Chapter 4
Structural Health Monitoring of a Ferry Quay: Instrumentation and Impact of Tidal Levels on Modal Parameters

Luigi Sibille, Torodd Skjerve Nord, Ba Tung Le, Bartosz Siedziako, and Alice Cicirello

Abstract This study investigates the influence of environmental factors on the modal parameters of linkspans, one of the two main structures of ferry quays, focusing specifically on tidal level variations. The Structural Health Monitoring (SHM) system implemented on the Magerholm ferry quay, part of a collaboration between Møre og Romsdal County and the Norwegian University of Science and Technology (NTNU), was used to collect acceleration responses over a six-month period. An Automated Operational Modal Analysis (AOMA) algorithm was performed to identify the modal parameters of the structure considering a 20 second window for each day of the monitoring campaign. Tidal levels were monitored independently, and for each day, a strong correlation between tidal levels and the identified first natural frequency of the linkspan was distinguished. To explicitly quantify and remove the majority of the tidal level effects, a well-established Blind Source Separation (BSS) technique, the so-called Principal Component Analysis (PCA) was carried out directly on the first natural frequency and tidal levels. Despite the fact that the assumptions of the AOMA were violated due to the non-white noise conditions caused by tidal levels and operational loads, this preliminary investigation demonstrates, for the first time, the strong correlation between tidal level fluctuations and modal parameters of linkspans.

Keywords Marine Structures · Ferry Quay · Structural Health Monitoring · Automated Operational Modal Analysis · Environmental effects

Introduction

Ferry quays operate in challenging environments that significantly influence their structural integrity and longevity. Subjected to harsh weather conditions, including strong winds, heavy rainfall, and fluctuating temperatures, these structures face continuous exposure to harsh conditions that accelerate wear and degradation [1, 2]. The marine environment poses additional challenges, with saltwater exposure leading to the corrosion of steel components and the deterioration of concrete. Furthermore, operational factors, such as the repeated impacts from ferries and the vibrations caused by vehicle traffic, increase the mechanical stresses experienced by these quays [3].

Despite being designed for a service life of approximately 50 years, many ferry quays experience deterioration earlier than expected, necessitating more frequent repairs or even premature replacement. Inspections, such as the annual and five-year protocols established by the Norwegian Public Roads Administration (NPRA), aim to monitor the condition of these structures [4]. However, these inspections are often insufficient to detect all potential issues, as structural damage can go unnoticed until the next scheduled inspection, increasing the risk of costly repairs or even structural failure. Structural Health Monitoring (SHM) systems can complement these inspection protocols by providing continuous, real-time data on the structural condition of ferry quays. SHM techniques enable asset owners to monitor changes in structural parameters, providing valuable information for maintenance planning and decision-making [5].

The influence of environmental conditions, such as tidal level variations, plays a significant role in the structural behavior of ferry quays and, consequently, in the application of SHM techniques [6]. Tidal levels affect the dynamic characteristics,

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including their modal parameters, such as natural frequencies and mode shapes. These modal parameters are essential indicators of a structure's health and are often used to detect changes in stiffness, mass distribution, or boundary conditions [7, 8]. Therefore, the assessment of the health of the structure requires filtering out environmental effects, particularly if they are expected to have a significant influence [9]. SHM techniques should consider these environmental influences [10] and apply appropriate filtering to ensure that variations in modal parameters reflect the structural condition rather than external environmental factors. However, the methodologies employed for system identification and environmental effect filtering must respect certain conditions. If modal parameters are found to be dependent on environmental effects, such as the periodic nature of tidal variations, or operational loads, such as the adjusting position maneuvers of linkspans of ferry quays, the assumptions for performing common System Identification (SI) algorithms, such as the Stochastic Subspace Identification (SSI) method, may no longer be valid. In such cases, it is better to use SI algorithms that do not require respecting the white noise condition, allowing for a more accurate identification of modal parameters.

To explore this challenge, the Magerholm ferry quay was instrumented with an SHM system in 2023, transforming it into the Magerholm Research Quay (MQR). The monitoring system, implemented in collaboration with Møre og Romsdal County and the Norwegian University of Science and Technology (NTNU), consists of 22 accelerometers, 2 GPS antennas for synchronization, and 1 thermometer for evaluating thermal effects. The system aims to provide insights into how ferry quays are influenced by EOVs and tools for hazard alarming and damage detection.

This paper is a preliminary study that aims to evaluate the correlation between tidal levels and the modal parameters, particularly the first natural frequency, of linkspans for the first time. It gives an overview of the monitoring system that has been set up at the Magerholm Research Quay. It describes its design, sensor layout, and data acquisition system. Additionally, it presents a detailed analysis of time histories of the acceleration responses recorded on the linkspan. An Automated Operational Modal Analysis (AOMA) algorithm based on the SSI method was applied to 20-second-long recordings collected daily over a six-month period. Next, the correlation between tidal levels and the first identified natural frequency of the structure was investigated by performing Least Squares Regression. Additionally, Principal Component Analysis (PCA) was performed to explore the temporal fluctuations of the principal components and separate the tidal effects from the natural frequency.

The Magerholm Research Quay

The MRQ is a collaborative project between Møre og Romsdal County and NTNU. The project aims to use real-time data collected from the structure to investigate quays' structural behavior and optimize maintenance practices. Situated along Route 60, the Magerholm ferry quay serves as a critical link between Magerholm and Sykkylven. This quay transports around 950,000 vehicles annually, making it the fifth most utilized quay in Norway for vehicle traffic. The quay, along with its main components, is illustrated in Fig 1.

The quay consists of two primary structures: a reinforced concrete pier and a steel linkspan. Originally constructed in 1997, it underwent a major renovation in 2015 to handle larger ferries, including a 25-meter extension of the concrete pier and modifications to the linkspan.

The pier now spans 110 meters and is supported by end-bearing circular steel piles filled with C45 concrete, used for both the deck and the piles. Thirteen fenders are distributed across the quay to absorb ferry-induced impacts. In response to the upgrade to electric ferries, a charging station has been installed on the pier. A vacuum anchoring system provides stability, minimizing sway during loading and unloading operations. The steel linkspan, measuring approximately 15 meters in length and 9 meters in width, facilitates vehicle and passenger transfers. It incorporates longitudinal beams made from S355 steel and cross beams of S235 steel, with a front beam made of Hardox400 steel to resist the powerful ferry impacts. The linkspan is supported vertically by a concrete abutment and two lifting towers. The lifting towers, operated by a ferry operator, adjust the linkspan's position to account for water-level changes such as tides and waves. Four conical fenders, positioned between the linkspan and the concrete foundation, absorb longitudinal movements in the surge direction.

The monitoring system comprises 22 accelerometers, 2 GPS antennas, and 1 thermometer. The SHM system is illustrated in Fig 2. On the pier, 5 submersible uni-axial (Dytran 3211B2) sensors, 3 uni-axial (DY3055D3) sensors, and 4 tri-axial (DY3233A) sensors from Dytran, with sensitivities of 100 mV/g, 500 mV/g, and 1000 mV/g, respectively, are installed. Additionally, 10 submersible uni-axial (Dytran 3211B2) sensors are positioned on the linkspan, where they are exposed to waves during high tide and are partially submerged during storm surges.

The sensors on the pier are labelled with "P", while those on the linkspan are labelled with "L". Uni-axial sensors are identified by "T" for transversal (sway direction), "L" for longitudinal (surge), and "V" for vertical (heave) orientations, while tri-axial sensors are marked with "A" as the final letter. All the sensors deployed are Integrated Electronic

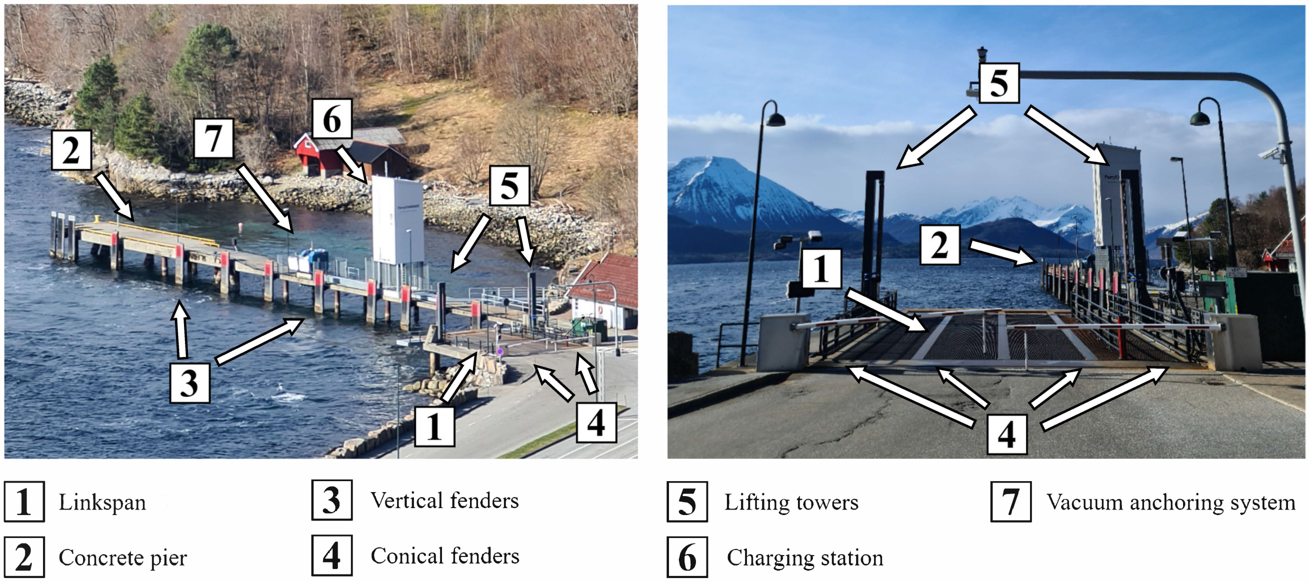

Fig. 1 The Magerholm Research Quay and its main components

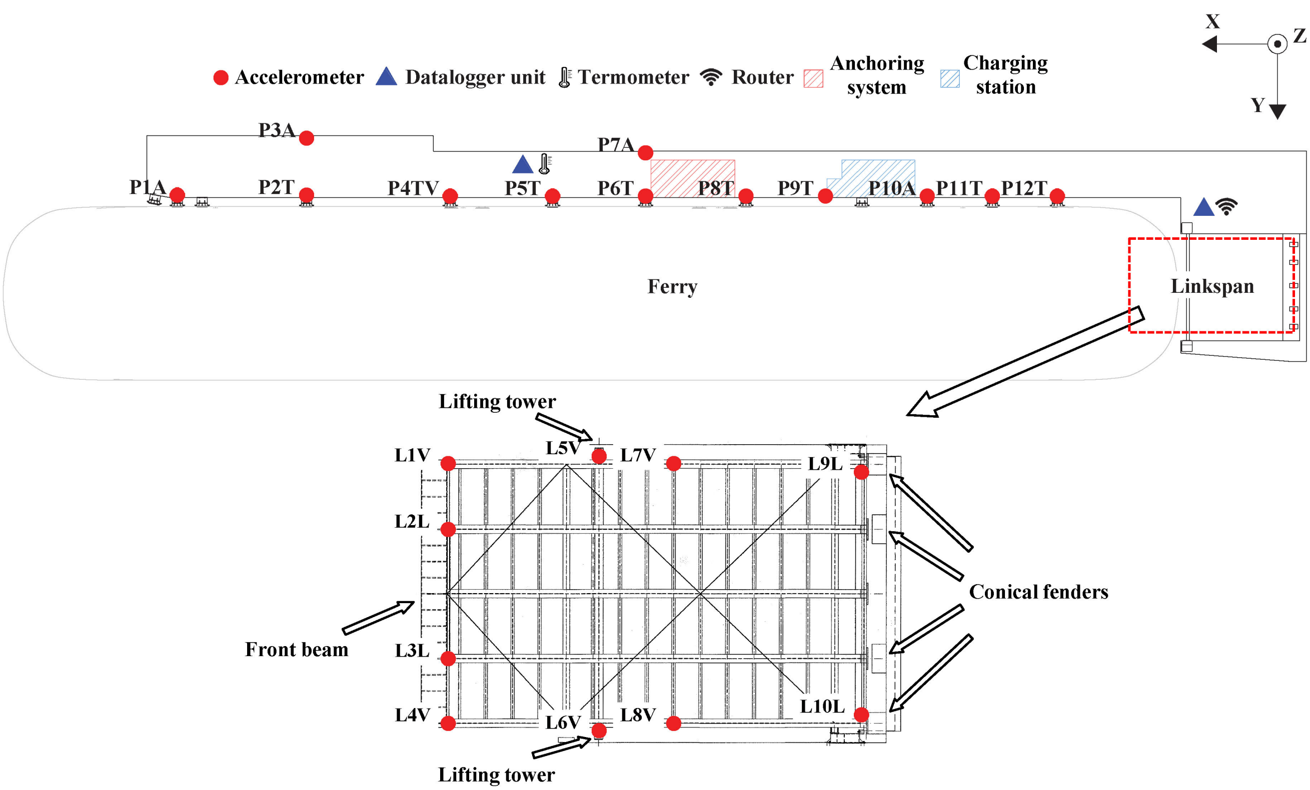

Fig. 2 Position of sensors on the Magerholm Research Quay

Piezo-Electric (IEPE) using AC coupling. The sampling frequency is adjustable up to 2560 Hz, and is typically set at 512 Hz for efficient data processing and storage. A scheme of the monitoring system is depicted in Fig 3. The sensors are connected to data logger units through waterproof wires, while a MAX BR1 LTE router ensures seamless 4G+ data transfer to a server. The data acquisition system is controlled by a cRIO 9035, integrating sound and vibration, GPS, and temperature modules. Synchronization with the server occurs twice per hour, with local storage on two 4TB hard drives for redundancy. The data logger units are programmed to be controlled via the Internet.

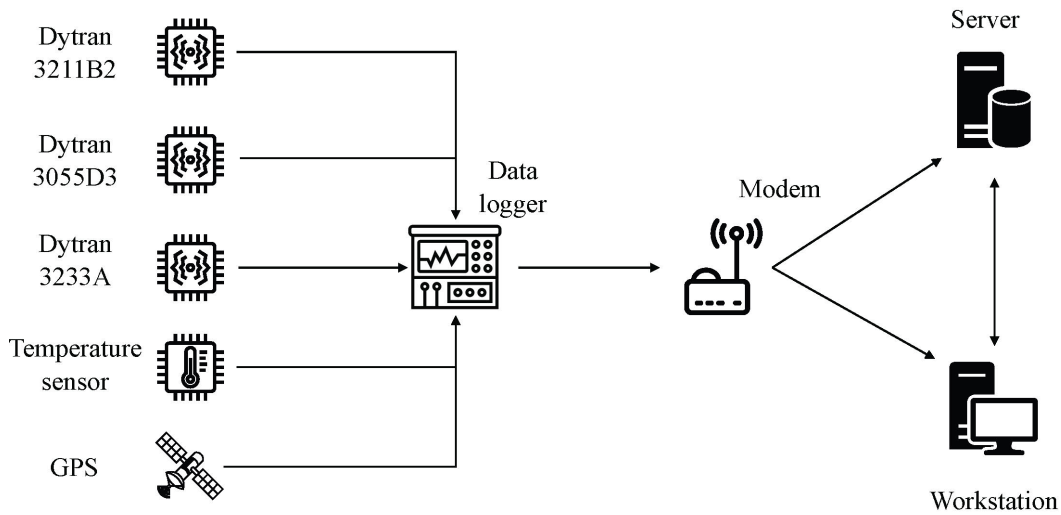

Fig. 3 Scheme of the monitoring system

Analysis of the Time Histories

In what follows, while both the concrete pier and linkspan have been described to provide a more comprehensive understanding of the sensor instrumentation, this paper focuses exclusively on the data recorded from sensors positioned on the linkspan. Of the 10 sensors installed on the linkspan, only 4 are utilized in this study, as the remaining sensors were damaged during the storm "Ingunn" in February 2024, which led to the collapse of the linkspan. Specifically, data from sensors L5V, L6V, L7V, and L8V (refer to Fig 2b) collected over a six-month period from March to August 2024, are analyzed. The selected accelerometers recorded accelerations only in the vertical direction. To illustrate typical daily time histories, accelerations recorded over a 24-hour period, starting at midnight, from accelerometer L5V are presented in Fig 4. Acceleration peaks generally correspond to ferry impacts on the linkspan. The variation in acceleration response across different impacts highlights the influence of operational and environmental factors on the dynamic of the quay. The duration of the docked state varies, ranging from 8 minutes during peak hours to up to 2 hours at night. On the depicted day in Fig 4, a total of 55 impacts are identifiable from the time history, aligning with the ferry schedule [11].

Figure 5 illustrates the acceleration response during a complete ferry docking event. Initially, small variations in acceleration are observed as the linkspan aligns to ensure that the impact occurs at a precise location on the ferry. The clearance of the ferry changes based on the tidal level, requiring the linkspan to be aligned before each impact. This is followed by the ferry impact, marked by a significant spike in acceleration as the ferry contacts the quay, representing the peak forces during

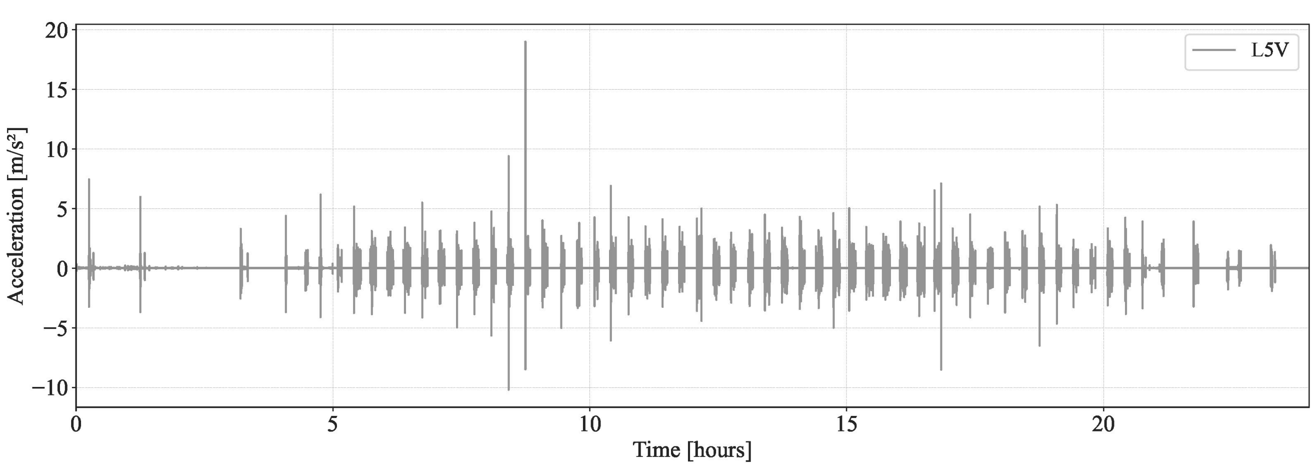

Fig. 4 Time history recorded over 24 hours from midnight from sensor L5V

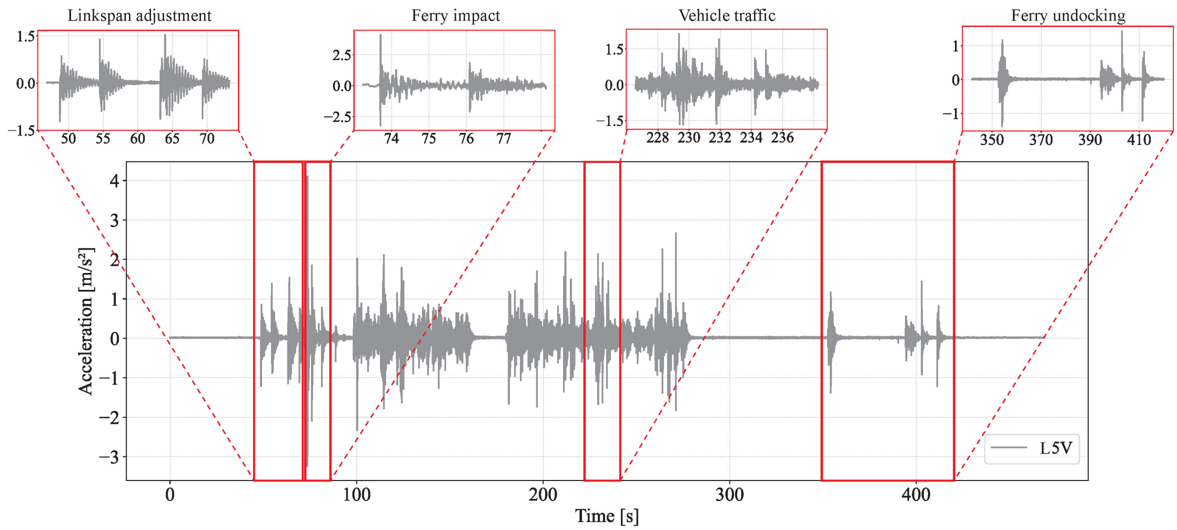

Fig. 5 Time history and main events of one docking recorded from sensor L5V

the event. After the impact, moderate vibrations are recorded as vehicles disembark and board the ferry. Finally, smaller fluctuations in acceleration are observed as the ferry undocks, indicating the departure of the ferry and the structure's return to its resting state.

Tital Level Variations and Modal Analysis

The tide fluctuations are obtained by the Norwegian Mapping Authority. Figure 6a shows the tidal level fluctuations over 6 months of data. The reference point 0 corresponds to the Chart Datum or Lowest Astronomical Tide levels. One measurement is taken per day at 10 a.m. Notably, the tides result in continuous fluctuations driven by lunar cycles and climatic factors. The tidal levels capture both short-term daily tidal fluctuations and long-term season variations. Local environmental factors, such as wind, atmospheric pressure, and coastal geography, can also contribute to deviations from the regular tidal cycle.

A previous operational modal analysis of the Magerholm ferry quay was conducted using a covariance-driven SSI algorithm by Ba Tung et al. [12]. This modal analysis was validated against a Finite Element Model (FEM) of the structure, which shows that the first bending mode has a natural frequency of 2.48 Hz. However, for the sake of conciseness, the mode shapes identified in Ba Tung's analysis, as well as those calculated by the FEM model are not reported in this paper. In our study, an AOMA method, based on the covariance-driven SSI algorithm, was applied, with the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm automatically filtering and selecting stable poles in the stabilization diagram. The AOMA was performed on time histories recorded at approximately 10 a.m. each day over a 6-month period to automatically identify the modal parameters of the linkspan. This AOMA method has demonstrated its robust performance across various applications, including a reinforced concrete (RC) road bridge [13], a long suspension bridge [14], and a helicopter blade [15]. The time window used for modal analysis corresponded to the 20-second period before the ferry impact, during the adjustment phase of the linkspan. This period was selected because the level of ambient excitation in other time windows was insufficient for reliable modal identification. The SSI was performed with a band-pass filter set between 0.5 and 20 Hz. The lower cutoff frequency of 0.5 Hz corresponded to the low-frequency limit of the sensors, while frequencies above 20 Hz were excluded as they were beyond the range of interest for the modal analysis. The number of orders in the SSI varied from 10 to 130, and the number of block rows was set to 100. Additionally, the modal analysis was conducted using only four accelerometers positioned relatively close to one another. This limited spatial coverage made it challenging to consistently identify many modes of the structure. It is important to note that the SSI was applied during the adjustment of the linkspan, a period when multiple operational loads, such as short-duration forces exerted from the lifting towers, were applied. This means that the white noise assumption was not fully respected. Despite this, the approach was still sufficient to investigate the fluctuation of the tidal level. However, in order to properly identify the modal properties of the structure, more suitable system identification algorithms should be considered to handle non-white noise conditions.

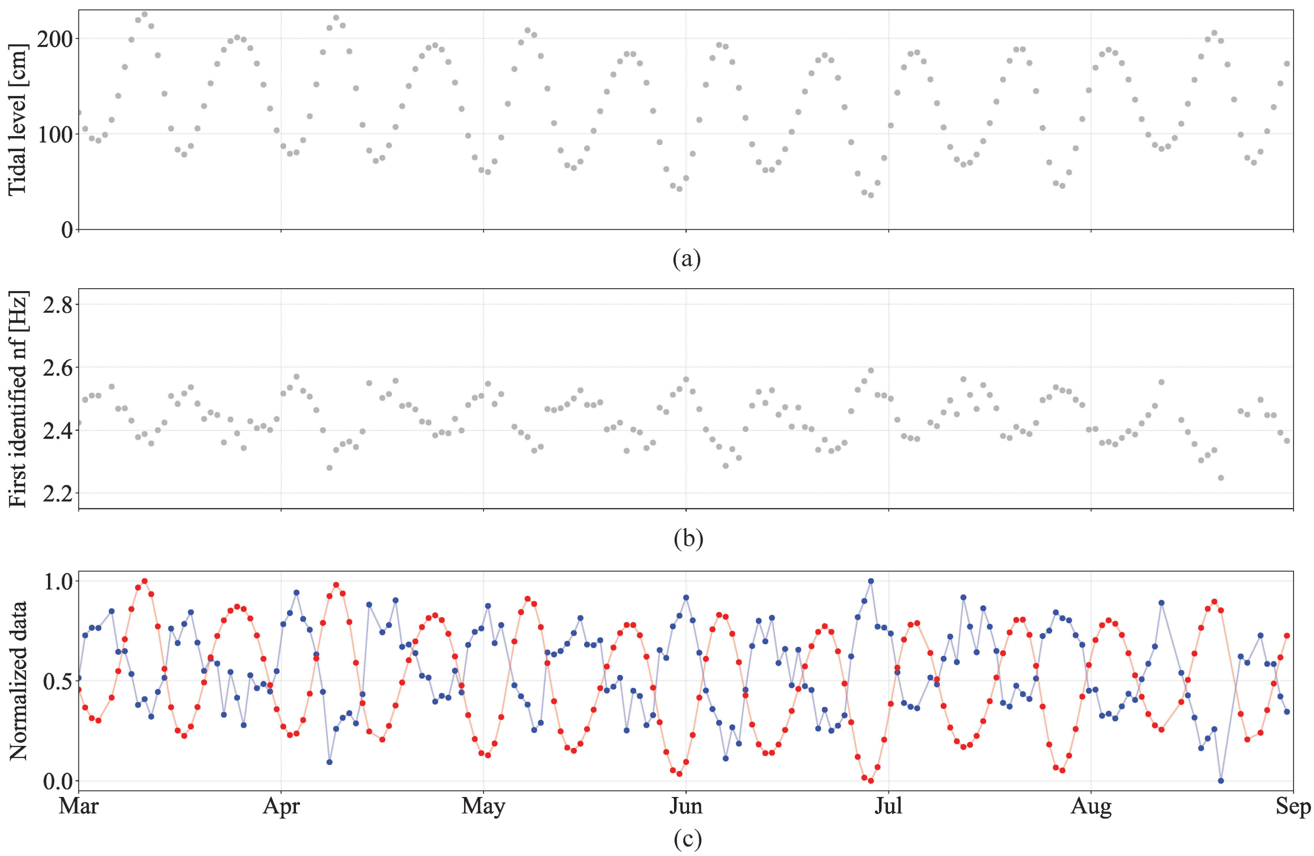

Fig. 6 Six months of data recorded once a day at approximately 10 a.m.: (a) Tidal level; (b) First identified natural frequency; (c) Normalized data: tidal level (red) and first identified natural frequency (blue), where the dots correspond to measurements, and the curves are obtained by interpolation for clarity

The investigation focused primarily on the first bending mode which natural frequency identified over the 6 months is shown in Fig 6b. The natural frequency fluctuates between approximately 2.25 Hz and 2.58 Hz, closely matching the FEM-calculated frequency of 2.48 Hz. The first identified natural frequency and tidal levels are normalized in order to compare their trends and are shown in Fig 6c. The dots represent the actual measurements taken once per day, while the curves are interpolations added to clarify trends in the data. A clear inverse relationship is observed between the two parameters: when the tidal level rises (red dots and line), the natural frequency drops (blue dots and line). This suggests that the boundary conditions of the structure are influenced by the tidal levels, with higher tidal levels likely changing the stiffness of the quay, leading to lower natural frequencies. This behavior is likely related to changes in the stiffness of the lifting towers, as they are hydraulic, or of the conical fenders, which vary depending on their inclination.

Correlation between Tidal Levels and Natural Frequency

Figure 7a shows the cross-correlation coefficient between the two parameters as a function of lag, with the lag on the x-axis representing the number of days the two parameters are shifted relative to each other. The y-axis represents the Pearson correlation coefficient, which ranges from -1 (perfect inverse correlation) to +1 (perfect direct correlation). At a lag of 0 days, the cross-correlation coefficient is approximately -0.83, indicating a strong inverse correlation between the first natural frequency and the tidal level when no shift is applied. This coefficient demonstrates that the two parameters are strongly and inversely correlated. The periodic oscillations in the cross-correlation plot suggest that the relationship between the two parameters is cyclical, likely driven by the regular tidal cycles. Peaks and troughs in the cross-correlation correspond to the natural periodicity of tidal variations, reinforcing the idea that tidal levels show a regular, predictable influence on the dynamic behavior of the structure.

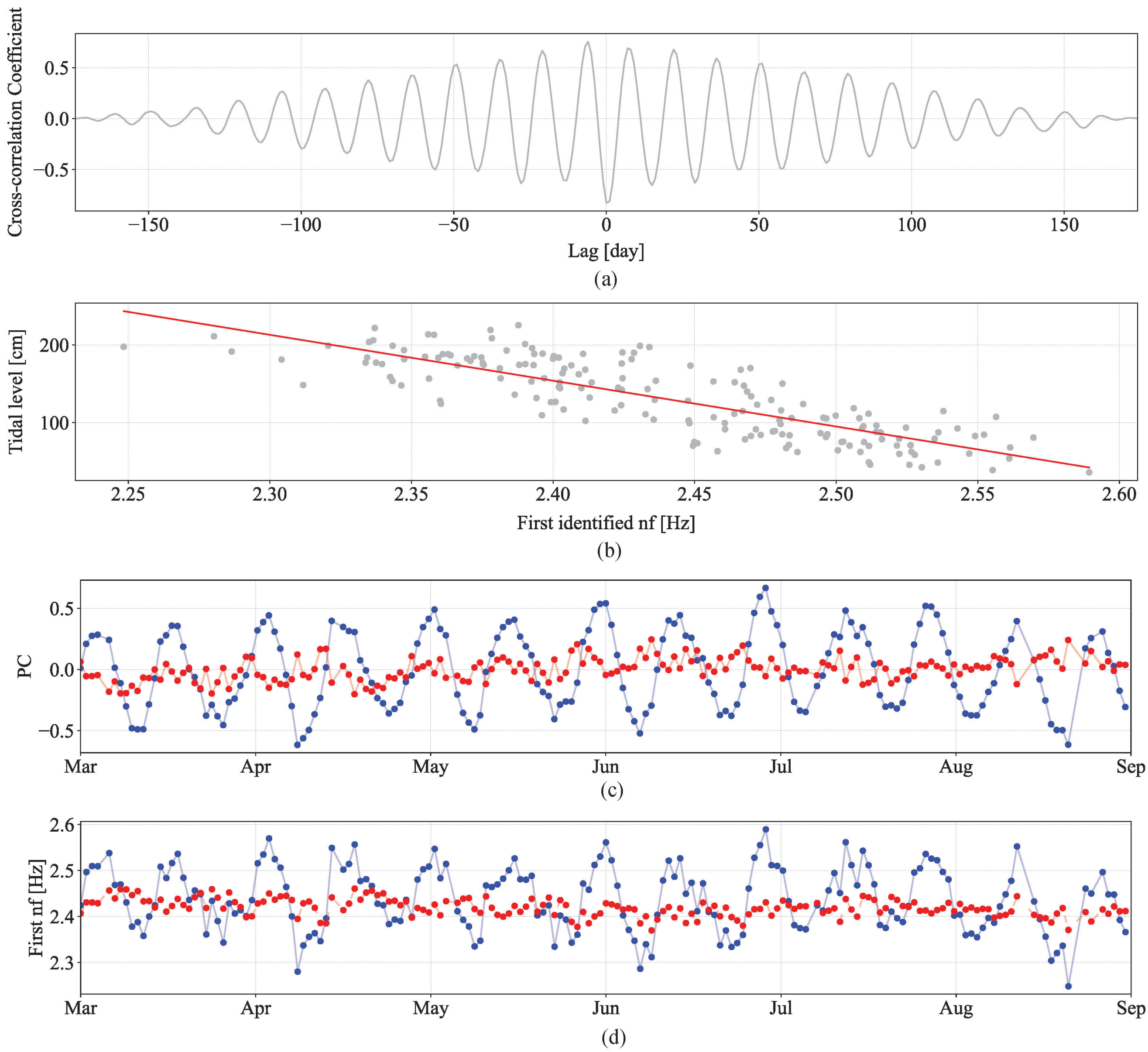

Fig. 7 a) Cross-correlation coefficient between tidal levels and the first natural frequency as a function of lag; b) Scatter plot of tidal level versus first natural frequency with least squares regression line; c) First (blue) and second (red) principal component of tidal levels and first identified natural frequency; d) First natural frequency before (blue) and after (red) the removal of the principal component

Figure 7b further supports this finding by showing the scatter plot of the first identified natural frequency of the linkspan and the tidal level. The scatter plot shows a strong correlation between the data, with points distributed within a relatively narrow band. The red line, obtained via least-squares regression, provides a linear approximation of the overall trend, clearly indicating that as the natural frequency increases, the tidal level decreases. This suggests that higher water levels reduce the stiffness of the dock structure, subsequently lowering its natural frequency.

In addition to the least-squares regression, the correlation between tidal levels and the first identified natural frequency is further investigated using PCA. PCA is a well-established "Blind Source Separation" technique. It enables to separate a set of source signals from a mixed signal without (or with little) info about the source and mixing process. PCA can be used for two temporal signals that are highly correlated with each other to evaluate the independent set of principal components. The principal components are the eigenvectors of the data's covariance matrix, and they are orthogonal to each other. The PCA representation is an optimal linear dimension reduction technique in the mean-square sense. Usually the last principal component is the one mostly due to noise. The results obtained by applying PCA to the first natural frequency and tidal levels are shown in Fig. 7c. It is observed that the largest variability represented by the the first principal component (blue dots and line in Fig 7c), is primarily due to the tidal fluctuations. The Pearson correlation coefficient between the tidal level and the first principal component is -0.98, confirming the very high inverse correlation between the two.

Finally, Fig 7d presents a comparison between the first identified natural frequency (blue dots and line) and the adjusted natural frequency (red dots and line) after removing the first principal component. From the plot, it is evident that the first identified natural frequency fluctuates between approximately 2.3 Hz and 2.6 Hz. After the adjustment, the natural frequency stabilizes, fluctuating in a narrower range around 2.45 Hz, which is close to the natural frequency of the FEM model. The reduction in fluctuation indicates that the tidal effects have been largely removed, and the adjusted natural frequency is now predominantly influenced by other operational and environmental variabilities, such as temperature, wind, and wave height.

It is worth clarifying that this analysis is based on the assumptions that: the different sensors used are affected by the same noise; the signal can be decomposed as a combination of linear independent set of principal components; the first one is mainly due to the tidal effect.

Conclusions

This paper presents the SHM system implemented at the Magerholm ferry quay, developed as part of a collaboration between Møre og Romsdal County and NTNU. The SHM system comprises 22 accelerometers, 2 GPS antennas, and 1 thermometer, all connected through wires to two logger units and a router for data transmission. An AOMA algorithm was used to identify the daily variation of the modal parameters of the linkspan over a six-month period. The environmental effects on the first natural frequency of the linkspan were investigated, with a particular focus on tidal levels.

The analysis revealed a significant inverse linear relationship between tidal levels and the first natural frequency, with a Pearson correlation coefficient of -0.83. Least Squares Regression was applied to quantify this relationship. Additionally, PCA was applied to the first natural frequency and tidal levels, showing that the first principal component is mainly caused by the tidal levels. After removing the first principal component, the resulting adjusted natural frequency displays fluctuations. These fluctuations are likely caused by changes in stiffness due to varying boundary conditions, specifically related to the hydraulic lifting towers and conical fenders, which change their mechanical properties based on the inclination of the linkspan. Additionally, other environmental and operational factors may also contribute.

Even though the AOMA might have resulted in inaccurate estimates of the modal properties, as the assumption of uncorrelated white noise excitation across the structure was violated by tidal levels and operational loads during the linkspan's adjustment phase, this is a preliminary study aimed at exploring the influence of tidal levels on the structure. Further analysis should focus on applying SI techniques capable of handling non-white noise assumptions to improve the accuracy of modal parameter identification under these complex environmental and operational conditions.

This preliminary analysis lays the groundwork for the application of more advanced techniques, such as the Hybrid Operational Modal Analysis [16] and Multivariate Nonlinear or Metric Learning approaches [17], to a broader dataset that includes additional environmental variabilities such as temperature, wind, and waves. These advanced techniques can help further filter out the environmental effects, improving the accuracy of the modal parameter identification and enhance structural analysis including FEM Updating, SI, and Damage Detection.

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References

1. Siedziako, B., Fenerci, A., and Nord, T.S. "Experimental vibration analysis on the rykkjem ferry dock during ferry berthing". In *Society for Experimental Mechanics Annual Conference and Exposition*, pages 103–111. Springer (2023).
2. Siedziako, B., Nord, T., and Fenerci, A. "Finite element model updating of a ferry dock bridge". *Journal of Physics: Conference Series*, 2647:182001 (2024).
3. Sibille, L., Nord, T.S., Siedziako, B., and Fenerci, A. "Impact force identification on a ferry dock bridge". *Journal of Physics: Conference Series*, 2647(18):182012 (2024).
4. Vegvesen, S. "Brutus - management system for bridges, ferry quays and other load-bearing structures in norway" (2023).
5. Olivieri, C., Fortunato, A., and DeJong, M. "A new membrane equilibrium solution for masonry railway bridges: the case study of marsh lane bridge". *International Journal of Masonry Research and Innovation*, 6(4):446–471 (2021).

6. Steenackers, G. and Guillaume, P. “Structural health monitoring of the z24 bridge in presence of environmental changes using modal analysis”. In *Proceedings of IMAC*, volume 23 (2005).
7. Martucci, D., Civera, M., and Surace, C. “Bridge monitoring: Application of the extreme function theory for damage detection on the i-40 case study”. *Engineering Structures*, 279:115573 (2023).
8. Farrar, C.R. and Worden, K. *Structural health monitoring: a machine learning perspective*. John Wiley & Sons (2012).
9. Magalhães, F., Cunha, Á., and Caetano, E. “Vibration based structural health monitoring of an arch bridge: From automated oma to damage detection”. *Mechanical Systems and signal processing*, 28:212–228 (2012).
10. Peeters, B. and De Roeck, G. “One-year monitoring of the z24-bridge: environmental effects versus damage events”. *Earthquake engineering & structural dynamics*, 30(2):149–171 (2001).
11. Fjord1. “Sykkelven-magerholm, ferry schedule” (2023).
12. Le, B.T., Siedziako, B., Nord, T.S., and Sibille, L. “Outcomes from field measurements on the magerholm ferry dock bridge: System identification, finite element model updating and sensitivity analysis”. *Society for Experimental Mechanics Annual Conference and Exposition* (2025).
13. Civera, M., Sibille, L., Fragonara, L.Z., and Ceravolo, R. “A dbscan-based automated operational modal analysis algorithm for bridge monitoring”. *Measurement*, 208:112451 (2023).
14. Civera, M., Rosso, M.M., Marano, G.C., and Chiaia, B. “Validation and comparison of two aoma approaches for the ambient vibration testing of long suspension bridges under strong wind loads”. In *International Operational Modal Analysis Conference*, pages 475–484. Springer (2024).
15. Sibille, L., Civera, M., Zanotti Fragonara, L., and Ceravolo, R. “Automated operational modal analysis of a helicopter blade with a density-based cluster algorithm”. *AIAA Journal*, 61(3):1411–1427 (2023).
16. ter Meulen, D.W.B., Cabboi, A., and Antonini, A. “Hybrid operational modal analysis of an operative two-bladed offshore wind turbine”. *Mechanical Systems and Signal Processing*, 223:111822 (2025).
17. García Cava, D., Avendaño-Valencia, L.D., Movsessian, A., Roberts, C., and Tcherniak, D. “On explicit and implicit procedures to mitigate environmental and operational variabilities in data-driven structural health monitoring”. *Structural Health Monitoring Based on Data Science Techniques*, pages 309–330 (2022).