR93A transistor (Fig. 1).

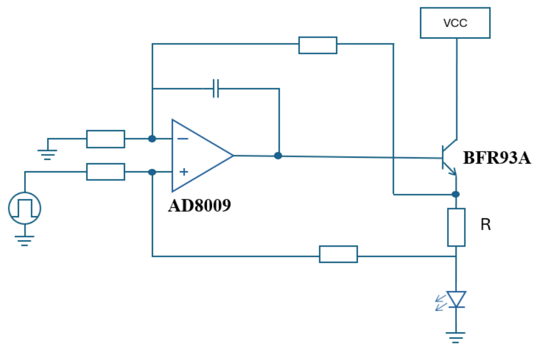

Fig. 1. Laser diode driver implementation for pulse generation

The reflected backscatter is received by an InGaAs PIN photodiode. The photodiode current is converted to voltage using an OPA857 transimpedance amplifier; an internal switch allows selecting a resistance of 5 kΩ (bandwidth 120 MHz) or 20 kΩ (bandwidth 60 MHz). The amplified signal is converted to a fully differential format by an ADA4937-1 driver and fed into a 12-bit AD9226 ADC operating at 65 MHz (Fig. 2).

For this implementation, $\Delta z_{\text{imp}} \approx 0.5$ m and $\Delta z_{\text{adc}} \approx 1.54$ m, which gives a spatial resolution of approximately 1.5 m. This value refers to the primary discretization: subsequent digital processing and interpolation between adjacent samples allow estimating the bend position with up to 0.5 m accuracy. The dynamic range of the developed system is 67 dB when averaging 100 measurements. In practice, this range allows simultaneously tracking large deformations (attenuation increase by several decibels) and subtle deviations around 0.2 dB, corresponding to sub-millimeter deflections.

Instead of an FPGA, we use the STM32F4's DCMI to capture a 12-bit parallel stream; DMA writes frames to RAM without CPU. This replacement cut PCB cost by ~25% and reduced digital power to 0.7 W; total active power is ≤2 W with the 1.5 W analog front end switchable. A measurement takes ~0.5 s, after which the system enters deep sleep.

To address the issue of energy-efficient communication, two approaches are proposed. Synchronous LPWAN mesh networks provide ultra-low power consumption due to their synchrony and offer wide coverage through optimized message routing. In fully isolated areas, the "Gonets-M1" satellite modem or its counterpart "Marathon-IoT" can be used; a 40-second session once per hour transmits incremental reflectograms and consumes approximately 0.15 W·h.

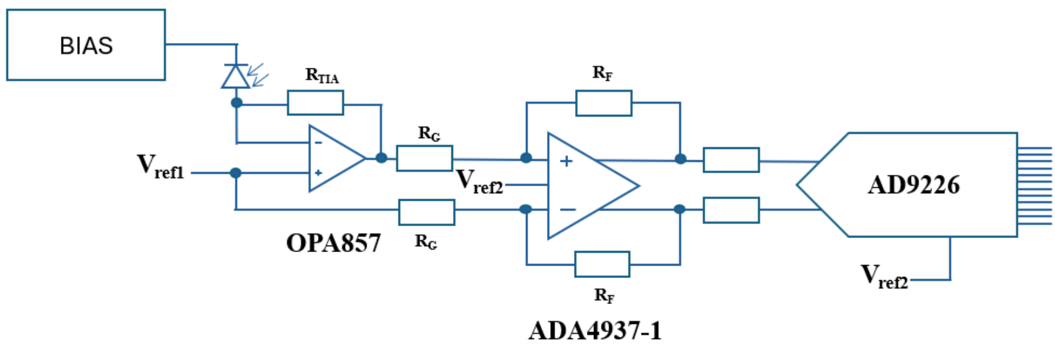

Fig. 2. Receiver circuit diagram of the reflectometer

Results and discussion

To verify the prototype's functionality, a stationary setup was built with an adjustable fiber bend radius (from 50 to 20 mm). Dozens of stretch-and-release cycles were performed, measuring attenuation changes at each step. The experiments confirmed the exponential nature of losses and showed that a fiber displacement of just 0.4 mm led to a clearly detectable increase in attenuation, defining the system's sensitivity. With repeated tests, variation in results for the same radius did not exceed 0.05 dB, indicating good measurement reproducibility and no fiber degradation from repeated bending.

Field tests were conducted on a rural bridge made of reinforced concrete slabs (Fig. 3). U-shaped bends with a diameter of 25 mm were formed at the slab joints, and the measurement module was placed under the span, powered by an autonomous battery.

Fig. 3. Field testing on the bridge and bend formation

The load was applied by a passenger car weighing 1,500 kg, which crossed the center of the span three times with a stop. Each cycle caused an additional attenuation of about 1.5 dB, which completely disappeared after unloading. Fig. 4 presents the results of the bridge slab displacement studies.

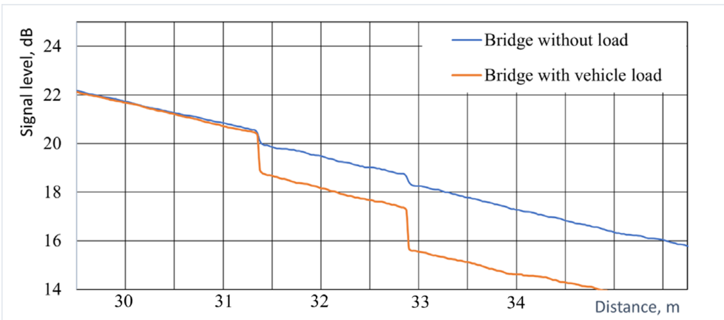

Fig. 4. Detected deformation on the reflectogram segment

Analysis of the obtained results (Fig. 4) confirmed the operability of the laboratory setup (prototype) and the adequacy of the technical solutions used in its implementation, both in terms of measurement and signal processing.

Conclusion

Laboratory and field experiments in the Leningrad Region confirm the feasibility of the macro-bending OTDR system for remote monitoring of transportation structures. The prototype achieved a 67 dB dynamic range, 1.5 m base resolution (0.5 m by interpolation), 0.4 mm displacement sensitivity, and ≤2 W active power, supporting deployment with >100 sensing points and enabling low-cost, long-term monitoring of bridges, overpasses, and tunnels.

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Received 25.09.2025. Approved after reviewing 27.10.2025. Accepted 27.10.2025.