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Urban Dark Fiber Distributed Acoustic Sensing for Bridge Monitoring

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Keywords:	Bridge, Modal analysis, Urban area, Monitoring, Telecom fiber, Distributed Acoustic Sensing (DAS)
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	and damping identity of structures, highlighting soil-structure coupling between the bridge and underlying soil. This study shows that it is possible to assess the spatial and temporal variability of bridge dynamic response from DAS data using existing fiber networks.



1 Urban Dark Fiber Distributed Acoustic Sensing for Bridge Monitoring

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11 12 **Abstract**

13 Distributed Acoustic Sensing (DAS) technology applied to telecommunication fiber optic
14 networks offers new possibilities for Structural Health Monitoring (SHM). The dynamic
15 responses of five bridges are extracted along a 24 km long optical fiber crossing the Lyon
16 metropolitan area in France. **From their characteristics signals**, three physical parameters
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27 and temporal variability of bridge dynamic response from DAS data using existing fiber
28 networks.

29
30 **Keywords:** Distributed Acoustic Sensing (DAS) – Monitoring – Modal analysis – Telecom
31 fiber – Bridge – Urban area

1. Introduction

The recent collapse of several bridges such as the Morandi Bridge in Genoa in 2018 (Calvi et al., 2019) and the Florida International University Pedestrian Bridge (Cao et al., 2020) has highlighted the need for society to devise monitoring strategies to prevent such failures (Figueiredo and Brownjohn, 2022). Failure often occurs due to design flaws, inadequate materials, overloading, or maintenance. Following the Morandi bridge collapse, nearly 35 000 French structures were diagnosed as being in poor structural condition and requiring close inspection (Maurey et al., 2019). Depending on operational conditions (Jacobsen et al., 2007; Chen et al., 2021; Anastasopoulos et al., 2021) and types of damage (Hearn and Testa, 1991; Khoo et al., 2004; Ernst et al., 2022), Operational Modal Analysis (OMA) based on periodic or continuous measurements with sensor networks (Brownjohn et al., 2010; Magalhães et al., 2008) can be a suitable solution for anomaly detection and early warnings before a potential collapse (Doebling et al., 1996; Peeters and De Roeck, 2001; Farrar et al., 2001; Farrar and Worden, 2007). Most of the sensors currently in use are point sensors, such as inclinometers, velocimeters, accelerometers and extensometers, with maximum sampling lengths of a few tens of meters. These technologies are laborious to implement when it comes to multiplying measurement points over kilometers of linear length (Glisic and Inaudi, 2012; Rizzo and Milazzo, 2021), or to achieve very high spatial sampling on particularly stressed structures subject to earthquakes, extreme environmental conditions, or significant traffic load such as motorway bridges (Gara et al., 2019). In urban environments, the installation of such sensors, dedicated to monitoring, can also prove difficult due to the density and complexity of the layout (various traffic, transport infrastructures, buildings) (Snover et al., 2021).

Distributed Acoustic Sensing (DAS) technology is an emerging alternative offering new observational possibilities, by giving easy access to hundreds to thousands of data points along telecom optic fiber networks (Jousset et al., 2018; Ajo-Franklin et al., 2019). This technology consists in making laser scattering measurements on an optical fiber to estimate the deformation of the cable associated with environmental vibrations. Initially developed for the oil and gas industry for detecting leaks along pipelines (Tanimola and Hill, 2009), building vertical seismic profiles in wells (Mestayer et al., 2011; Hartog et al., 2014) and doing reservoir monitoring (Johannessen et al., 2012; Mateeva et al., 2014), this technology is now exploited in various applications for fault detection (Jousset et al., 2018; Wang et al., 2018), subsurface imaging (Ajo-Franklin et al., 2019), statistical analysis of road traffic (Van den Ende et al., 2022; Song et al., 2021), ambient noise analysis (Dou et al., 2017; Zeng et al., 2017), and studying the

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3 65 interaction of ocean masses with the solid Earth (Hartog et al., 2018; Lindsey et al., 2019;
4 66 Sladen et al., 2019). We use here the technology in the frame of the Distributed Acoustic
5 67 Sensing Auvergne Rhone-Alpes (DASARA) project, to characterize the urban seismic
6 68 environment.
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10 69 **The main goal of this study is to assess the effectiveness of utilizing dark fiber, which refers**
11 70 **to non-illuminated fiber for internet data transfer, in monitoring spatially distributed bridges**
12 71 **within an urban setting using modal-based methods (Cunha et al., 2018).** To achieve this, we
13 72 conducted Operational Modal Analysis (OMA) on five bridges using DAS data. The DAS data
14 73 was continuously collected over 53 hours at a distance from the structures, covering a 24km
15 74 urban telecommunication dark optical fiber. To determine the utility of urban fiber optics for
16 75 structural monitoring, we compared the results obtained from the DAS measurements with
17 76 independently acquired velocimetric data from one of the five bridges.
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25 77 After a description of the experiment in section 2, we outline in section 3 the numerical
26 78 methods used to extract modal parameters from the experimental data. Then, we present in
27 79 section 4 the results of the comparison between the two types of data (DAS and velocimeters)
28 80 for one bridge, before showing the results of the OMA performed on the other bridges along
29 81 the interrogated fiber (section 5). Finally, we interpret our results in section 6 and highlight the
30 82 main conclusions of the study in section 7.
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38 84 **2. A 24 km-long urban optical fiber experiment**

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41 86 With a population nearing 1.33 million, the Lyon metropolitan area is advancing its
42 87 smart city capabilities through a network encompassing over 900 km of optical fiber and 14
43 88 operator access points (Figure 1a). In this study, the DAS interrogator was linked to the fiber at
44 89 an operator access point (POP) in the northwest. **The dark fiber utilized here is a G657-A1 step-**
45 90 **index single-mode telecom fiber, a specification set by the International Telecommunications**
46 91 **Union (ITU). It is designed to function at 1310nm or 1550nm and features a 9 μ m diameter**
47 92 **silica core, allowing light to travel extensive distances without requiring re-amplification. To**
48 93 **preserve signal quality across long distances, this fiber type minimizes chromatic dispersion**
49 94 **and signal losses through attenuation; specifically, the attenuation is less than 0.2dB per km for**
50 95 **the 1550nm wavelength employed in this experiment.**
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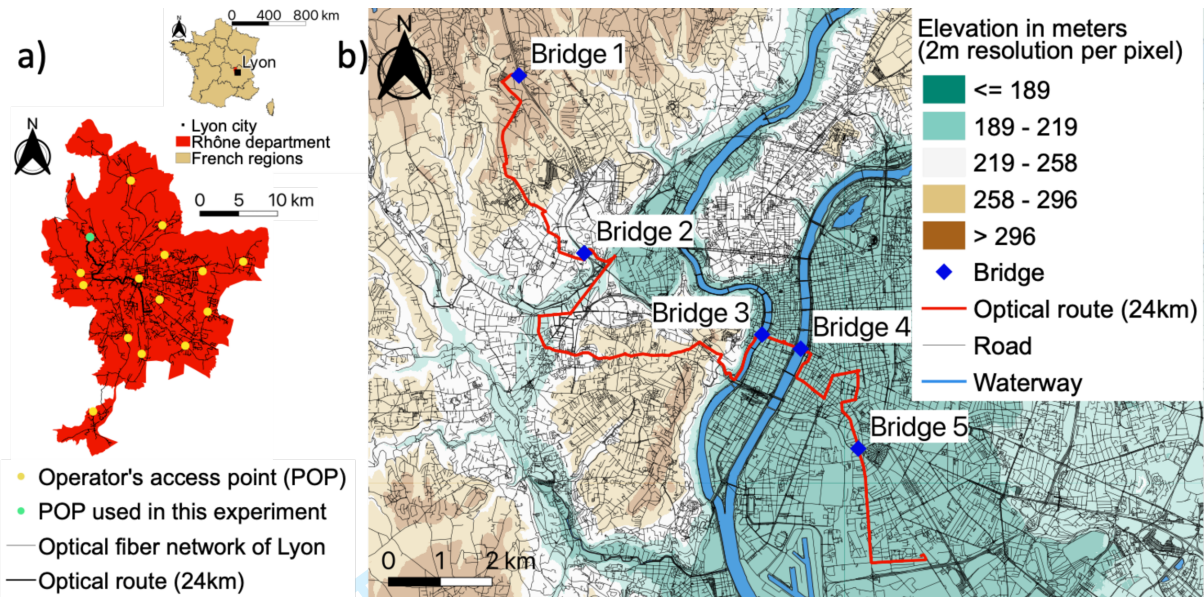
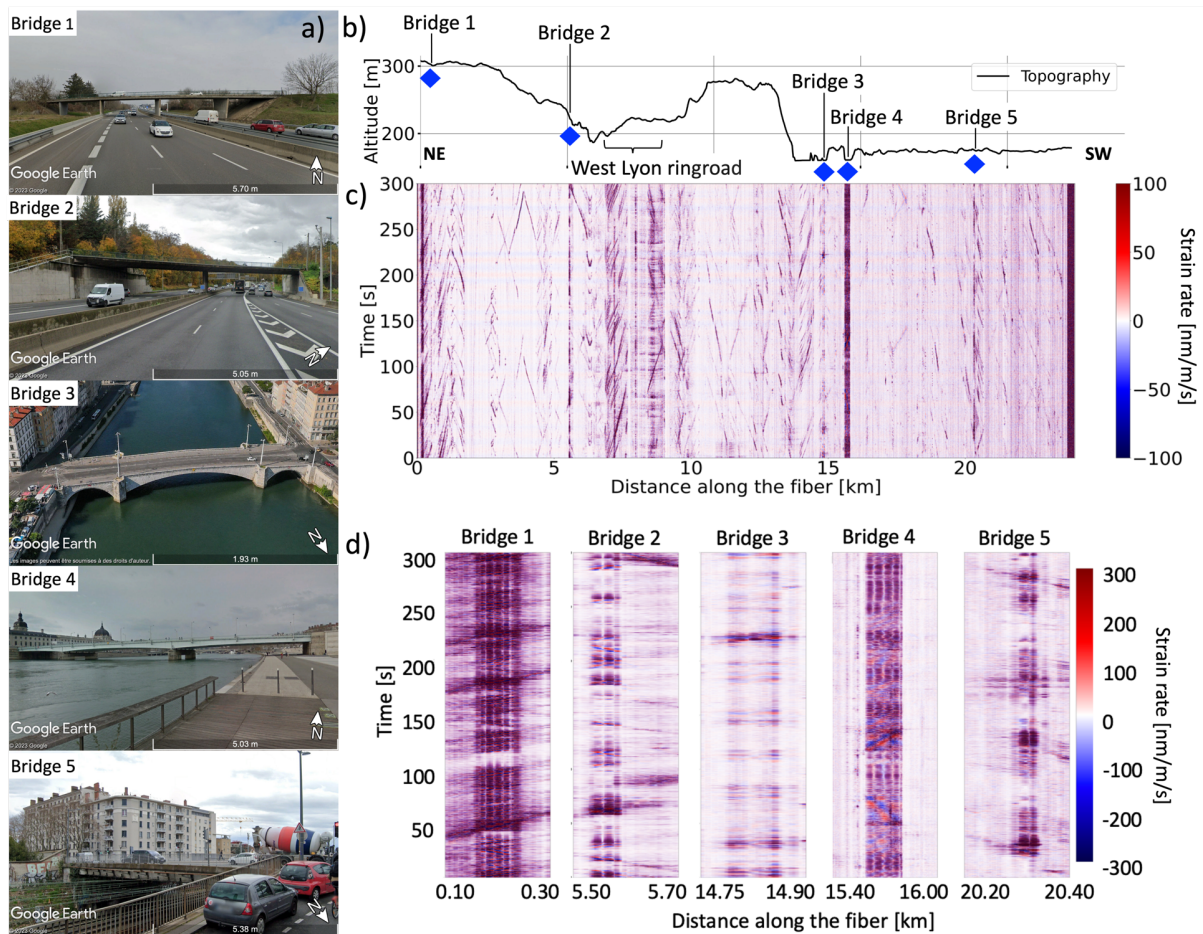


Figure 1: a) Map displaying the Lyon fiber network in black and highlighting fiber access points in the Lyon metropolitan area in yellow. The green dot denotes the access point used in the initial DASARA experiment. b) Map illustrating the region's topography, optical path, and the position of the structures. The access point is situated near Bridge 1 in the northwest. This map was generated using the Density Analysis plugin of the geographic information system software QGIS (Quantum GIS) and a DTM made available from the Metropole of Lyon. The DTM was generated in 2018 from raw data (slope break lines and points on the ground) on the territory of the Metropole of Lyon with a resolution of 2m per pixel.

DAS data are acquired along the 24 km of optical fiber (Figure 1b), sampling three types of geology, three different urban fabrics and five bridges. The raw data are dominated by transient signals associated with road traffic, as well as high-amplitude quasi-stationary bands associated with bridges over the A6 Lyon-Paris highway and the Saône and Rhône rivers (Figure 2c,d).

Telecom optical fiber is passed through technical ducts of bridge decks. Bridges 1 and 2 are similar road bridges with prestressed concrete girders: the first one is 64 meters long and has 5 spans, the second one is 56 meters long and has two spans. Bridge 3 is also in prestressed concrete, but with a 124-metre-long arch structure comprising three arches: a large 67.50-metre central arch and two 25.75-metre lateral arches (Figure 2a). A special feature of this bridge is its decorative ashlar cladding. Unlike the previous ones, Bridge 4 is a steel box girder bridge with a total length of 205 meters and three spans. Finally, Bridge 5 is a small, 35-meter-long prestressed concrete frame bridge. Bridges 1, 2 and 5 date from the 1970s, while bridges 3 and 4 date from the 1950s.

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123 **Figure 2:** a) Photo of each instrumented bridge. b) Vertically exaggerated topographic profile
 124 extracted along the 24 km of fiber. c) 5 minutes of strainrate data along the 24 km of fiber. The
 125 strainrate corresponds to the time derivative of the strain and is expressed in nm/m/s. d) 5
 126 minutes-long sections of strainrate data emphasizing the signals from the five bridges. Bridge
 127 1: Highway Paisy (A6), Bridge 2: Interchange (A6), Bridge 3: Saône river, Bridge 4: Rhône
 128 river, Bridge5: Railway.

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130 3. Materials and Methods

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132 Ambient vibration recordings offer a reliable and consistent source of dynamic
 133 information regarding structural behavior (Peeters and De Roeck, 2001; Magalhães et al.,
 134 2008). The main sources of structural excitation include traffic on the deck and ambient
 135 anthropogenic noise, such as external traffic, construction activities, and industrial operations,
 136 as well as natural elements like wind and earthquakes. Particularly, ambient vibration
 137 recordings enable the estimation of dynamic parameters associated with variations in the

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3 138 physical properties of the structure (De Roeck et al., 2003; Xia et al., 2003; Cunha and Caetano,
4 139 2006). Consequently, they serve as a valuable tool for monitoring the condition of structures
5 140 (Farrar et al., 2001; Magalhães et al., 2012).

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9 142 **3.1 DAS acquisition**

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13 144 By sending high-frequency laser pulses into the fiber, an optoelectronic interrogator
14 145 unit records and analyzes the backscattered light from heterogeneities along the cable
15 146 (Tanimola and Hill, 2009). The silica constituting the core of the telecom optical fiber contains
16 147 defects inherent to the manufacturing process. These heterogeneities disturb the flow of photons
17 148 and reflect part of the light according to the principle of Rayleigh scattering. Since it is related
18 149 to defects in the structure of the optical fiber, Rayleigh backscattering is repetitive all along the
19 150 optical fiber (Froggatt et al., 2004). When the fiber is disturbed by an external event (passage
20 151 of a car, an earthquake, etc.), the fiber locally deforms, in compression or dilatation. This
21 152 introduces a phase shift in the backscattered light (e.g. Fichtner et al. 2022), and the scattering
22 153 spectrum of the fiber is modified accordingly (Gifford et al., 2007). This phase shift makes it
23 154 possible to locate and measure the variation of the physical parameter at the origin of the
24 155 disturbance. In our experiments, we use an optoelectronic interrogator unit FEBUS A1-R from
25 156 the FEBUS Optics company.

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36 157 The optical phase shift between two positions along the optical fiber is linked to the
37 158 longitudinal strain applied to the fiber through the following equation:

$$39 \quad \varepsilon_{yy} = \frac{\lambda \cdot d\theta}{4\pi \cdot n \cdot GL \cdot \xi} \quad (Eq. 1)$$

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44 160 where ε_{yy} is the longitudinal strain, λ is the optical wavelength, $d\theta$ is the phase shift, n is the
45 161 optical fiber index, and ξ is a correction factor. The measurement of optical phase shift is
46 162 obtained along an integration distance called the gauge length (GL). The main acquisition
47 163 parameters are the length l of the interrogated fiber, the frequency f of the interrogation pulses
48 164 (giving the temporal sampling interval), the spatial sampling interval Δx , and the gauge length
49 165 GL to optimize the optical signal. These parameters must be adjusted according to the signal to
50 166 be detected, as well as the acquisition rate to guarantee the integrity of the recorded data.

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56 167 Generally, the gauge length should be less than the wavelengths of the acoustic signal
57 168 of interest. The smaller the gauge length, the finer the spatial sampling and, in theory, higher
58 169 frequency bridge deformation modes can be measured. But the smaller the gauge length, the

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3 170 higher the noise level in the data because the strain measurement is integrated over a smaller
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5 171 distance. As a compromise, we opted for a gauge length of 10m and a spatial sampling interval
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7 172 of 5m, enabling the extraction of the bridges' dynamic characteristics. The data were collected
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9 173 in strain rate ($\text{nm.m}^{-1}.\text{s}^{-1}$) at a sampling frequency of 400Hz and subsequently resampled at
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11 174 100Hz before undergoing digital processing.
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176 **3.2 LE-3D/5s MkIII sensors and CityShark acquisition**

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178 To assess the significance of the measurements taken on the bridges with the telecom
179 fiber, these are compared with conventional measurements. Fifteen-minute-long measurements
180 are taken along the deck of the Bridge 1 using a Cityshark acquisition system (Chatelain et al.,
181 2012) and four velocimeters LE-3D/5s MkIII (Figure 3a), over rolling positions every 4 meters
182 to mimic synchronous measurements of structure deformation (see procedure given by Michel
183 et al., 2010). The first horizontal component of the velocimeters is placed in the direction of the
184 longitudinal axis of the bridge, assuming that the fiber is oriented along this axis. These
185 conventional data have been acquired with a sampling frequency of 200Hz.

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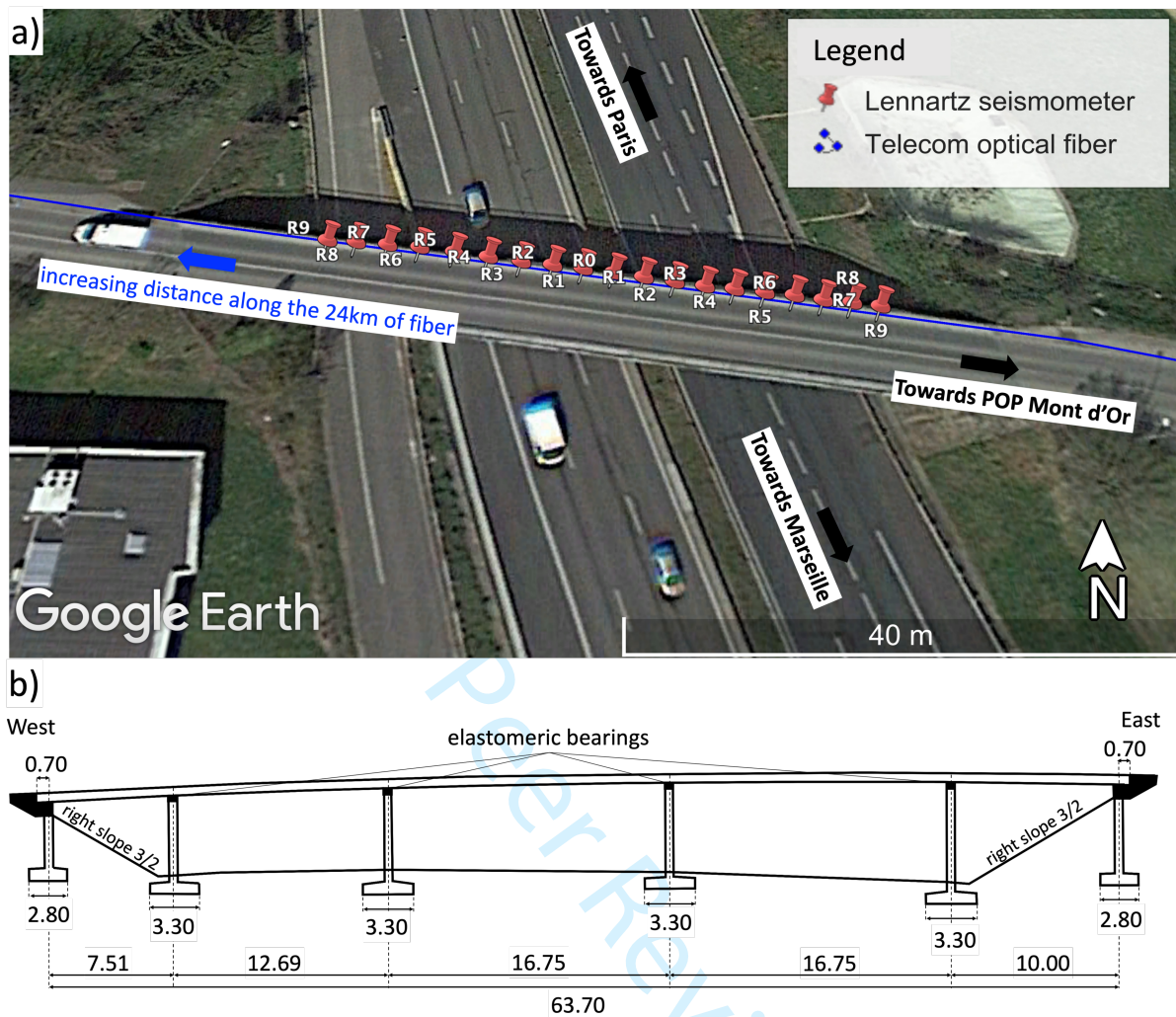


Figure 3: a) Satellite image of the Bridge 1 (Paisy bridge) crossing the A6 highway, with the positions of the velocimeters used to acquire conventional measurements. b) Longitudinal section of the Bridge 1 (modified from a plan of the Ministry of Equipment, Rhône Department, Boussiron Company). The dimension is given in meters.

3.3 Postprocessing

3.3.1 Power Spectral Density

To perform the comparison between conventional data and the fiber data, power spectral density (PSD) functions are calculated using the Welch's method (Welch, 1967) (Figure 4). Spatial variations in frequency along the bridges (Figure 5) are estimated from PSDs computed over the 53h of data with 50% overlap in time, to reduce the error of the PSD estimate. From the PSDs, we perform temporal tracking of bridge responses and modal frequencies (Figures 6

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3 201 and 7). For frequency monitoring, the 53h data are segmented into half-hour portions. Then,
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5 202 the PSDs are calculated for the 15 2-minute-long windows of each half-hour without overlap.
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8 204 **3.3.2. Singular Value Decomposition**

10 205 We decompose the dynamic response of structures into independent orthogonal
11 206 eigenvectors using singular value decomposition (SVD) (Rao, 1973,). SVD provides the
12 207 eigenmodes of the structure, useful to identify modes that are very close in frequency and detect
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14 208 changes in vibration modes of the structure (Magalhaes and Cunha, 2011). The SVD is applied
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16 209 to a matrix comprising all the spectra along a bridge evaluated at all discrete frequencies
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18 210 between 0 and 50 Hz. SVD enables us to reduce the dimension of the data and facilitate its
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20 211 visualization. The eigenvectors shown in section 5 are associated with the highest singular value
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22 212 and represent the dominant vibration modes of the bridge.
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26 214 **3.3.3 Random Decrement Technique**

29 215 The damping coefficient of the bridge structure is calculated using the random
30 216 decrement method (RDT) (Cole, 1973). Based on the principle that the response of a system to
31 217 any loading consists of three parts – the response to an initial displacement, the response to an
32 218 initial velocity and the response to a random load between the initial state and time t - this
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34 219 technique consists on averaging a large number of segments of the temporal response of the
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36 220 system with the same initial conditions (Mikael et al., 2013). By erasing the random component
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38 221 of the analyzed signal, this technique therefore allows access to the response of the system due
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40 222 to the initial conditions alone, also known as the impulse response or RD function. Averaging
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42 223 these time segments also helps to reduce the level of noise in the RD functions, which is
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44 224 particularly important as the measured structural responses are always partially noisy. We chose
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46 225 to look for all the places where the signal crosses zero to select the signal segments to be
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48 226 averaged (Rodrigues and Brincker, 2005).

50 227 In our study, the 53 hours of DAS data are divided into half-hour portions. One
51 228 frequency and damping values are obtained per half-hour without overlapping windows. Then,
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53 229 the RDT method, described in Gueguen et al., 2016 and Brossault et al., 2018, is applied to
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55 230 each of the 30-minute portions, corresponding to more than 8000 periods of the first mode of
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57 231 Bridge 1 (around 4.6Hz). The calculation of the RD function assumes that each signal window
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59 232 of length τ is stationary. For each half-hour portion, $N = 1800/5 = 360$ windows are selected as
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3 233 a minimum (without overlap). In practice, there is considerable overlap between each 5 s
4 234 window, so N is greater than 500 windows, which is essential to obtain a stable and relevant
5 235 estimate of the damping (Jeary, 1997). For each half hour, a RD function is obtained for each
6 236 mode. This function is exponentially damped and satisfies the so-called logarithmic decrement
7 237 of the damping (Clough and Penzien, 1993). The damping value ξ is obtained by performing a
8 238 linear regression on the natural logarithm of $\exp(-\xi\omega t)$, which corresponds to the envelope
9 239 of the RD function. Before windowing and calculating the RD function, a bandpass filter is
10 240 applied to the time signal. This filter is a 20% frequency band centered on each vibration mode.
11 241 Each damping value is calculated in the middle of the structure assuming that the deformation
12 242 is the most important there.
13 243

24 244 **3.3.4. Operational Modal Analysis**

25 245 In our study, the shape of the vibration modes is reconstructed from both types of data
26 246 (velocimeters and optical fiber) using the non-parametric SSI-COV method. The Stochastic
27 247 Subspace Identification (SSI) method is a time domain method allowing the identification of
28 248 modal parameters (Van Overschee and De Moor, 1996) and a variant of this method is the
29 249 Covariance-Driven SSI (SSI-COV) algorithm (Magalhaes and Cunha, 2011). To calculate the
30 250 modal shapes from the records, we use the Python implementation of the SSI-COV method
31 251 from the CESSIPy module (Carini and Rocha, 2022).
32 252

33 253 **3.3.5. Modal Assurance Criterion (MAC)**

34 254 Correlation coefficients such as the modal assurance criterion (MAC) are often used to
35 255 detect structural damage from the modal deformations of a structure (Allemang and Brown,
36 256 1982). This coefficient allows to evaluate the degree of correlation between two measured
37 257 modal deformations. After validation of the modal shapes of Bridge 1 obtained with the fiber
38 258 (Figure 8a, b), this MAC index is calculated between the first modal shape recorded (considered
39 259 to be the reference) and the modal shapes of each half-hour during the 53 hours of recording.
40 260 A coefficient of one represents a perfect correlation between the curves and no damage
41 261

42 262 **3.3.6. Uncertainty estimates**

43 263 The raw DAS signal is cut in half-hour windows, over which are estimated the frequencies
44 264 through direct measurement, and the damping coefficient through the RDT method. In both
45 265 cases, the uncertainties are calculated by constructing distributions of measurements through
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3 266 the bootstrap resampling method (Efron and Tibshirani, 1991). To perform time tracking of
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5 267 frequencies and structural damping, a mean value and standard deviation are determined for
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7 268 each 30-minute signal window. For this purpose, 100 bootstrap samples per 30-minute window
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9 269 are created. Each sample is the result of randomly drawing 15 2-minute windows for the
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11 270 frequency measurement and a set of initial conditions (greater than 4000) for the damping
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13 271 measurement. For each sample, an average PSD or RD curve and a damping value are
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15 272 calculated. The measurement and error on the measurement are obtained from the average and
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17 273 standard deviation over the 100 bootstrap samples.
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20 275 **4. Comparison between conventional and DAS measurements**

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22 277 **4.1 Characteristic spectral signature of the Paisy bridge**

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25 279 The singular value decomposition (SVD) of the seismic signal recorded at the center of
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27 280 Bridge 1 reveals two distinct characteristic modes at 4.6Hz and 6.0Hz, respectively. Notably,
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29 281 the frequency response exhibits clear distinctions between measurements taken on and outside
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31 282 the bridge for both data types. Despite uncertainties, the velocimetric and fiber-optic
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33 283 measurements consistently indicate identical frequency values for these predominant modes
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35 284 (see Figure 4). Additionally, at higher frequencies, other modes can be identified, aligning
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37 285 closely with velocimetric measurements. All these modes offer valuable insights for
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39 286 characterizing the dynamic response of the bridge, as discussed in section 4.4.
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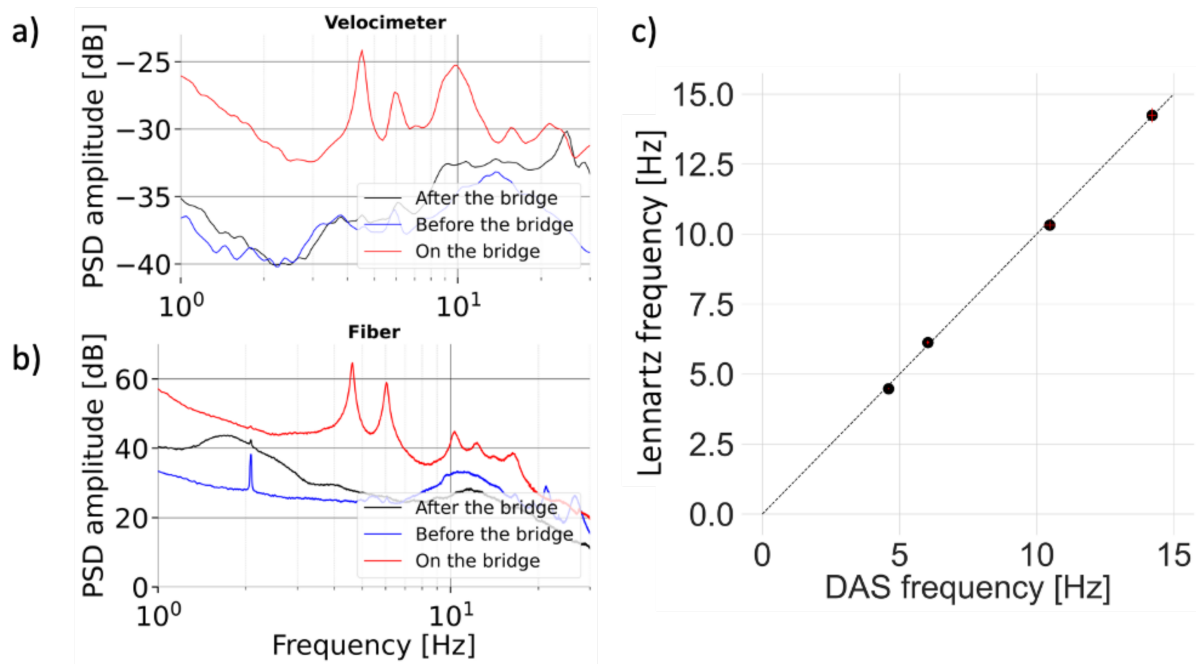


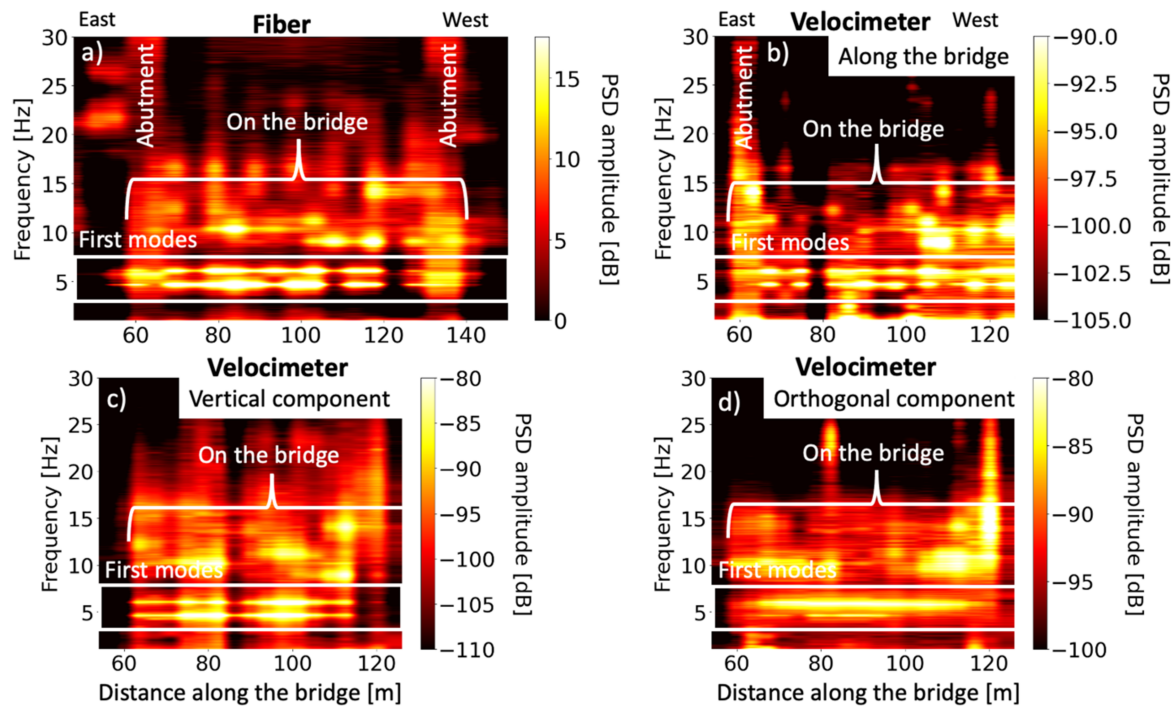
Figure 4: Fifteen minute PSDs of three traces obtained on the bridge (at the midpoint), after (152 meters beyond the west abutment) and before (60 meters before the east abutment) Bridge 1 (Paisy bridge) for the velocimeter a) and the telecom fiber b). a) Correlation diagram illustrating the relationship between velocimetric and fiber frequency measurements for the initial four vibration modes of Bridge 1. The uncertainties in red are smaller than the width of the measuring points shown in black.

4.2 Spatial variation of the Paisy bridge dynamic response

We evaluate the relevance of making measurements of the dynamic response of the bridge by exploiting the fine spatial sampling provided by the optical fiber. We use the velocimetric measurements for validation. Both data give consistent results for the modal frequencies and spatial variations of their relative amplitudes (Figure 5), despite differences in terms of spatial sampling. The two modes at 4.6 Hz and 6 Hz are clearly tracked along the bridge, both for fiber (Figure 5a) and velocimeter data (Figure 5b, d).

From the fiber data, the dynamic response of the abutments is identified and has a much wider frequency band (up to 30Hz) than the deck which is lower frequency (lower than 17Hz) (Figure 5a). This broadband response of the abutments is also observed on the velocimeter data, on the eastern side of the bridge (Figure 5b). The west abutment is not visible in the velocimetric data because we did not make enough measurement points in the western direction to observe it. Figure 5a and Figure 5b, c show areas where the spectral amplitude of the PSDs is attenuated

310 compared to the rest of the structure. These nodes can be considered as bearing areas, where
 311 there is less deformation and displacement due to the presence of the bridge piers. Compared
 312 to velocimeter measurements (Figure 5), the dynamic response of the structure seems to be
 313 equally well resolved with the fiber, even for the higher vibration modes. A better resolution
 314 could be obtained by decreasing the gauge length GL and the spatial resolution Δx in the DAS
 315 acquisition, and by decreasing the spacing of the velocimeters along the structure.



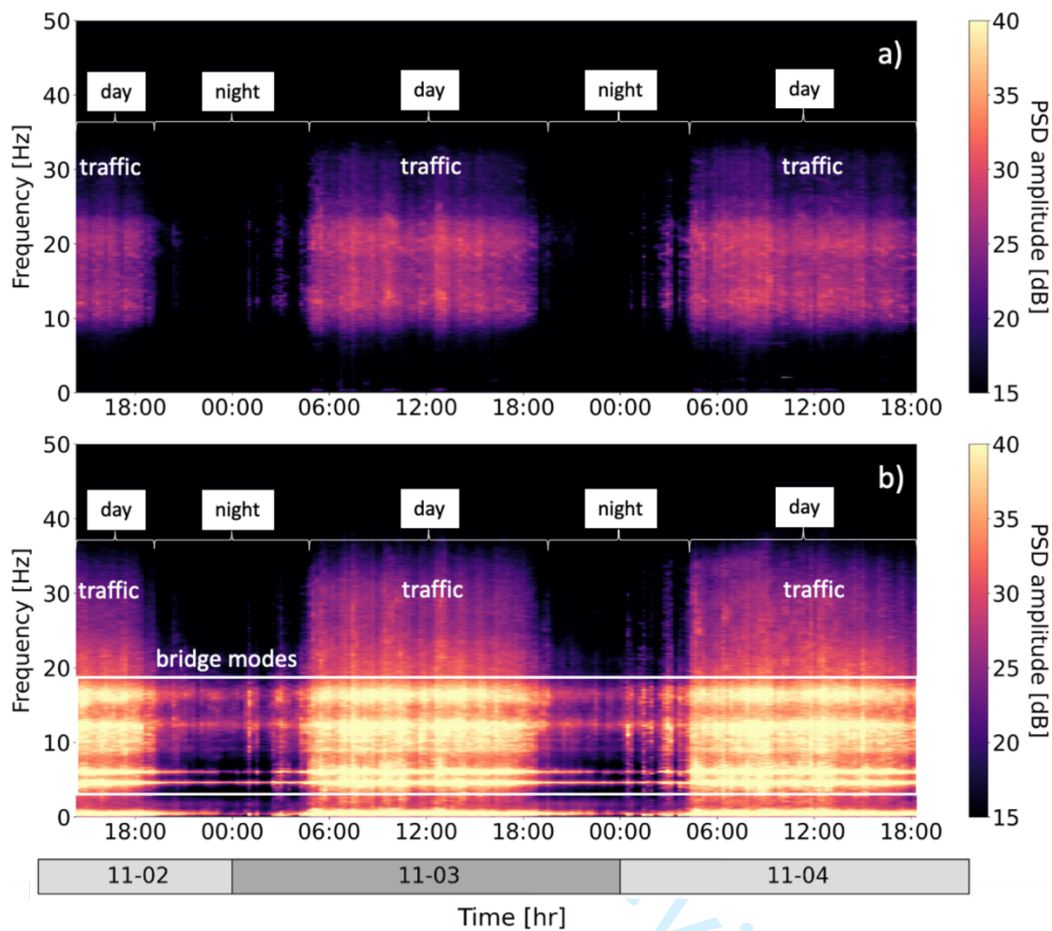
317
 318 **Figure 5:** Spatial variations of the frequencies obtained for 15 minutes of recording from the
 319 telecom fiber a) and the three velocimeter components along the bridge b), in the vertical
 320 direction c) and orthogonal to the bridge d).

322 4.3 Temporal variation of the Paisy bridge dynamic response

324 We present in Figure 6 the temporal evolution of the dynamic response in the middle
 325 and outside the bridge 1 during the 53 hours of the DAS experiment. A clear day/night cycle
 326 appears, due to variations in the noise level originating from anthropic activity, mainly road
 327 traffic sources (Figure 6a, b). The noise level is much lower at night than during the day, and
 328 the dynamic response of the bridge can be observed continuously day and night (Figure 6b).
 329 The first clearly visible vibration modes are at 0.3, 4.6 and 6Hz. Other higher modes are visible

330 between 10 and 18Hz. A comparison of the two spectrograms shows that the traffic response
 331 between 25Hz and 35Hz appears to be amplified by the structure.

332



333
 334 **Figure 6:** Spectrograms over 53 hours of data acquisition representing the temporal variations
 335 of anthropogenic activity and the cyclicity of the source a) **outside (158 meters beyond the west**
 336 **abutment)** and b) in the middle of the structure. The date in November is indicated in gray at
 337 the bottom. These spectrograms are obtained from the power spectral densities of the fiber
 338 signals.

339

340 In order to assess the stability of the dynamic measurements made with the telecom
 341 fiber, we observed the temporal variations of the natural frequencies and their respective
 342 amplitudes during the 53 hours of acquisition (Figure 7). **We do not correct for the effect of**
 343 **temperature (see section 6.3).** The frequencies of the first two modes vary by 0.0986Hz and
 344 0.0852Hz respectively. The first mode therefore seems to be the most influenced by
 345 environmental conditions. Overall, these two modes follow a cyclic evolution with a slight
 346 increase in frequency during the night (Figure 7a, b).

Amplitudes vary over time, following the day/night cycle, and fluctuate with human activity (Figure 7c, d). The amplitudes increase during the day and decrease at night, which seems consistent with the fact that the traffic excites the bridge during the day (Figure 6). The amplitude variability of daytime measurements is larger than the one of nighttime measurements (Figure 7c, d).

We present in Figure 7e, f the damping measurements obtained from the RDT method in the middle of Bridge 1. Variations also tend to follow a day/night cycle, with a slight decrease during nighttime.

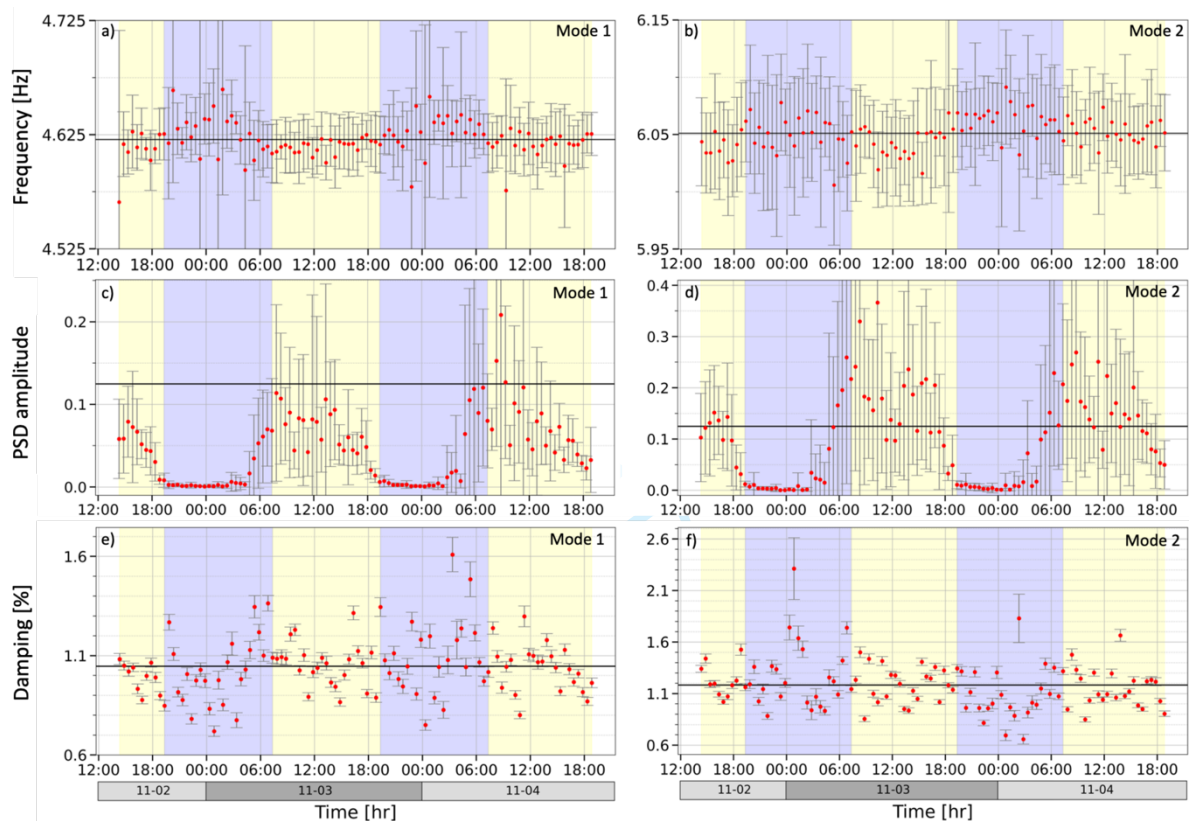


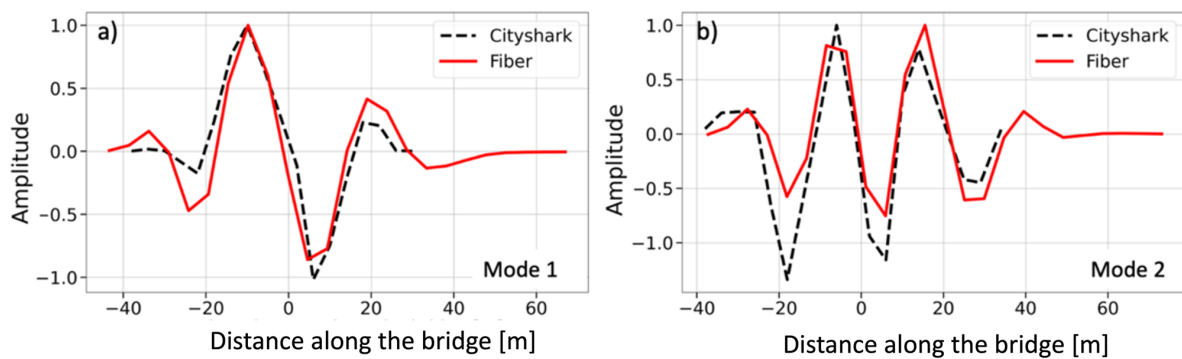
Figure 7: Temporal variations of the frequency, the amplitude and damping of the Paisy bridge from telecom fiber data for mode 1 a), c) and e) and mode 2 b), d) and f). Uncertainties are calculated using bootstrap resampling. Frequencies are measured on power spectral densities and damping is calculated using the RDT method.

4.4 Modal shapes of the Paisy bridge

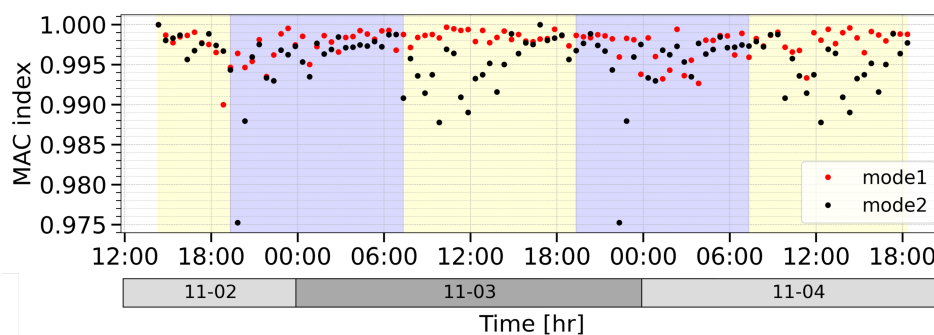
Modal shapes for the two vibration modes at 4.6 and 6Hz are associated with two bending modes. Indeed, according to the velocimetric measurements, the 4.6Hz and 6Hz modes correspond to the first vertical (Y-Z plane) and transverse (X-Y plane) modes of the structure

366 respectively. With the fiber, the same modal shapes are identified with the position of the five
 367 spans and the bridge piers blocking the vertical movement (Figure 8). In both types of data, the
 368 amplitude of the vertical mode is higher on the western span than on the eastern span (Figure
 369 8a). In contrast, the transverse mode is more symmetrical and its oscillations are more regular
 370 (Figure 8b). For higher modes, the difference in space sampling for the velocimeter and the
 371 DAS provide the largest differences in modal shapes. Because of its continuous space sampling,
 372 DAS solution is much more efficient than velocimeters for mode shape reconstruction.

373 Figure 9 shows some variations in the value of the MAC index during the DAS
 374 acquisition. Occurring mainly at night, these variations are transient and their amplitude does
 375 not exceed 0.01. MAC indices tend to decrease during the night and then rise and stabilize
 376 during the day. The decreases in observed MAC index cannot be associated with damage to
 377 Bridge 1 because they are not irreversible (Gueguen and Tiganescu, 2018). These variations
 378 reflect a change in the dynamic behavior of the bridge during the night, and seem to be
 379 correlated with variations in other modal parameters (Figure 7).



380
 381 **Figure 8:** Modal shapes obtained with the SSI-COV method for the two first modes of Bridge
 382 1 from the data recorded by the velocimeters and telecom fiber.



384
 385 **Figure 9:** Variations in the MAC index over the 53 hours of acquisition for the Bridge 1. The
 386 MAC index is calculated every half-hour in relation to the reference modal deformation,
 387 corresponding to the first half-hour of acquisition.

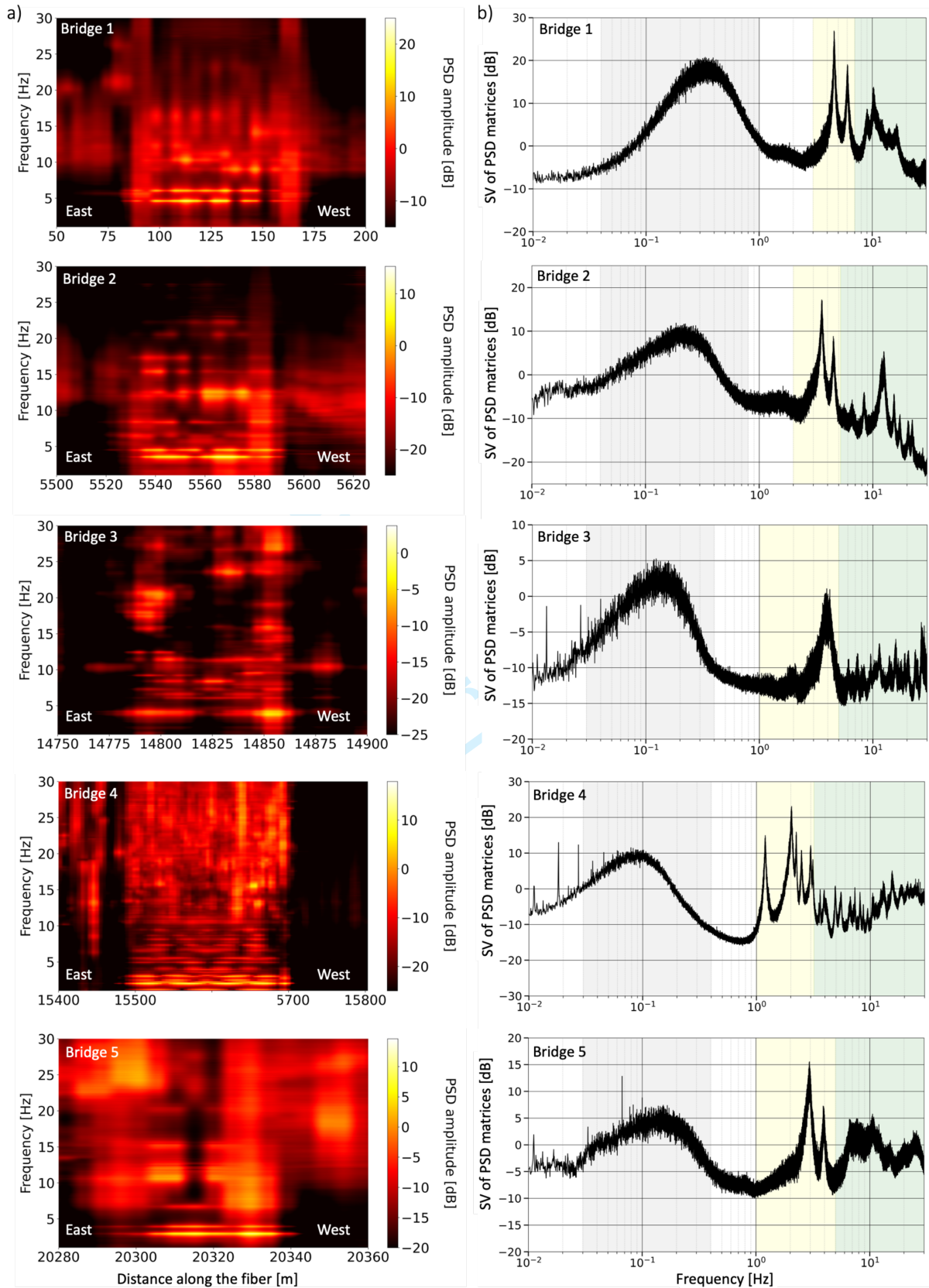
5. Dynamic responses of the five bridges from a single DAS acquisition

Following the validation of fiber measurements on Bridge 1 through comparison with velocimetric data, we extended our analysis to the four other bridges situated along the same optical path. Modal characteristics such as natural frequencies, damping, and modal shapes were extracted and are presented in Figures 10-12.

Bridges 2, 3, and 5 are reinforced, pre-stressed concrete structures with approximately 60 meters in length, resulting in vibrational signatures akin to that of Bridge 1 (see Figure 10). Notably, the first modes of Bridge 3 exhibit a less distinct double peak compared to Bridges 1, 2, and 5 (Figure 10b). Unlike the others, Bridge 3 is an arch bridge with a white Hauteville stone cover (Figure 12a). This architectural feature could explain the deviation in its signature, especially if the fiber is routed between the concrete frame and the stone cover.

In contrast, Bridge 4 is a 205-meter-long steel bridge with a unique vibrational signature reflecting multiple resonances attributed to its extended length and construction materials (Figure 10). Given its greater length, the first vibration modes of Bridge 4 have significantly lower frequencies than the other bridges (refer to Table 1), making it the most flexible structure in this study. Notably, in Figure 10a, the two frequency bands associated with the abutments of Bridge 1 are not consistently visible for all bridges. While the western abutment is discernible for bridges 2 and 3, it is less clear for bridges 4 and 5. This variation could stem from differences in the environment, such as soil conditions, design, or vibration source. However, the nodal positions with minimal deformations and the alignment of piers along the deck are evident for all five bridges (Figure 10a).

On the bridge SVDs (Figure 10b), a broad peak is observed at low frequencies between 0.1 and 0.3 Hz. This mode appears to be physical, as it is also visible in the spectra calculated from the velocimetric data for Bridge 1. We hypothesize that this mode corresponds to the secondary peak of the microseismic noise.



414
 415 **Figure 10:** a) Spatial variations and b) SVD of the dynamic response of the five bridges . Bridge
 416 1: Paisy; Bridge 2: A6; Bridge 3: Saône; Bridge 4: Rhône; Bridge 5: Railway.

In contrast to other bridges, Bridges 3 and 5 exhibit a first mode that is more damped than the second, as outlined in Table 1. It is noteworthy that the damping values derived from velocimetric measurements consistently appear slightly lower than those obtained from fiber measurements, with a difference ranging from 0.03% to 0.04% for the first mode and up to 0.09% for the second mode (refer to Table 1). Additionally, minor variations of less than 0.05 Hz are evident between the two types of recorded frequencies.

Given the asynchronous nature of the two measurement methods, differences in environmental conditions, particularly excitation sources and temperatures, could account for these disparities in frequencies and damping.

Name of the bridge	Telecom fiber				Lennartz sensors			
	ksi1 [%]	ksi2 [%]	fr1 [Hz]	fr2 [Hz]	ksi1 [%]	ksi2 [%]	fr1 [Hz]	fr2 [Hz]
Bridge 1 (Paisy)	1.07	1.22	4.61	6.02	1.04	1.13	4.56	5.99
Bridge 2 (A6)	1.54	1.78	3.54	4.50	-	-	-	-
Bridge 3 (Saône)	2.03	1.21	4.10	6.11	1.99	1.17	4.10	6.13
Bridge 4 (Rhône)	1.08	3.78	1.19	2.03	-	-	-	-
Bridge 5 (Rail)	2.27	1.97	2.86	3.89	-	-	-	-

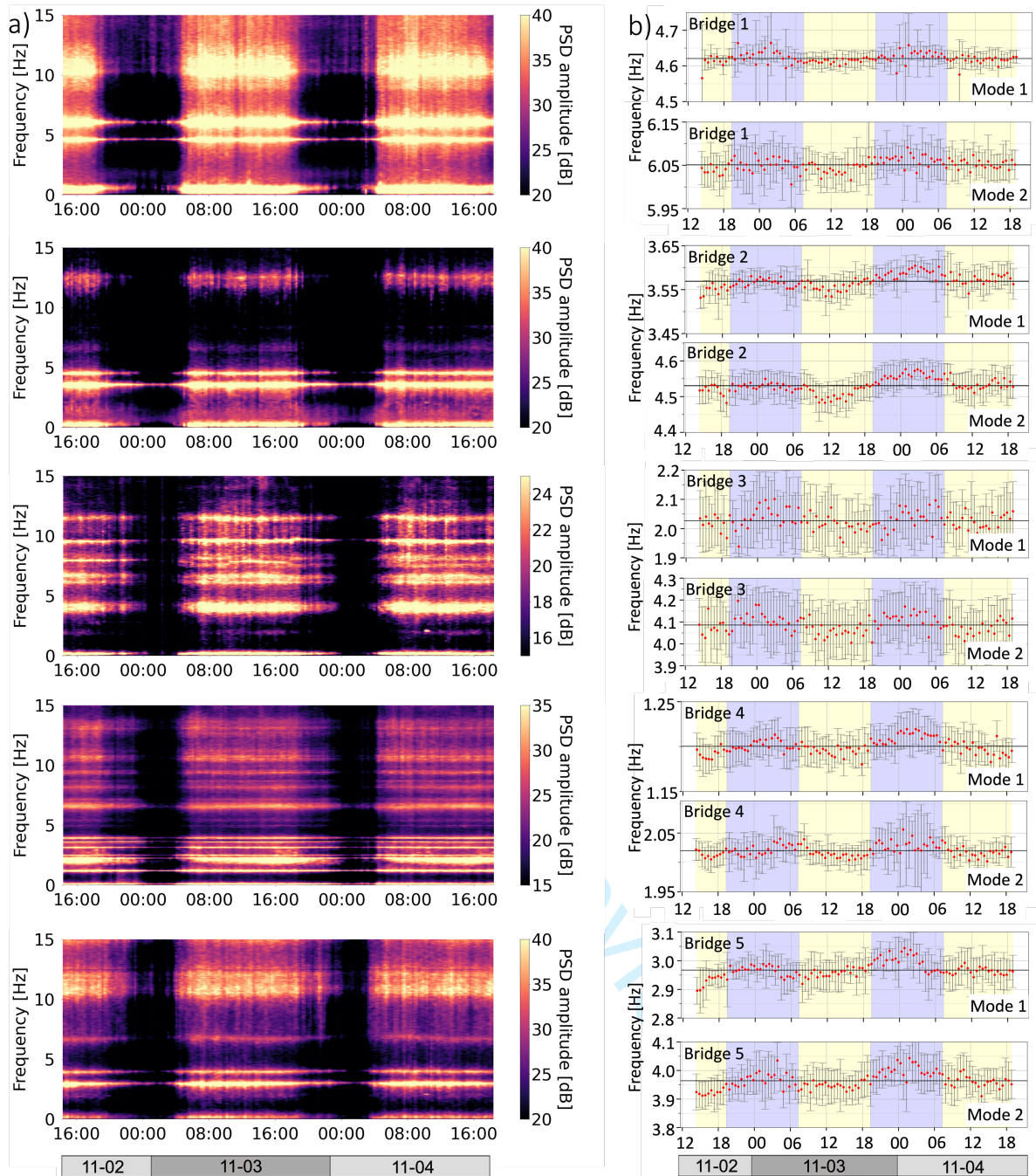
Table 1. Mean frequencies (fr1, fr2) and damping (ksi1, ksi2) of the first two modes for the five bridges studied.

The spectrograms presented in Figure 11a showcase the fiber's capability to concurrently monitor the frequencies of five bridges in a single continuous acquisition over time. Similar to Figure 7, the vibration modes of different bridges and the influence of traffic are observed. The frequency monitoring across the five bridges (Figure 11b) reveals a distinct day/night cycle. Given that all five bridges are located within the same geographical area, it can be presumed that these variations stem from temperature changes between day and night, as this environmental factor significantly influences the dynamic response of structures (Peeters and De Roeck, 2001).

The most considerable frequency variations occur for the first two modes of bridges 3 and 5, ranging between 0.15 and 0.22Hz. For bridges 1 and 5, the first mode exhibits more variation than the second, contrary to bridges 2, 3, and 4, where the second mode experiences more significant changes. Hence, the cyclic variations observed affect modes differently based on the structure type and its environment. Notably, uncertainties in the frequency measurements for bridge 3 are larger than those for other bridges. Due to noisier and less distinct SVD peaks (Figure 10b), the frequencies measured on the spectra for each bootstrap sample are more

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3 446 dispersed, resulting in increased uncertainties. Nevertheless, uncertainties in frequency
4 447 measurements obtained through bootstrap resampling remain consistent throughout the 53
5 448 hours (Figure 11b) and do not appear influenced by shifts in environmental conditions.
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8 449 Figure 12a displays the modal shapes for the first two modes of each structure. The
9
10 450 position of nodes and antinodes enables clear identification of spans and pier positions. Notably,
11 451 for bridges 1, 2, and 4, the shapes of the second modes are more symmetrical than those of the
12 452 fundamental modes. The amplitude of the fundamental mode for bridge 2 is more pronounced
13 453 on the eastern span, closest to the fiber's origin (POP). Conversely, the fundamental mode shape
14 454 of bridge 4 has a slightly larger amplitude on the third span to the west of the structure. Bridge
15 455 3's fundamental mode shape appears distorted compared to the other bridges, attributed to its
16 456 non-girder bridge structure. Additionally, bridge 5 stands out with the peculiarity that its first
17 457 two modes exhibit nearly identical modal deformations. It is important to note that, with the
18 458 uniaxial nature of the fiber alone, determining the principal directions of deformation for each
19 459 mode is not feasible (refer to section 6.2).
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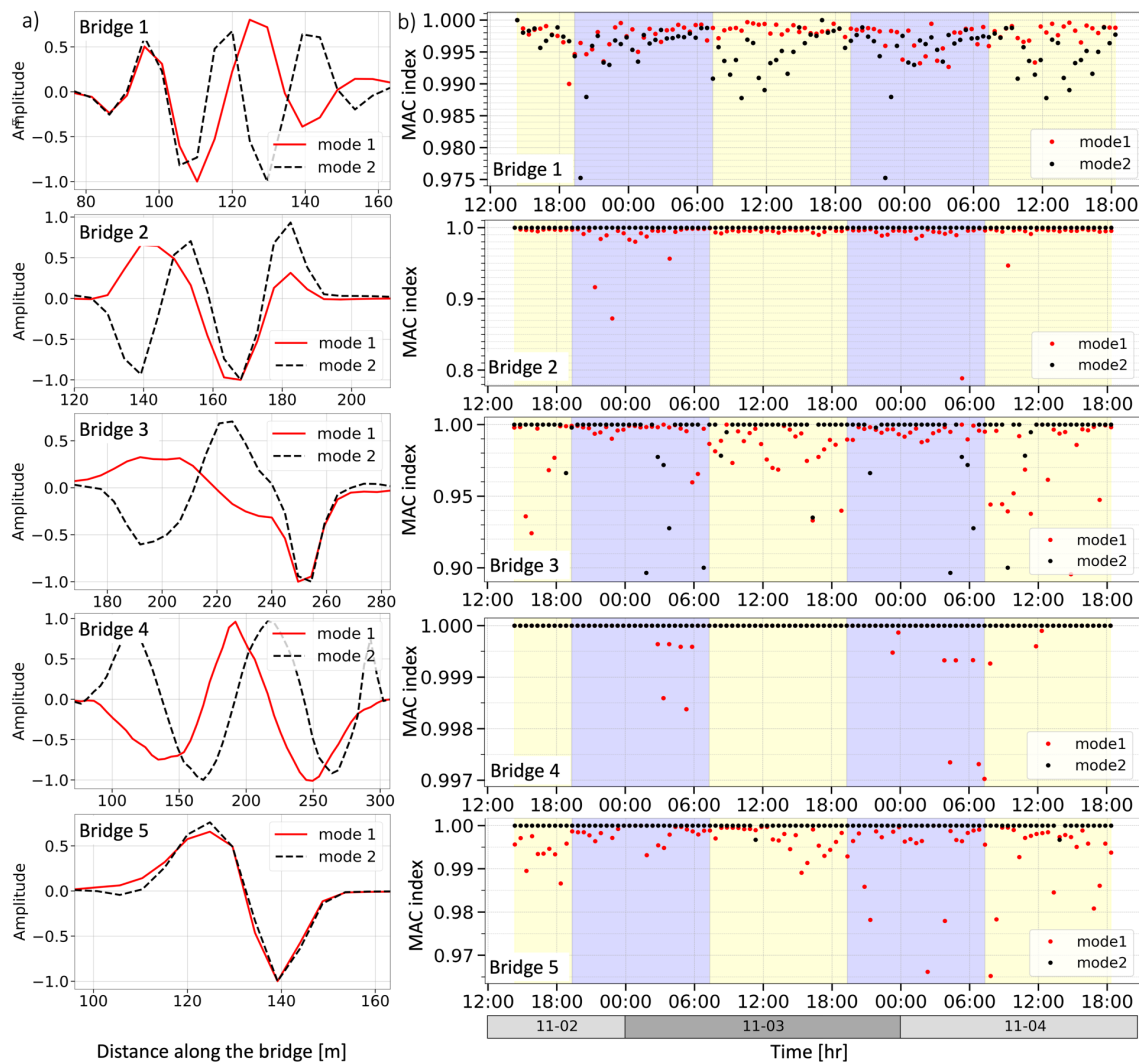


460
 461 **Figure 11:** a) Spectrogram of each instrumented bridge. b) Frequency monitoring of the first
 462 two modes. Bridge 1: Paisy; Bridge 2: A6; Bridge 3: Saône; Bridge 4: Rhône; Bridge 5:
 463 Railway.

464
 465 The Modal Assurance Criterion (MAC) index, reflecting the correlation between modal
 466 shapes for different modes, varies among bridges and reaches its minimum for the fundamental
 467 mode of bridge 2, with a low value of 0.787 (Figure 12b). Notably, across all bridges, the shape
 468 of the fundamental mode appears more susceptible to environmental variations compared to the

second mode (Figure 12b). For example, the shape of the second mode remains consistent for bridges 2 and 4 throughout the 53 hours of recording. In contrast, the shapes of the second mode for bridges 1 and 3 undergo some changes during the acquisition period. Additionally, it is observed that the shape of the fundamental mode for bridge 4 exhibits minimal variation over time, potentially attributed to its unique construction as the only steel bridge in the set.

Figures 11, 12, and Table 1 demonstrate that each bridge displays distinct dynamic behavior depending on factors such as its structure, materials, traffic conditions (higher ambient noise in the city center, hence more excited structures), and the environment (presence of rivers, highways, roads, railways), among others. This considerable variability underscores the importance of monitoring the dynamic behavior of each structure to ensure their safe operation by detecting or locating anomalies.



481
482 **Figure 12:** a) Modal shapes and b) MAC index of the first two modes reconstructed for each
483 bridge. Bridge 1: Paisy; Bridge 2: A6; Bridge 3: Saône; Bridge 4: Rhône; Bridge 5: Railway.

6. Discussion

The telecom fiber enables the measurement of the dynamic response of bridges in the same way as synchronous acquisition from point velocimeters. Modal parameters obtained from the fiber and velocimeters are nearly identical (Table 1), and modal detection remains stable over time (Figure 8). However, the noise level in the fiber data is slightly higher. **We constrain the signal to noise ratio (SNR) by measuring the ratio of the amplitude of the first resonance peak at 4.6Hz with respect to the base level. For bridge 1, this SNR from the fiber is approximately 85% of that of the velocimetric measurements.** This observation testifies to the good sensitivity of the telecom fiber.

In contrast to frequency, the amplitude of the bridge modes undergoes fluctuations corresponding to the intensity of anthropogenic activities before stabilizing at night. Daily variations in vibration sources, predominantly traffic, lead to significant differences in amplitudes within a same bootstrap sample (containing 100 average PSDs), introducing substantial measurement uncertainties during the day (Figure 7 c, d). This observation underscores the impact of external factors on amplitude behavior and emphasizes the need for careful consideration of anthropogenic influences in dynamic response analysis.

6.1 Mode reconstruction

The vibratory identity cards (Figure 5) reveal that the fiber's response shares similarities but differs in details from any of the velocimetric component responses. This suggests that the fiber records a combination of the three directional components. Additionally, based on the telecom fiber data (Figure 8), we can concurrently reconstruct vertical and transverse vibration modes. In light of the "vibratory identity cards" and the mode shapes of Bridge 1, it appears that the telecom optical fiber is capable of measuring deformations in various directions, including those orthogonal to the fiber's axial direction or the longitudinal axis of the bridge. Considering our results (Figures 8, 10-12), we can reasonably assume that we are capturing all the elongations and compressions of the fiber resulting from the 3D deformations of the structure. Since vibration modes of a structure are physically independent of each other, we effectively distinguish them (Figure 12a) within a composite signal where all the information is amalgamated.

This conclusion appears at odd with the usual intuition of DAS vibrations being measured in the single fiber axial direction. For instance in classical optic fiber-based earthquake seismology, it is commonly admitted that little energy from a teleseismic P-wave is recorded

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3 518 on the fiber because the P-wave incidence is small and the wave polarization is almost
4 519 orthogonal to the fiber direction. So how do we explain the ability to reconstruct modes in any
5 520 direction? In the case of a bridge which is embedded on both sides, the structure deforms and
6 521 stretches dynamically, which results in a change through time of the elongation of the structure.
7 522 If the fiber is coupled to the structure, the fiber itself stretches accompanying the motion of the
8 523 structure following its different modes. The fiber elongation then introduces a change in the
9 524 path length of the light emitted by the DAS interrogator, and consequently a phase shift. By
10 525 measuring this phase shift, the DAS therefore makes it possible to reconstruct the deformation
11 526 modes of the structure in all directions.

527 528 **6.2 Limitations**

529 From the fiber alone, which is uniaxial, deducing the principal directions of deformation
530 for each mode is not feasible. The fiber records a combination of components, complicating the
531 identification of deformation modes. Achieving such identification would require, for instance,
532 the utilization of a three-component translational sensor to determine the principal mode
533 directions.

534 *In contrast to accelerometric networks, measurements on telecom fiber lack precise*
535 *localization on structures. Despite not providing exact information on the dynamic data's*
536 *location, recordings along the optical fiber enable the estimation of the same dynamic*
537 *parameters as those obtained with accelerometers. Even without access to the precise location*
538 *of the information, continuous monitoring of parameters over time remains feasible, proving*
539 *crucial for damage detection (Gueguen and Tiganescu, 2018). This approach offers significant*
540 *advantages, allowing for the simultaneous monitoring of dynamic parameters across various*
541 *spatially distributed structures in a single acquisition. Moreover, it leverages existing*
542 *infrastructure, eliminating the need for field deployment.*

543 The analysis of Bridge 1's vibratory characteristics, shown in Figure 5, highlights how the
544 structure's deck connects with the underlying soil through its piles and foundation system.
545 These connection areas coincide with the deck's least deformed sections, aligning with the
546 bridge's pier positions. However, when comparing fiber and velocimeter data directly,
547 discrepancies arise in the number and location of low amplitude nodes. Several factors
548 contribute to these differences. We are comparing deformation measurements over a 10-meter
549 gauge length with specific point measurements, making their spatial resolutions inherently
550 mismatched. Also, the asynchronous nature of velocimeter and fiber data, influenced by
551 different excitation sources and recording positions, can alter the nodes' count and position,

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3 552 causing disparities. Moreover, when interpolating velocimeter and fiber data with distinct
4 553 spatial samplings, aliasing effects might occur, affecting node positions. Additionally, while
5 554 assuming the fiber aligns perfectly with the bridge's axis, variations in the cable's orientation
6 555 within the network sheath might cause deviations. However, these potential offsets don't
7 556 impede the measurement of cable elongation and compression due to structural deformation in
8 557 various spatial directions, illustrated in Figure 8.

13 558

15 559 **6.3 Temperature effects**

17 560 **Rayleigh backscattering in optical fibers is primarily influenced by temperature-induced**
18 561 **variations in fiber length due to thermal expansion. As temperature changes, the fiber either**
19 562 **expands or compresses, leading to local density and refractive index fluctuations along the**
20 563 **cable, contributing to Rayleigh backscattering. The impact of temperature on Rayleigh**
21 564 **backscattering in optical fibers is typically more pronounced at lower frequencies (Kreger et**
22 565 **al., 2009; Leggett et al., 2022). Given our operational frequencies (> 1Hz) and the limited**
23 566 **thermal amplitude during the experiment (8°C), variations in fiber length due to temperature**
24 567 **can be considered negligible.**

25 568 The observed frequency fluctuations of 1.4% and 2.1% for the first two modes of bridge 1
26 569 (Figure 7a, b) are in reasonable agreement with the influence of temperature changes recorded
27 570 in Lyon in November 2021, ranging between 6°C and 14°C. This amplitude variation is
28 571 consistent with other experiments demonstrating frequency changes of less than 5% for
29 572 temperature fluctuations of approximately 15°C (Wahab and De Roeck, 1997; Peeters and De
30 573 Roeck, 2001). The slight increase in eigenmode frequencies and the decrease in damping during
31 574 the night (Figure 7a, b, e, f) may indicate an elevation in the Young's modulus of the concrete,
32 575 leading to an overall stiffening of the structure under lower temperatures (Peeters and De
33 576 Roeck, 2001). However, it is crucial to note that the frequency-temperature relationship isn't
34 577 universally applicable, as shown by studies on the Alamosa Canyon bridge (USA) by Cornwell
35 578 et al. (1999) and Sohn et al. (1999). The sensitivity of modal parameters to climatic variations
36 579 is structure-specific, necessitating the consideration and prediction of these variations to detect
37 580 potential structural damage (Peeters and De Roeck, 2001; Gueguen and Tiganescu, 2018).
38 581 Figure 7e, f illustrates reduced energy dissipation during the night. However, the overall
39 582 variations in frequency (Figure 7a, b) and damping (Figure 7e, f) during the night are associated
40 583 with low amplitude measurements (Figure 7c, d). Consequently, the small variations observed
41 584 in modal parameters might also result from nonlinear effects on the structure.

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3 585 The observation of normal day/night variations emphasizes the system's ability to detect
4 586 changes in the elastic parameters of materials (concrete, surface course) due to temperature.
5 587 Environmental effects have intentionally not been corrected to observe temperature-induced
6 588 fluctuations and quantify the normal variation range of modal parameters for each structure.
7 589 Studies on environmental effects on modal parameters, such as those by Cornwell et al. (1999),
8 590 Fu et al. (2001), Peeters et al. (2001), and Liu et al. (2007), have similarly concluded that modal
9 591 shapes are less sensitive to temperature effects than frequencies. Correction of temperature
10 592 effects primarily applies to frequency measurements and can be implemented in both fiber and
11 593 velocimetric measurements using correction models (Rohrmann et al., 2000; Sohn et al., 1999;
12 594 Peeters and De Roeck, 2001; Cury and Cremona, 2010). However, these models become
13 595 unnecessary in decision-making for Structural Health Monitoring once temperature effects have
14 596 been experimentally characterized (Gueguen and Tiganescu, 2018).
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26 598 7. Conclusion

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29 600 We demonstrate that a single telecom optical fiber, without prior deployment and in a single
30 601 acquisition, can efficiently monitor multiple bridges spatially distributed along the cable.
31 602 Consequently, the established telecom networks serve as an effective means to assess the modal
32 603 parameters of several structures simultaneously, providing insights into the health of bridges
33 604 without the need for deploying numerous synchronous stations. This use of existing
34 605 infrastructure is particularly advantageous in hard-to-access locations, such as urban areas.
35 606 Ultimately, this approach is in line with the vision of the smart city of tomorrow, utilizing
36 607 information and communication technologies to enhance the operation of structures and ensure
37 608 user safety.
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9. References

- Ajo-Franklin, J. B., Dou, S., Lindsey, N. J., Monga, I., Tracy, C., Robertson, M., ... & Li, X. (2019). Distributed acoustic sensing using dark fiber for near-surface characterization and broadband seismic event detection. *Scientific reports*, 9(1), 1328.
- Allemang, R.J. & Brown, D.L. (1982). A correlation coefficient for modal vector analysis. Proceedings of the 1st International Modal Analysis Conference, Orlando, FL, USA.
- Anastasopoulos, D., De Roeck, G., & Reynders, E. P. (2021). One-year operational modal analysis of a steel bridge from high-resolution macrostrain monitoring: Influence of temperature vs. retrofitting. *Mechanical Systems and Signal Processing*, 161, 107951.
- Brossault, M. A., Roux, P., & Guéguen, P. (2018). The fluctuation–dissipation theorem used as a proxy for damping variations in real engineering structures. *Engineering Structures*, 167, 65-73.
- Brownjohn, J. M. W., Magalhaes, F., Caetano, E., & Cunha, A. (2010). Ambient vibration re-testing and operational modal analysis of the Humber Bridge. *Engineering Structures*, 32(8), 2003-2018.
- Calvi, G. M., Moratti, M., O'Reilly, G. J., Scattarreggia, N., Monteiro, R., Malomo, D., ... & Pinho, R. (2019). Once upon a time in Italy: The tale of the Morandi Bridge. *Structural Engineering International*, 29(2), 198-217.
- Cao, R., El-Tawil, S., & Agrawal, A. K. (2020). Miami pedestrian bridge collapse: Computational forensic analysis. *Journal of Bridge Engineering*, 25(1), 04019134.
- Carini, M. R., & Rocha, M. M. (2022). CESSIPy: A Python open-source module for stochastic system identification in civil engineering. *SoftwareX*, 18, 10109
- Chatelain, J. L., Guillier, B., Gueguen, P., Fréchet, J., & Sarrault, J. (2012). Ambient vibration recording for single-station, array and building studies made simple: CityShark II. *International Journal of Geosciences*, 3, 1168-1175.
- Chen, W., Jin, M., Huang, J., Chen, Y., & Song, H. (2021). A method to distinguish harmonic frequencies and remove the harmonic effect in operational modal analysis of rotating structures. *Mechanical Systems and Signal Processing*, 161, 107928.
- Clough, R. W., and J. Penzien (1993). Dynamics of Structures, McGraw- Hill, New-York, 2nd edition, 768 pp., ISBN-10 0071132414,
- Cole Jr, H. A. (1973). *On-line failure detection and damping measurement of aerospace structures by random decrement signatures* (No. NASA-CR-2205). NASA.
- Cornwell, P., Farrar, C. R., Doebling, S. W., & Sohn, H. (1999). Environmental variability of modal properties. *Experimental techniques*, 23(6), 45-48.

- 1
2
3 660
4 661 Cunha, Á., & Caetano, E. (2006). Experimental modal analysis of civil engineering structures.
5
6 662
7 663 Cunha, Á., Caetano, E., Magalhães, F., & Moutinho, C. (2018). Dynamic identification and continuous dynamic
8
9 664 monitoring of bridges: different applications along bridges life cycle. *Structure and Infrastructure*
10 665 *Engineering*, 14(4), 445-467.
11 666
12
13 667 Cury, A., & Crémona, C. (2010). Long term dynamic monitoring of a PSC box girder bridge. In IABSE
14 668 Symposium: Large Structures and Infrastructures for Environmentally Constrained and Urbanised Areas, Venice,
15 669 Italy, 22-24 September 2010 (pp. 484-485).
16 670 Doebling, S. W., Farrar, C. R., Prime, M. B., & Shevitz, D. W. (1996). Damage identification and health
17 671 monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review.
18 672
19 673 Dou, S., Lindsey, N., Wagner, A. M., Daley, T. M., Freifeld, B., Robertson, M., ... & Ajo-Franklin, J. B. (2017).
20 674 Distributed acoustic sensing for seismic monitoring of the near surface: A traffic-noise interferometry case
21 675 study. *Scientific reports*, 7(1), 11620.
22
23 676
24
25 677 Efron, B., & Tibshirani, R. (1991). Statistical data analysis in the computer age. *Science*, 253(5018), 390-395.
26 678
27
28 679 Ernst, R., Lauridsen, P., Klein, C., & Buffetti, B. (2022, May). The effect of damage position on Operational
29 680 Modal Analysis of wind turbine blades for SHM. In *Journal of Physics: Conference Series* (Vol. 2265, No. 3, p.
30 681 032099). IOP Publishing.
31 682
32 683 Farrar, C. R., Doebling, S. W., & Nix, D. A. (2001). Vibration-based structural damage
33 684 identification. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and*
34 685 *Engineering Sciences*, 359(1778), 131-149.
35 686
36 687 Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. *Philosophical Transactions*
37 688 *of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 365(1851), 303-315.
38 689
39 690 Fichtner, A., Bogris, A., Nikas, T., Bowden, D., Lentas, K., Melis, N. S., ... & Smolinski, K. (2022). Theory of
40 691 phase transmission fibre-optic deformation sensing. *Geophysical Journal International*, 231(2), 1031-1039.
41 692
42 693 Figueiredo, E., & Brownjohn, J. (2022). Three decades of statistical pattern recognition paradigm for SHM of
43 694 bridges . *Structural Health Monitoring*, 21(6), 3018-3054.
44
45 695
46 696 Froggatt, M., Soller, B., Gifford, D., & Wolfe, M. (2004, February). Correlation and keying of Rayleigh scatter
47 697 for loss and temperature sensing in parallel optical networks. In *Optical fiber communication conference* (p.
48 698 PD17). Optica Publishing Group.
49
50 699
51
52 700 Fu, Y., & DeWolf, J. T. (2001). Monitoring and analysis of a bridge with partially restrained bearings. *Journal of*
53 701 *Bridge Engineering*, 6(1), 23-29.
54 702
55
56 703 Gara, F., Regni, M., Roia, D., Carbonari, S., & Dezi, F. (2019). Evidence of coupled soil-structure interaction and
57 704 site response in continuous viaducts from ambient vibration tests. *Soil Dynamics and Earthquake*
58 705 *Engineering*, 120, 408-422.
59
60 706

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2
3 707 García-Macías, E., & Ubertini, F. (2021). Structural assessment of bridges through ambient noise deconvolution
4 708 interferometry: application to the lateral dynamic behaviour of a RC multi-span viaduct. *Archives of Civil and*
5 709 *Mechanical Engineering*, 21(3), 123.
6 710
7 711 Gifford, D. K., Kreger, S. T., Sang, A. K., Froggatt, M. E., Duncan, R. G., Wolfe, M. S., & Soller, B. J. (2007,
8 712 October). Swept-wavelength interferometric interrogation of fiber Rayleigh scatter for distributed sensing
9 713 applications. In *Fiber Optic Sensors and Applications V* (Vol. 6770, pp. 106-114). SPIE.
10 714
11 715 Glisic, B., & Inaudi, D. (2012). Development of method for in-service crack detection based on distributed fiber
12 716 optic sensors. *Structural Health Monitoring*, 11(2), 161-171.
13 717
14 718 Guéguen, P., Johnson, P., & Roux, P. (2016). Nonlinear dynamics induced in a structure by seismic and
15 719 environmental loading. *The Journal of the Acoustical Society of America*, 140(1), 582-590.
16 720
17 721 Guéguen, P., & Tiganescu, A. (2018). Consideration of the effects of air temperature on structural health
18 722 monitoring through traffic light-based decision-making tools. *Shock and Vibration*, 2018.
19 723
20 724 Hartog, A., Frignet, B., Mackie, D., & Clark, M. (2014). Vertical seismic optical profiling on wireline logging
21 725 cable. *Geophysical Prospecting*, 62(4-Vertical Seismic Profiling and Microseismicity Frontiers), 693-701.
22 726
23 727 Hartog, A. H., Belal, M., & Clare, M. A. (2018). Advances in distributed fiber-optic sensing for monitoring marine
24 728 infrastructure, measuring the deep ocean, and quantifying the risks posed by seafloor hazards. *Marine Technology*
25 729 *Society Journal*, 52(5), 58-73.
26 730
27 731 Hearn, G., & Testa, R. B. (1991). Modal analysis for damage detection in structures. *Journal of structural*
28 732 *engineering*, 117(10), 3042-3063.
29 733
30 734 Jacobsen, N. J., Andersen, P., & Brincker, R. (2007). Eliminating the influence of harmonic components in
31 735 operational modal analysis. In *Conference Proceedings: IMAC-XXIV: A Conference & Exposition on Structural*
32 736 *Dynamics*. Society for Experimental Mechanics.
33 737
34 738 Jeary, A. P. (1997). Damping in structures. *Journal of wind engineering and industrial aerodynamics*, 72, 345-
35 739 355.
36 740
37 741 Johannessen, K., Drakeley, B., & Farhadiroushan, M. (2012, March). Distributed acoustic sensing-a new way of
38 742 listening to your well/reservoir. In *SPE Intelligent Energy International Conference and Exhibition* (pp. SPE-
39 743 149602). SPE.
40 744
41 745 Jousset, P., Reinsch, T., Ryberg, T., Blanck, H., Clarke, A., Aghayev, R., ... & Krawczyk, C. M. (2018). Dynamic
42 746 strain determination using fibre-optic cables allows imaging of seismological and structural features. *Nature*
43 747 *communications*, 9(1), 2509.
44 748

- 1
2
3 749 Khoo, L. M., Mantena, P. R., & Jadhav, P. (2004). Structural damage assessment using vibration modal
4 750 analysis. *Structural Health Monitoring*, 3(2), 177-194.
5 751
- 6 752 Kreger, S. T., Sang, A. K., Gifford, D. K., & Froggatt, M. E. (2009, April). Distributed strain and temperature
7 753 sensing in plastic optical fiber using Rayleigh scatter. In *Fiber Optic Sensors and Applications VI* (Vol. 7316, pp.
8 754 85-92). SPIE.
9 755
- 10 756 Leggett, S. E., Zhu, D., & Hill, A. D. (2022). Thermal effects on far-field distributed acoustic strain-rate
11 757 sensors. *SPE Journal*, 27(02), 1036-1048.
12 758
- 13 759 Lindsey, N. J., Dawe, T. C., & Ajo-Franklin, J. B. (2019). Illuminating seafloor faults and ocean dynamics with
14 760 dark fiber distributed acoustic sensing. *Science*, 366(6469), 1103-1107.
15 761
- 16 762 Liu, C., & DeWolf, J. T. (2007). Effect of temperature on modal variability of a curved concrete bridge under
17 763 ambient loads. *Journal of structural engineering*, 133(12), 1742-1751.
18 764
- 19 765 Magalhães, F., Cunha, Á., & Caetano, E. (2008). Dynamic monitoring of a long span arch bridge. *Engineering*
20 766 *Structures*, 30(11), 3034-3044.
21 767
- 22 768 Magalhães, F., & Cunha, Á. (2011). Explaining operational modal analysis with data from an arch
23 769 bridge. *Mechanical systems and signal processing*, 25(5), 1431-1450.
24 770
- 25 771 Magalhães, F., Cunha, Á., & Caetano, E. (2012). Vibration based structural health monitoring of an arch bridge:
26 772 From automated OMA to damage detection. *Mechanical Systems and signal processing*, 28, 212-228.
27 773
- 28 774 Mateeva, A., Lopez, J., Potters, H., Mestayer, J., Cox, B., Kiyashchenko, D., ... & Detomo, R. (2014). Distributed
29 775 acoustic sensing for reservoir monitoring with vertical seismic profiling. *Geophysical Prospecting*, 62(4-Vertical
30 776 Seismic Profiling and Microseismicity Frontiers), 679-692.
31 777
- 32 778 Maurey, H., Chaize, P., & Dagbert, M. (2019). Sécurité des ponts : Éviter un drame.
33 779
- 34 780 Mestayer, J., Cox, B., Wills, P., Kiyashchenko, D., Lopez, J., Costello, M., ... & Lewis, A. (2011). Field trials of
35 781 distributed acoustic sensing for geophysical monitoring. In *Seg technical program expanded abstracts 2011* (pp.
36 782 4253-4257). Society of Exploration Geophysicists.
37 783
- 38 784 Michel, C., Guéguen, P., El Arem, S., Mazars, J., & Kotronis, P. (2010). Full-scale dynamic response of an RC
39 785 building under weak seismic motions using earthquake recordings, ambient vibrations and modelling. *Earthquake*
40 786 *Engineering & Structural Dynamics*, 39(4), 419-441.
41 787
- 42 788 Mikael, A., Gueguen, P., Bard, P. Y., Roux, P., & Langlais, M. (2013). The analysis of long-term frequency and
43 789 damping wandering in buildings using the random decrement technique. *Bulletin of the Seismological Society of*
44 790 *America*, 103(1), 236-246.
45 791

- 1
2
3 792 Peeters, B., & De Roeck, G. (2001). One-year monitoring of the Z24-Bridge: environmental effects versus damage
4 793 events. *Earthquake engineering & structural dynamics*, 30(2), 149-171.
5
6 794
7 795 Peeters, B., Maeck, J., & De Roeck, G. (2001). Vibration-based damage detection in civil engineering: excitation
8 796 sources and temperature effects. *Smart materials and Structures*, 10(3), 518.
9 797
10
11 798 Rao, C. R., Rao, C. R., Statistiker, M., Rao, C. R., & Rao, C. R. (1973). *Linear statistical inference and its*
12 799 *applications* (Vol. 2, pp. 263-270). New York: Wiley.
13 800
14
15 801 Rizzo, P., & Milazzo, A. (Eds.). (2021). *European Workshop on Structural Health Monitoring: Special Collection*
16 802 *of 2020 Papers-Volume 1* (Vol. 127). Springer Nature.
17 803
18
19 804 Rodrigues, J., & Brincker, R. (2005). Application of the random decrement technique in operational modal
20 805 analysis. In *Proceedings of the 1st International Operational Modal Analysis Conference, April 26-27, 2005,*
21 806 *Copenhagen, Denmark* (pp. 191-200). Aalborg Universitet.
22 807
23
24 808 Roeck, G. D. (2003). The state-of-the-art of damage detection by vibration monitoring: the SIMCES
25 809 experience. *Journal of Structural Control*, 10(2), 127-134.
26 810
27
28 811 Rohrmann, R. (2000). Structural causes of temperature affected modal data of civil structures obtained by long
29 812 time monitoring.
30 813
31
32 814 Sladen, A., Rivet, D., Ampuero, J. P., De Barros, L., Hello, Y., Calbris, G., & Lamare, P. (2019). Distributed
33 815 sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables. *Nature*
34 816 *communications*, 10(1), 5777.
35 817
36
37 818 Snover, D., Johnson, C. W., Bianco, M. J., & Gerstoft, P. (2021). Deep clustering to identify sources of urban
38 819 seismic noise in Long Beach, California. *Seismological Society of America*, 92(2A), 1011-1022.
39 820
40
41 821 Sohn, H., Dzwonczyk, M., Straser, E. G., Kiremidjian, A. S., Law, K. H., & Meng, T. (1999). An experimental
42 822 study of temperature effect on modal parameters of the Alamosa Canyon Bridge. *Earthquake engineering &*
43 823 *structural dynamics*, 28(8), 879-897.
44 824
45
46 825 Song, Z., Zeng, X., Xie, J., Bao, F., & Zhang, G. (2021). Sensing shallow structure and traffic noise with fiber-
47 826 optic internet cables in an urban area. *Surveys in Geophysics*, 42, 1401-1423.
48 827
49
50 828 Tanimola, F., & Hill, D. (2009). Distributed fibre optic sensors for pipeline protection. *Journal of Natural Gas*
51 829 *Science and Engineering*, 1(4-5), 134-143.
52 830
53
54 831 Van den Ende, M., Ferrari, A., Sladen, A., & Richard, C. (2022). Deep Deconvolution for Traffic Analysis with
55 832 Distributed Acoustic Sensing Data. *IEEE Transactions on Intelligent Transportation Systems*.
56 833
57
58
59
60

- 1
2
3 834 Van Overschee, P., & De Moor, B. (1996). Continuous-time frequency domain subspace system
4 835 identification. *Signal Processing*, 52(2), 179-194.
5
6 836
7 837 Wahab, M. A., & De Roeck, G. (1997). Effect of temperature on dynamic system parameters of a highway
8 838 bridge. *Structural Engineering International*, 7(4), 266-270.
9
10 839
11 840 Wang, H. F., Zeng, X., Miller, D. E., Fratta, D., Feigl, K. L., Thurber, C. H., & Mellors, R. J. (2018). Ground
12 841 motion response to an ML 4.3 earthquake using co-located distributed acoustic sensing and seismometer
13 842 arrays. *Geophysical Journal International*, 213(3), 2020-2036.
14
15 843
16
17 844 Welch, P. (1967). The use of fast Fourier transform for the estimation of power spectra: a method based on time
18 845 averaging over short, modified periodograms. *IEEE Transactions on audio and electroacoustics*, 15(2), 70-73.
19
20 846
21
22 847 Xia, Y., & Hao, H. (2003). Statistical damage identification of structures with frequency changes. *Journal of Sound*
23 848 *and Vibration*, 263(4), 853-870.
24
25 849
26 850 Zeng, X., Lancelle, C., Thurber, C., Fratta, D., Wang, H., Lord, N., ... & Clarke, A. (2017). Properties of noise
27 851 cross-correlation functions obtained from a distributed acoustic sensing array at Garner Valley, California. *Bulletin*
28 852 *of the Seismological Society of America*, 107(2), 603-610.
29
30
31 853
32
33
34
35
36
37
38
39
40
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42
43
44
45
46
47
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