The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Distributed Acoustic Sensing for Intelligent Transportation Systems: Applications in Traffic Monitoring and Infrastructure Safety

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ABSTRACT

Distributed Acoustic Sensing (DAS) transforms optical fibers into dense sensor networks, enabling continuous long-distance monitoring with high spatial resolution. This paper presents DAS principles and its transportation applications, focusing on three areas: (1) real-time vehicle tracking, (2) road subsurface monitoring using ambient noise tomography, and (3) bridge structural health monitoring. This work shows that DAS effectively addresses traffic challenges in urban mobility management and infrastructure maintenance.

1. INTRODUCTION

Distributed fiber optic sensing (DFOS) has emerged as a groundbreaking technology since its initial development in the 1970s (Bucaro et al., 1977). By converting standard optical fibers into distributed sensing elements through advanced light-scattering analysis, DFOS enables continuous monitoring of physical parameters over extended distances. This technology primarily focuses on three measurable quantities: low-frequency strain, temperature variations, and acoustic signals. As a specialized branch of DFOS, distributed acoustic sensing (DAS) detects dynamic strain or strain rate by analyzing phase changes in rayleigh backscattered light, typically using phase-sensitive optical time-domain reflectometry (φ-OTDR) or optical frequency-domain Reflectometry (OFDR). Compared with conventional point sensors, DAS offers significant advantages, including long-distance coverage (up to tens of kilometers), high spatial resolution, and immunity to electromagnetic interference making it particularly suitable for harsh environmental conditions (Kou et al., 2024).

The application potential of DAS has been extensively explored across multiple domains. Early implementations demonstrated its effectiveness in infrastructure monitoring (e.g., pipelines and railways, geological hazard detection (e.g., landslides), and energy resource management (e.g., hydraulic fracturing monitoring). Recently, DAS-based traffic monitoring (DAS-TM) has attracted growing attention due to its unique capability to address limitations in traditional traffic surveillance systems. For example, the camera-based methods suffer from restricted coverage, weather dependency, and poor nighttime performance, DAS-TM utilizes existing dark fiber networks (unused communication cables) along roadways to provide real-time, weather-resistant

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monitoring over distances exceeding 40 km. This capability becomes increasingly critical as climate change exacerbates geological risks to transportation infrastructure, demanding robust solutions for early warning of road hazards.

2. Basic principle of DAS

When external vibrations or acoustic waves act on an optical fiber, minute fiber deformation (strain) alters the fiber's refractive index and length via the photoelastic effect and geometric changes. This, in turn, affects the phase and intensity of Rayleigh scattering signals (He et al., 2021). The specific relationship between the changes in phase and the strain are as equation (1). These phase changes are directly related to the acoustic signals, and the demodulation process as follows：

$$\Delta\varphi(x,t) = \frac{2\pi}{\lambda}\Delta L(x,t) \tag{1}$$

Where $\Delta\varphi(x,t)$ is the phase change at position x and time t, $\Delta L(x,t)$ is the change in fiber length at position x and time t caused by the acoustic wave and λ is the wavelength of the light used in the DAS system. Phase change is proportional to strain. The DAS system can demodulate the phase of the acoustic or vibration signals, enabling detection and localization of acoustic waves.

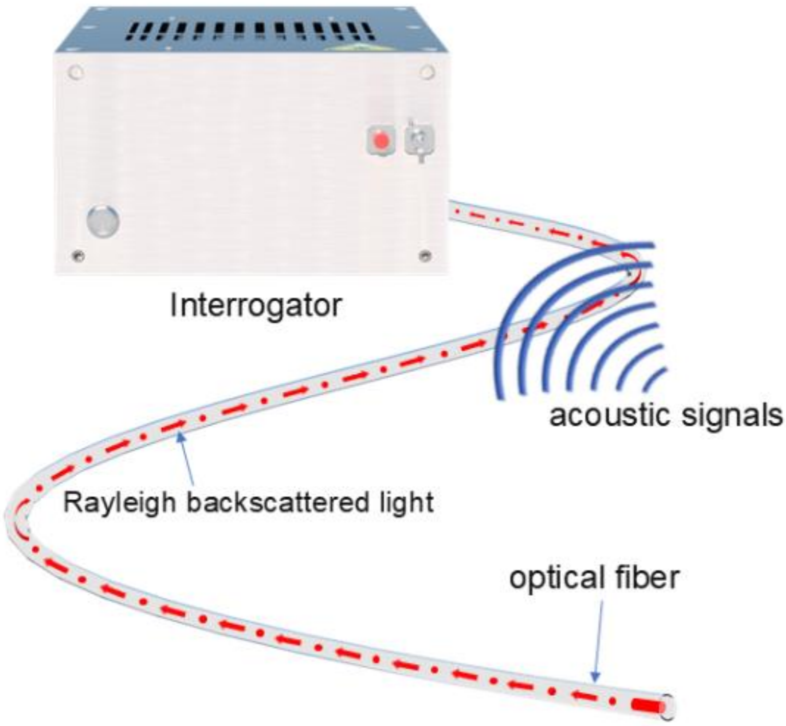


Fig.1 Basic working principle of DAS

3. Applications in Traffic Monitoring and Infrastructure Safety

3.1 Traffic monitoring

With the acceleration of urbanization and the increasing pressure of traffic, the development of intelligent transportation systems (ITS) has become particularly important. ITS can not only monitor and analyze key information such as traffic flow, vehicle speed, and vehicle load in real-time, but also optimize traffic management through data-driven decision-making, thereby effectively alleviating congestion, enhancing road safety, and improving transportation efficiency. DAS offers an innovative solution for ITS. Its immunity to electromagnetic interference and resilience to harsh environmental conditions make it stand out in complex deployment scenarios. When a vehicle travels on the road, the force exerted by its motion causes subtle localized deformations in the road structure (van den Ende et al., 2022). These deformations generate quasi-static waves, which propagate to the optical fiber and are acquired by DAS. Figure 2 illustrates the data processing workflow of DAS in traffic monitoring, which mainly includes the following four steps: (1) Data Acquisition and Filtering: Vibration information at each spatial point is acquired, and bandpass filtering is applied to remove noise and enhance the useful signals. (2) Trajectory Mapping: The spatiotemporal trajectories of vehicles are plotted based on the processed data, revealing the evolution of vehicle signals over space and time. (3) Data Augmentation: The trajectories are optimized to highlight weaker vehicle traces. (4) Trajectory Extraction: Image segmentation is performed on the spatiotemporal trajectory map to facilitate the subsequent extraction of traffic flow, vehicle speed information and location of each vehicle at each time point.

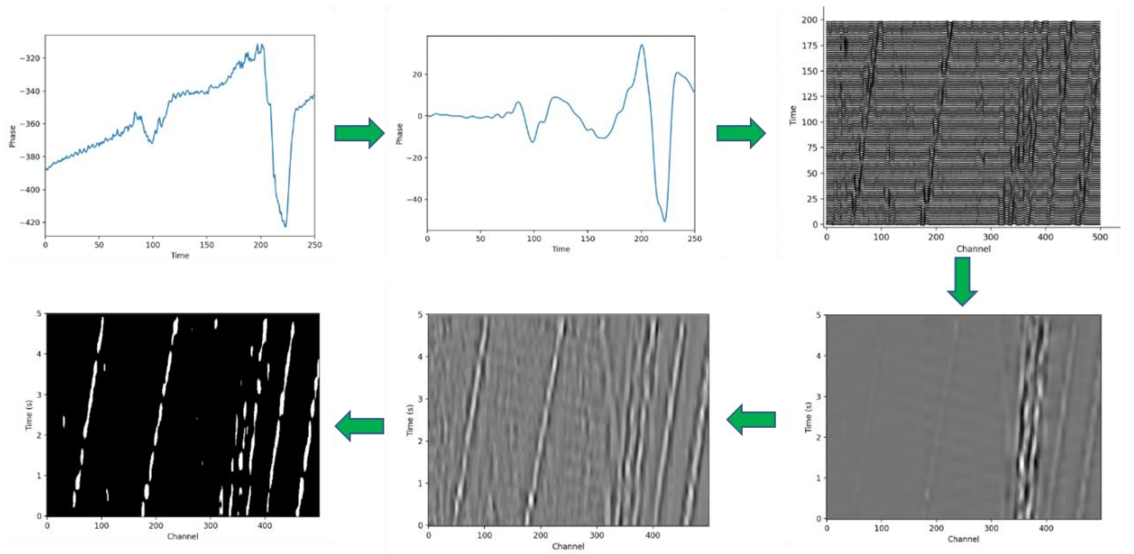
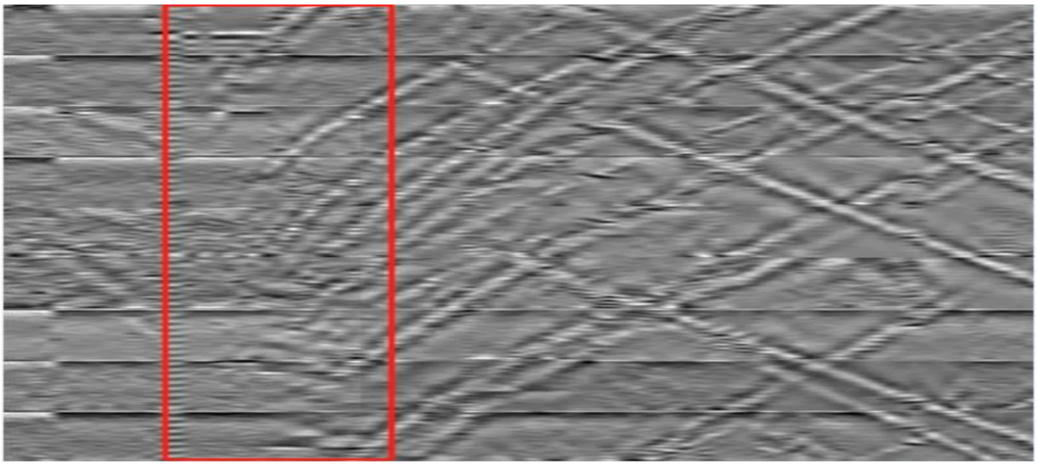
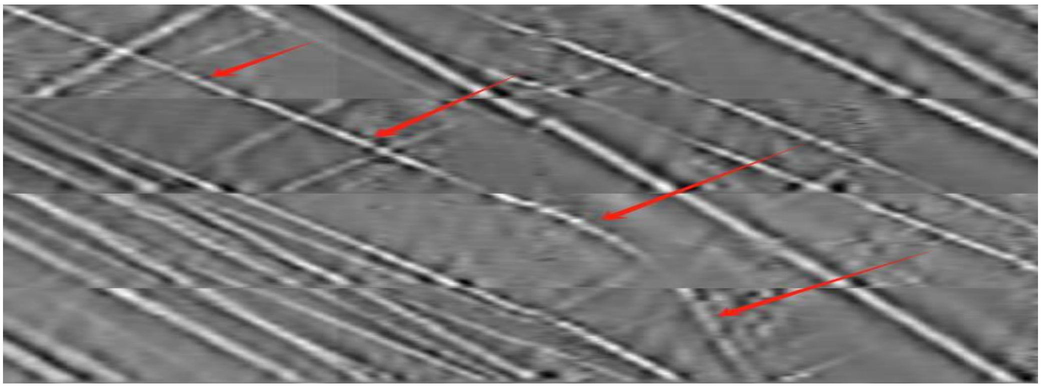


Fig.2 Traffic data processing workflow of DAS in traffic monitoring

The long-range and continuous vehicle trajectory tracking provided by DAS enables the clear visualization of vehicle status on a spatiotemporal graph, and the detection of information such as congestion and vehicle deceleration. Figure 3 shows the detected event data. Figure 3(a), the red-boxed area represents a congestion event, where the speed of multiple vehicles decreases simultaneously. Figure 3(b), the area indicated by the arrow shows an accident, where the vehicle's speed suddenly decreases.



(a)



(b)

Fig.3 The detected event data. (a) Congestion event, (b) Traffic accident.

3.2 Road subsurface monitoring

Acquiring geological structure information beneath highways is of significant importance for identifying and addressing structural safety hazards such as subgrade voids, soil loosening, and uneven geological subsidence. Ambient noise tomography has the advantages of being less susceptible to noise interference and achieving deeper exploration depths, making it the primary method currently used for shallow subsurface structure inversion (Cheng et al., 2023). Optical cables laid alongside roads can simultaneously record vehicle trajectory signals and surface wave signals, which can be used for ambient noise tomography. Figure 4 shows the vehicle signals and surface waves recorded by DAS, intuitively demonstrating the spatiotemporal correlation between surface wave signals and vehicle movement. Figure 5 describes the workflow of ambient noise tomography based on DAS. Figure 5(a) illustrates the process of calculating the cross-correlation functions of noise collected by DAS. One channel in the cable is used as a virtual source, and the others are used as receiver channels. The collected data are downsampled, detrended, and demeaned to reduce errors caused by instruments and random factors. The data are then truncated into sliced data using a certain window length; in this paper, a window length of 30 seconds is used as an example. The sliced data are normalized in time and spectrally whitened, and then the cross-correlation functions between the virtual source and receiver channels are calculated (Song et al., 2021). The obtained cross-correlation functions are stacked to enhance the signal-to-noise ratio. Figure 5(b) shows the process of performing ambient noise tomography along the cable to obtain a 2D S-wave velocity profile beneath the cable. The red solid line represents the laid cable, which can be regarded as a series of sensors. The black triangle represents the virtual source, and the red triangles represent the receiver channels. Common virtual shot gathers are selected along the cable direction, and the operations described in Figure 5(a) are performed on each receiver channel in the common virtual shot gathers. The dispersion curves are extracted using multi-channel analysis of surface waves (MASW) (Park et al., 1999), and after inversion, a 1D S-wave velocity profile beneath the virtual shot gather is obtained. After obtaining 1D velocity profiles at multiple locations, spatial interpolation is performed to finally obtain the 2D velocity profile beneath the cable.

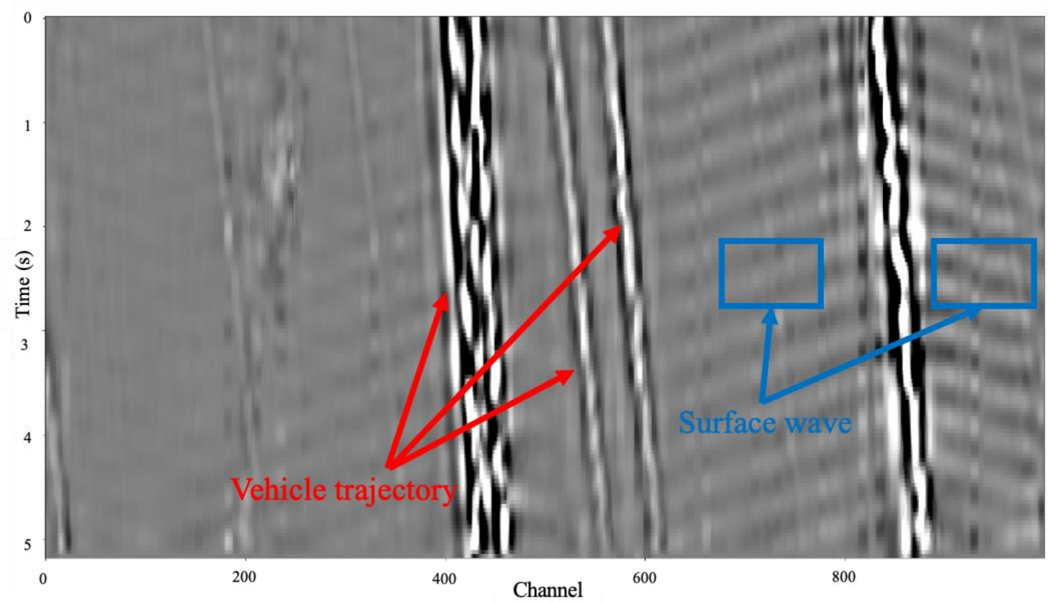


Fig.4 Vehicle trajectory and surface wave records

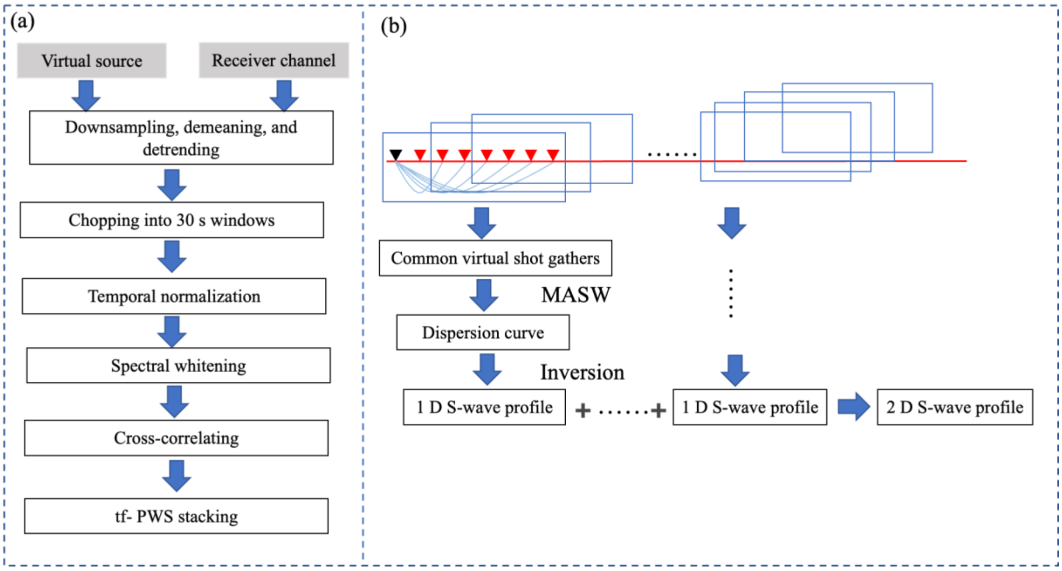


Fig.5 The workflow of ambient noise tomography based on DAS. (a) Workflow for calculating the cross-correlation functions of noise collected by DAS; (b) Workflow for ambient noise imaging along the cable

Based on the workflow illustrated in Figure 5, we can achieve long-term monitoring of the structural health beneath roadways, enabling timely countermeasures against potential safety hazards and ensuring the safety of both personnel and infrastructure.

3.3 Bridge structural health monitoring

Bridges, as a core components of transportation infrastructure, directly affect traffic safety and operational efficiency. By laying optical cables on the monitored bridges or using existing communication cables as distributed sensors, DAS can achieve high-resolution, long-distance, low-cost dynamic monitoring of bridge structures, providing an innovative solution for long-term bridge health management (Liu et al., 2023). Figure 6 shows the frequency characteristics of different bridge locations obtained by performing Fourier transforms on the vibration data collected by the cables laid on the bridge surface. The low-frequency band (<1 Hz) is mainly the quasi-static strain response caused by static vehicle loads. The characteristic frequency band (3-4 Hz) reflects the intrinsic frequency of the bridge, with different frequencies at different locations. For example, frequency discontinuities occur at bridge slab supports, and changes in intrinsic frequency can indicate local structural damage.

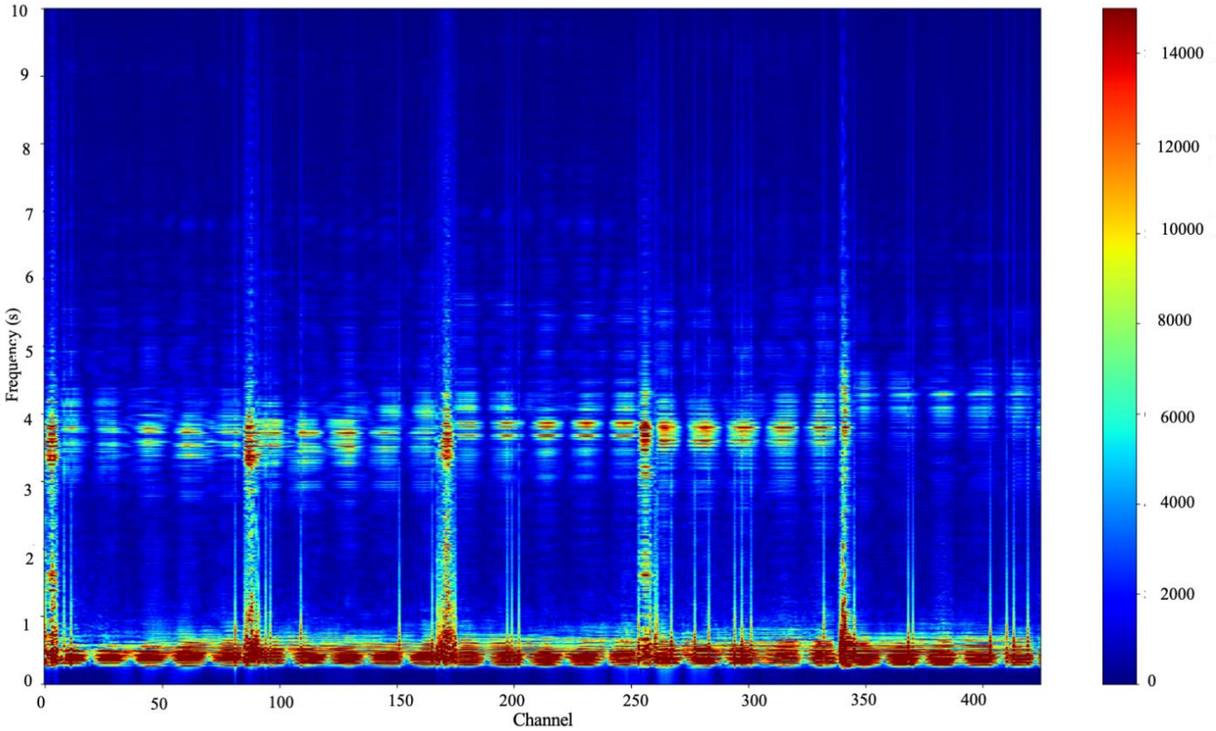


Fig.6 Frequency-domain response characteristics of bridges based on DAS

4 conclusions

This paper presentss the fundamental principles of DAS, highlighting its unique ability to convert optical fibers into dense sensor arrays through Rayleigh backscattering analysis. The technology's applications in traffic monitoring, road subsurface monitoring via ambient noise tomography, and bridge structural monitoring demonstrate its versatility in traffic monitoring and infrastructure health assessment. DAS's ability to provide actionable insights across spatial and temporal scales will be indispensable for resilient smart cities.

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