Chapter 18

Damage Detection Strategy Based on PCA/Mode-Shapes Developed on a Laboratory Truss Girder Subjected to Environmental Variations

M. Berardengo, F. Lucà, S. Manzoni, S. Pavoni, and M. Vanali

Abstract In recent years, Structural Health Monitoring has become a fundamental area within industrial, aerospace, and civil engineering, offering a wide range of techniques to predict, assess, and manage potential structural damage. Most of the proposed strategies focus on handling and analyzing damage-sensitive features of the system under observation, continuously monitoring and evaluating changes in these characteristics over time. Among the various methods developed recently, vibration analysis has proven to be particularly promising. This work presents an unsupervised learning approach for detecting structural damage using vibration data. The study involves a benchmark test exploiting a custom-designed laboratory truss girder to develop damage detection strategies based on acceleration measurements. The approach employs statistical pattern recognition employing mode-shapes as damage-sensitive features. Distinct attention is given to practical aspects such as sparse sensor layouts, managing long-term monitoring data, and introducing synthetic damage indicators to support maintenance decisions. The algorithm is validated using real data from acceleration measurements on the laboratory truss girder, which has been monitored for several months under varying environmental conditions, including temperature fluctuations and sunlight exposure.

Keywords Structural Health Monitoring · Damage Detection · Principal Component Analysis · Operational Modal Analysis · Environmental Variation

Introduction

Buildings, structures, and mechanical components inevitably deteriorate over time due to environmental exposure and material fatigue, leading to a loss of functionality. Structural Health Monitoring (SHM) plays a fundamental role in the investigation of the conditions of these systems. Indeed, detecting critical conditions or potential damage is essential for both safety and economic reasons, as it allows for planning the maintenance or renovations of determined components most efficiently [1]. In this branch, the interest in vibration-based techniques has grown significantly due to their practical benefit. Indeed, these methods do not require prior knowledge of damage location, and the use of accelerometers (common in these strategies) is non-destructive and can be easily applied to existing structures [2]. Several techniques have been developed to detect damage in real structures or models using modal parameters like natural frequencies [3], damping coefficients [4], and mode shapes [5]. While vibration-based methods appear intuitive, their practical application faces significant challenges due to the impact of environmental and operational conditions [6]. These factors can alter modal parameters to an extent comparable to or greater than possible incoming damage, limiting the effectiveness of these parameters in SHM. Several studies have demonstrated a high correlation between natural frequencies and both daily and seasonal environmental temperature drift

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[7]. On the other hand, the influence of thermal gradients on the mode shape evolution is still partially unexplored. Thermal gradients within a structure can affect mode shape estimation, particularly in large structures like bridges and skyscrapers, where uneven sunlight exposure creates non-uniform thermal characteristics. The most common methods for removing the environmental effects rely on the Principal Component Analysis (PCA), which is a powerful tool for detecting structural damage and reducing the ambient and operational impact on measured data [8]. However, this technique requires further exploration in strategies where mode shapes are used as damage-sensitive features. In the literature, mode shapes are commonly evaluated using the Modal Assurance Criterion (MAC), which is an index with a distribution represented by an inverse exponential [9]. Nevertheless, it is often reported that machine learning algorithms are much more effective when input data are characterized with a normal distribution.

This work proposes an unsupervised damage detection strategy using mode shapes as damage-sensitive features. The method employs robust PCA and Mahalanobis Squared Distance (MSD) to filter out outliers and mitigate environmental effects on mode shapes [10]. The method has been validated with real data from a laboratory truss girder structure subjected to environmental variability. Over several months, the structure was monitored under uncontrolled factors such as temperature fluctuations and sunlight exposure, with modal parameters continuously estimated via an automatic Operational Modal Analysis (OMA) algorithm, and environmental parameters tracked using thermocouples. The next section provides an introduction to the truss girder benchmark and data acquisition setup.

Benchmark and Experimental Setup

The benchmark of this work is a laboratory truss girder realized ad-hoc at the University of Parma for SHM purposes. The structure employed as a validation case study is a classic two-dimensional Pratt truss anchored to the floor through rigid support. The structure is secured by Teflon roller connections at both bottom ends through a clamp system. It presents a 4.20-meter span and a height of approximately 80 cm, and it is composed of diagonal and vertical aluminum rods with a 1.2 cm hexagonal cross-section and lengths of 50 cm (vertical) or 70 cm (diagonal). The horizontal members are two steel H-beams, each 430 cm long and 1.1 cm thick. Stability is enhanced by seven 15 kg masses at the base nodes. The structure is held upright by four struts positioned at 1/3 and 2/3 of the span, with stainless steel cylinders functioning as rollers to permit only vertical movement.

Unfortunately, the ambient excitation of the laboratory does not reach an adequate level for a reliable evaluation of the modal parameters. Therefore, an electro-dynamic PCB model 2007E shaker is employed to excite the structure vertically using a band-limited white noise signal up to 200 Hz. The dynamic of the system is measured with 6 Micro Electro Mechanical System (MEMS) accelerometers TE4030 model with a sensitivity of 1 V/g, a measurement range of ± 2 g, and a bandwidth of 0-200 Hz. Ambient conditions are tracked with 4 thermocouples type K placed at different points of the structure. Each test is then performed every 30 minutes to evaluate the evolution of modal and ambient parameters constantly. In Figure 1 the experimental setup layout is presented.

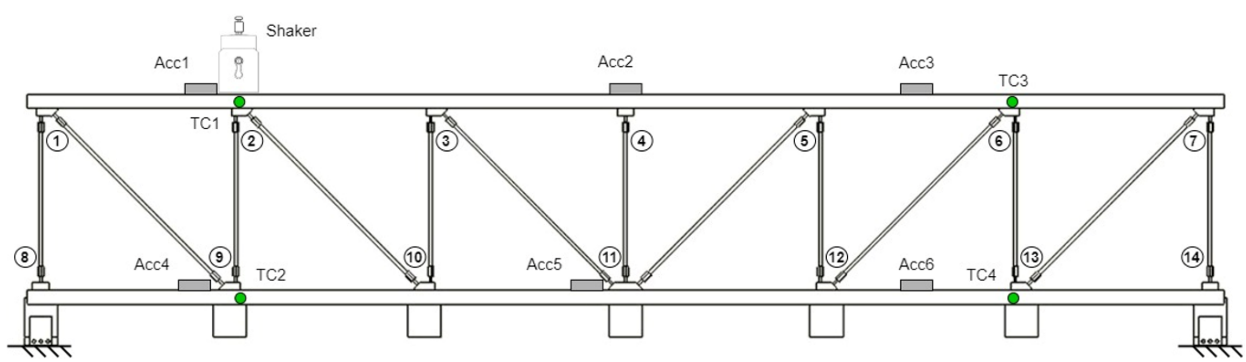

Fig. 1 Truss sketch with node numeration and data acquisition system layout with shaker, accelerometers (grey rectangles) and thermocouples (green circles) location.

Feature Extraction

In this work, the mode shapes of the structure are employed as damage-sensitive features. Modal parameters evaluation is performed employing an automatic OMA algorithm in MATLAB environment, using a poly-reference least-squares complex frequency-domain method [11]. The truss girder presents 5 modes in the frequency range of interest 0-200 Hz. The mode shapes estimated are normalized with respect to the accelerometer 1, which is positioned near the excitation point. Mode shapes experimentally evaluated from the truss girder are presented in Figure 2.

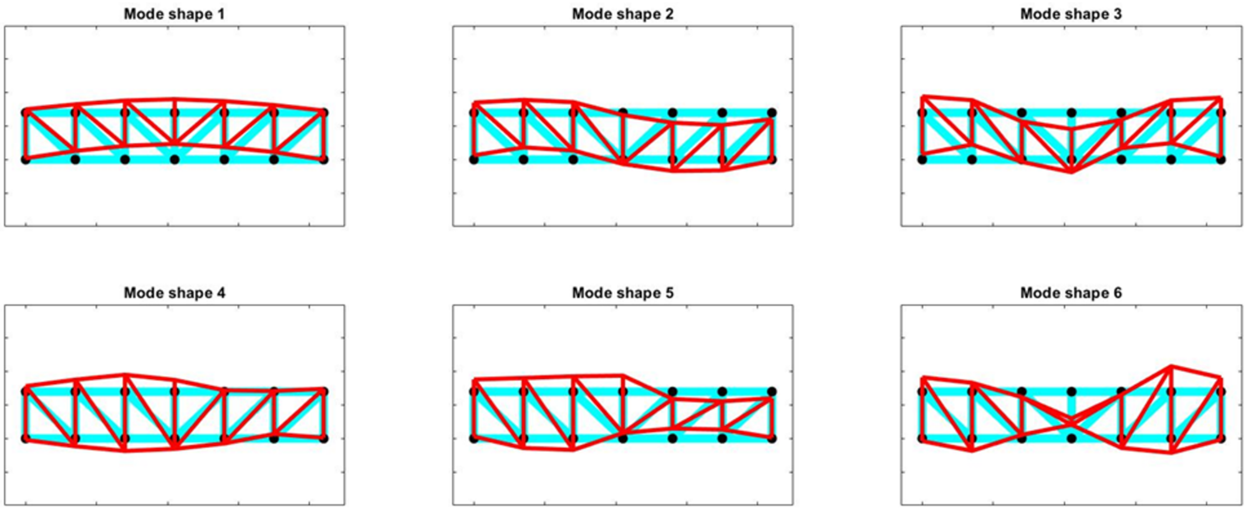

Fig. 2 Truss girder mode shapes experimentally evaluated.

Since the accelerometers employed are 6, for each mode the features available are 5, for a total amount of 25 values for each observation. Therefore, a new observation i obtained for each test results in a vector arranged as follows

$$x_i = [\quad \varphi_2^1 \quad \varphi_3^1 \quad \varphi_4^1 \quad \cdots \quad \varphi_5^5 \quad] \tag{1}$$

where φ_j^k is the eigenvector value corresponding to the accelerometer j of the mode k.

Once enough observations to establish a baseline including all ambient variations have been collected while the truss is maintained in healthy condition, PCA has been performed to remove the environmental impact on the data collected. In the case of the study, PCA is used to detect the principal components most sensitive to variations caused by the environmental evolution, in order to remove them and process the remaining principal scores which should represent the real structural state information. Unfortunately, the Pearson's coefficients evaluated between the principal scores and the temperature measurements have not demonstrated a high correlation between the investigated variables. Therefore, the first PCs to be removed have been selected using the Cumulative Variance Contribution Rate (CVCR) adopting a threshold of 99% [12]. The method proposed has shown that the first 11 PCs are representative of the 99% of the variance, as depicted in Figure 3, and, thus are removed from the damage detection strategy.

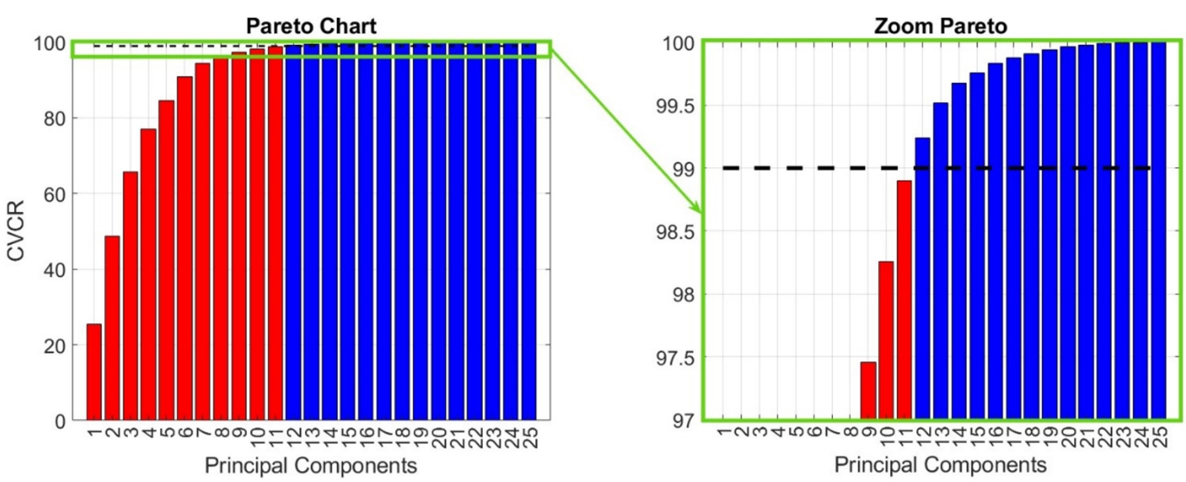

Fig. 3 Pareto chart of the Principal Components with the Cumulative Variance Contribution Rate (CVCR).

Damage Index Evaluation and Results

After the establishment of the baseline dataset and the alert threshold, the following step concerned the development of a synthetic index evaluated from each test performed on the truss girder. Each new damage-sensitive feature observation is standardized by employing the baseline averages and standard deviations. Then, a new vector of principal scores Z_i is achieved by projecting the standardized observation on the orthogonal system obtained from the PCA of the baseline. The first 12 elements are removed obtaining a new vector Z_i^* containing the structure characteristics without the environmental impact. Finally, a synthetic Damage Index (DI) is calculated by exploiting MSD with the following formula:

$$DI_i = \left(Z_i^* - \overline{Z_0^*}\right)^T \Sigma_0^{-1} (Z_i^* - \overline{Z_0^*}) \quad (2)$$

where $\overline{Z_0^*}$ are the baseline principal score averages without the first 12 elements and Σ_0 is the baseline covariance matrix.

Due to different environmental conditions, the baseline dataset has been selected including the period from 6th April to 22nd July. In Figure 4, the thermal gradients monitored during the baseline interval in the structure are shown.

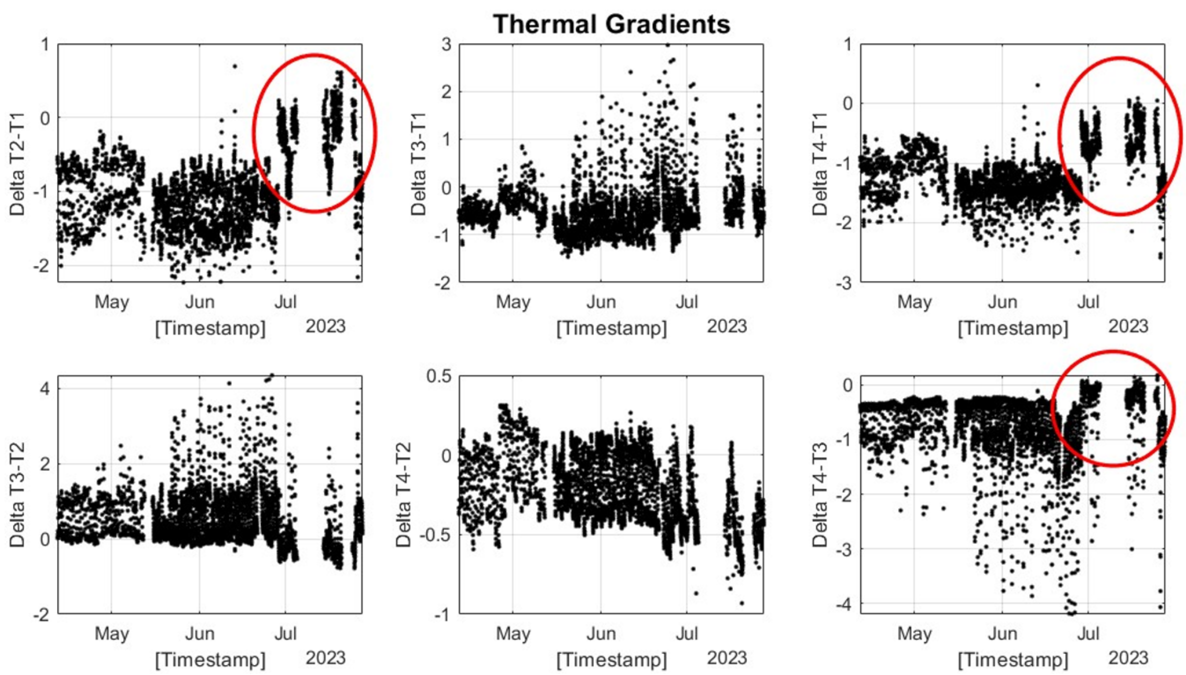

Fig. 4 Thermal gradients measured in the structure during the baseline interval, with different behaviors highlighted with red ellipses.

In the figure above it is possible to understand the extension of the baseline interval to the end of July, due to a completely different behavior of the thermal gradient of the structure.

Then, the strategy proposed has been validated against data measured from the structure, alternating healthy and damaged periods. The damages induced to the structure for the test case are:

- the application of 0.5 and 1 kg masses
- the reduction of the bolts torque in node connection elements.

In Figure 5, damages induced to the structure are presented.

Both scenarios simulate realistic damage typically experienced by a truss girder during its lifespan. The placement of additional masses represents a reduction in stiffness at specific locations of the structure. Given that the total mass of the truss girder is approximately 300 kg, the mass variation induced amounts to 0.17% and 0.33%, respectively. On the other hand, the reduction in bolts torque indicates a decrease in the effectiveness of the connection nodes (bolts or rivets). Initially, all bolts were tightened to a torque of 40 Nm, despite the nominal torque specification being around 12 Nm. The damage has been induced by decreasing it to 30, 20, 10, and 6 Nm.

(a) (b)

Fig. 5 Damage induced to the structure: a) mass application and b) bolts torque reduction.

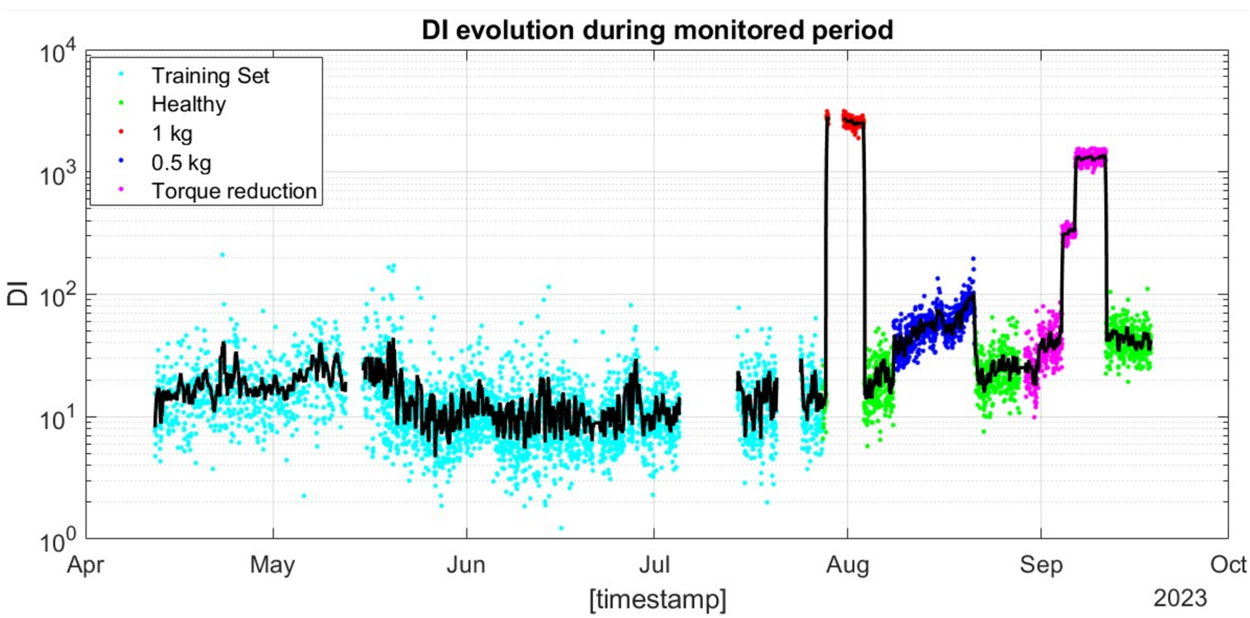

Fig. 6 DI evaluated with the strategy proposed against different damages induced to the structure.

DI results computed during the monitoring period are shown in Figure 6. The index proposed is even evaluated with a traveling mean (black line) to better understand its evolution during the monitored period.

Results show that the DI proposed in this work is not affected by the environmental impact. Furthermore, it is possible to appreciate the incredible increase in DI when the structure is affected by damage, while it returns to the baseline range when the structure is recovered to healthy conditions.

Conclusion

This paper proposes a new damage detection strategy with a strong immunity to environmental variations. A synthetic index DI is evaluated by analyzing the mode shapes of the structure in healthy conditions to establish a reference baseline. Then, mode shapes are processed using the PCA, excluding the first principal components (first eleven) affected by environmental factors by exploiting the CVCR method. The remaining principal scores, which are immune to ambient influences, are analyzed using statistical tools such as the MSD. Outliers in the proposed DI are interpreted as changes in the dynamic behavior of the structure caused by potential damage incoming. In order to validate the strategy proposed, two different damages have been induced to the structure: the positioning of different masses and the reduction of the tightening torque of the bolts in the connection elements between rods. Results obtained from the DI proposed demonstrate that the synthetic index effectively detects structural damage while remaining highly resistant to ambient variations.

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