

# Collaborative Structural Health Monitoring for Bridge Digital Twins

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CHONGJIE KANG, RALF HERRMANN, CEDRIC EISERMANN  
and STEFFEN MARX

## ABSTRACT

Structural Health Monitoring (SHM) is an effective tool that not only reduces reliance on periodic inspections but also enhances them by analyzing the current state of a structure based on the latest structural data. Collaborative SHM, which integrates various SHM systems within the scope of bridge digital twins (BDTs), enhances infrastructure resilience and maintenance strategies. However, it faces challenges in integrating distributed sensor networks and requires interdisciplinary collaboration. In this work, various aspects of enhancing collaborative SHM with BDTs are presented. As a pilot project, the Nibelungen Bridge in Worms (NBW), Germany, is introduced. Based on specific stakeholder and project requirements, various SHM systems have been installed on this bridge. To address these challenges, goal-oriented solutions have been developed and elaborated. Finally, conclusions and future outlooks are presented.

## INTRODUCTION

Effective lifetime management of structures increasingly requires diverse SHM use cases involving various technologies and stakeholders. To reduce sensor costs and maximize data value, combining ongoing and existing monitoring efforts is highly desirable. For the NBW [1], three major partners are involved: (i) the research program SPP 100+ at TU Dresden, focusing on environmental influences and structural behavior, with data feeding into a digital twin; (ii) LBM Worms, responsible for bridge operation, monitoring environmental effects and traffic conditions; and (iii) a project using innovative accelerometers to assess dynamic behavior and traffic loads. Due to administrative constraints, separate SHM systems were installed, but they are intended to operate in parallel.

To address this challenge, an open, collaborative SHM environment is proposed, enabling all three partners to share historical and real-time monitoring data. For economic efficiency, sensor data must be exchangeable between independently operated SHM systems. The following sections present the fusion of accelerometer data from two SHM systems (I and II), along with solutions and challenges.

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Chongjie Kang, Cedric Eisermann and Steffen Marx, Institute of Concrete Structures, TU Dresden, Dresden, Germany

Ralf Herrmann, Federal Institute of Material Research and Testing (BAM), Berlin, Germany

## SHM-SYSTEMS OF THE NBW

(1) SHM System I comprises six monitoring tasks from SPP 100+, totaling 20 measuring points focused on environmental conditions and structural behavior. All sensors are installed on the southern box girder of the pilot area. In coordination with SPP 100+, LBM Worms added a weather station and thermal camera to monitor air temperature, humidity, solar radiation, precipitation, and traffic flow. Since these tasks were jointly planned, all sensors were integrated into a shared technical infrastructure for data transmission, storage, processing, and access. As a result, all data, except thermal images and videos, is time-synchronized and available to research partners. A detailed description of SHM System I is provided in [2].

This work focuses on the fusion of accelerometer data, with the sensors described in detail. Two uniaxial IEPE accelerometers (see Figure 1) monitor the dynamic structural behavior, installed at the midpoint of the left cantilever beam and the Gerber joint. They measure in the direction of gravity with a range of  $\pm 5$  g ( $1$  g =  $9.81$  m/s<sup>2</sup>). In this scope, short-term measurements are taken at 200 Hz, with a 120-second data segment stored every hour (e.g., 09:59:55–10:01:55), as specified by the system requirements.

(2) SHM System II is developed and operated by the Federal Institute for Materials Research and Testing (BAM), Germany. It includes seven digital triaxial accelerometers and two analog geophones for continuous data acquisition. The system supports two monitoring tasks aimed at investigating transfer learning [3], as outlined in TABLE I. Notably, this work focuses only on the accelerometers.

TABLE I. OVERVIEW OF MONITORING TASKS OF THE SHM SYSTEM II.

Labelling	Sensor type	Measurement variable	No. of sensors	Measurement frequency	Monitoring task
B	capacitive triaxial MEMS accelerometers	acceleration at the box girder	7 with 3 axis (.B01 - (+Z) .B02 - (+Y) .B03 - (-X))	250 Hz	SD - structural dynamics
G	geophones	vibration velocity at expansion joint	2	250 Hz	LR - load recognition

The monitoring task SD realizes a distributed vibration measurement setup along the bridge between axis E and F, see Figure 1. Seven digital accelerometers were installed inside the bridge box girder, six of the sensors were installed in the southern box girder and the other one was installed in the northern box girder, see Figure 1. The accelerometers are based on capacitive Micro-Electro-Mechanical System (MEMS) technology to measure accelerations between 0 Hz and 1000 Hz. The measurement amplitude of the selected accelerometer type ranges from  $\pm 2$  g to  $\pm 8$  g (configured for  $\pm 8$  g until end of June 2024 and  $\pm 2$  g since 1st July 2024) and allows sampling rates up to 4 kHz per sensitive direction. They combine an internal microcontroller and transducer to be connected to a CAN network and three MEMS sensing elements.

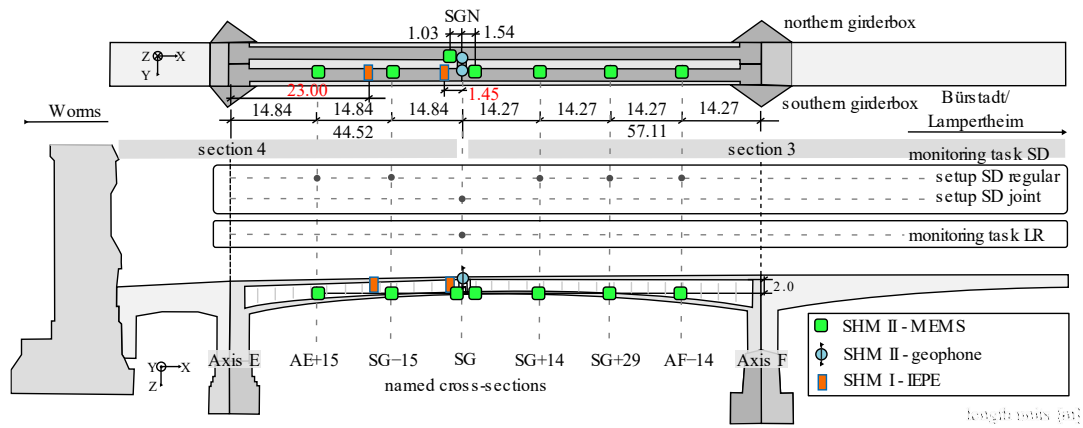


Figure 1. SHM System I and II - positions of acceleration sensors at the NBW.

During the planning phase, synergies between the two SHM systems (I and II) were considered to ensure the compatibility for time synchronization, while still allowing each system to operate independently and fulfill the objectives of its respective project. The idea of using just one data acquisition system (DAQ) for all measurements was not possible because the technologies of used sensors are different, resulting in significant differences in the configuration requirements of the DAQ system, that only can be solved with two systems. Also, all changes in the configuration needed for the research project would cause interruptions of the ongoing data acquisition.

## FUSION OF THE MEASUREMENT DATA OF ACCELEROMETERS

As aforementioned, SHM System I employs two analog IEPE accelerometers, while SHM System II uses seven digital MEMS accelerometers. The analysis focuses on the integration of digital and analog sensor data from different sensor types. To evaluate the feasibility of data fusion, the combined data quality must first be assessed. Although high data quality in both systems is essential, it does not guarantee high-quality fusion results, which are often only evident in retrospect. To enable effective data fusion, the following aspects are considered for SHM Systems I and II.

### (1) Data fusion according to data quality aspects

*Intrinsic data quality:* This is achieved by manually examining representative subsets of the data from both systems, along with associated metadata. In this case, the involved DAQ systems are used for SHM for a long time and hold intrinsic trust combined with calibration certificates.

*Contextual data quality:* In general, a modal analysis has very high requirements regarding the similarity of the transfer functions of the used sensors, the sampling resolutions and the synchronicity of the timestamps. To this end, both system clocks are synchronized in a master-slave-configuration: SHM System I provides the master clock and SHM System II is synced to it. This does not necessarily imply that measurements are recorded simultaneously. However, it is not possible to do modal analysis at all without proper synchronization.

*Representational data quality:* Both systems record the monitoring data independently. Then, data cleaning and data pre-processing steps are executed before the measurements are finally stored in a file and the folder structure or transmitted using an API interface. For monitoring the NBW, both systems used an ASCII text file format in a schema of comma separated values (CSV). While this is not storage efficient, it is easy for data interpretation and access. This makes it easy to achieve high representational data quality. Additionally, file name conventions and folder structures influence the representational data quality of SHM data.

*Data Access quality:* For an efficient access to the monitoring data of both systems, the folder structures of both systems are copied to an FTP-Server (File Transfer Protocol). Thereby, all the data files are accessible with credentials but still need to be downloaded. In addition, the data from the SHM System I already provides an API for data retrieval from the DT platform.

## (2) Data fusion of time shifted data

The raw data files from both systems are using local German time from the hardware synchronized system clocks. However, data files available for download on the network file share/FTP server of SHM System I use a different time zone due to different initial setup. Therefore, it is evident to synchronize the data of both systems. Figure 2 shows an excerpt of the vibration data with original timestamps of sensors which are in neighboring positions. Despite their close location at the bridge, there is no correlation in the vibrations visible. In comparison, the adjusted timeseries data of Figure 3 obviously shows the high correlation between the sensors at neighboring positions.

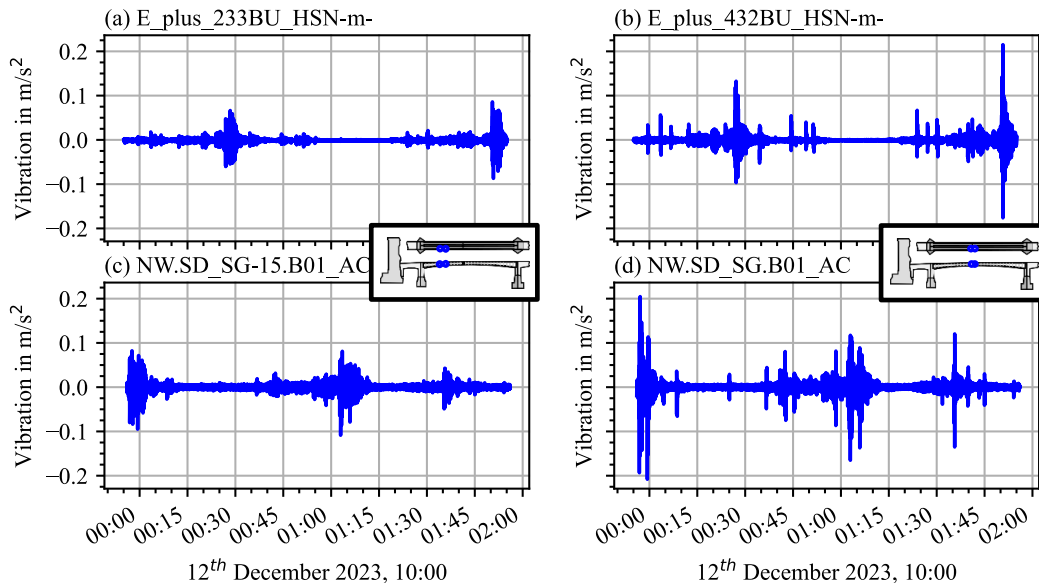


Figure 2. Vibration timeseries for 12<sup>th</sup> December 2023, 10:00 of accelerometers of SHM System I (a) in the middle of the left cantilever beam and (b) at the Gerber joint and of SHM System II (c) around 15 m away from Gerber joint and (d) at the Gerber joint, without time adjustment.

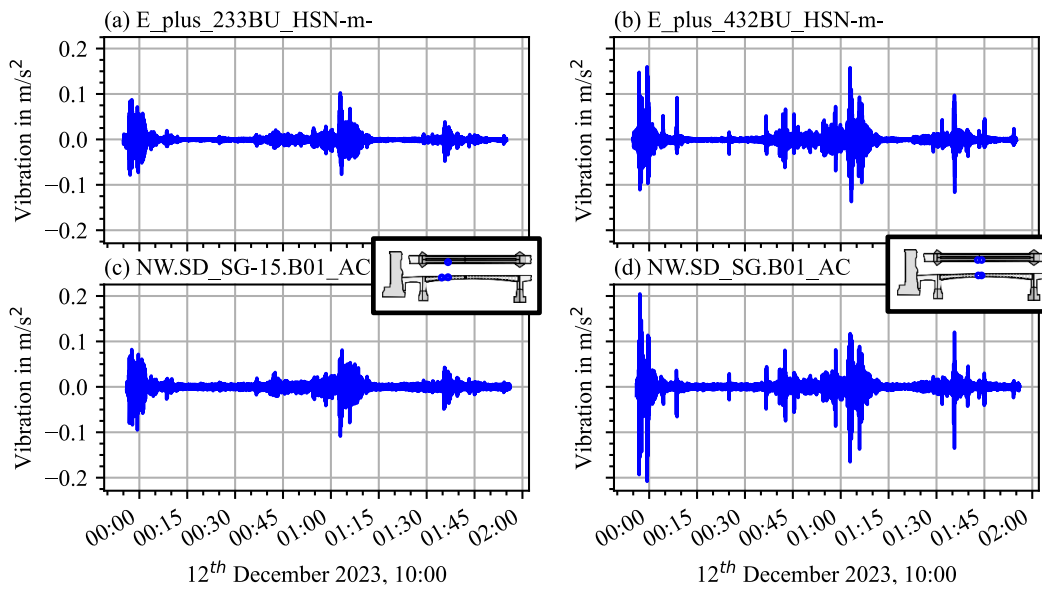


Figure 3. Vibration timeseries for 12<sup>th</sup> December 2023, 10:00 of accelerometers of SHM System I (a) in the middle of the left cantilever beam and (b) at the Gerber joint and of SHM System II (c) around 15 m away from Gerber joint and (d) at the Gerber joint, with time adjustment.

### (3) Data fusion of different time resolutions and jitter

The monitoring data in both systems contains absolute time stamps that differ from a constant sampling rate. Although the difference is very small, the histogram of the sampling interval durations of SHM System I is different from that of SHM System II (see Figure 4), not only in the expected mean value but also the distributions of shorter and longer sampling intervals. The mean value results from the sampling rate of 200 Hz in SHM System I and 250 Hz in SHM System II. Besides, SHM System I shows less precise time sampling intervals than SHM System II, as well as a slightly non-symmetric distribution. While the absolute difference seems small, the sampling rates used are considered low for dynamic vibration measurements, and they still result in more than 46 % of the sampling intervals being missed for SHM System I and more than 10 % of SHM system II. In this study, the recorded timestamps from SHM System II were used to interpolate the measurements to a 200 Hz sample frequency. This was done to align the data with SHM system I, employing linear interpolation to improve data accuracy.

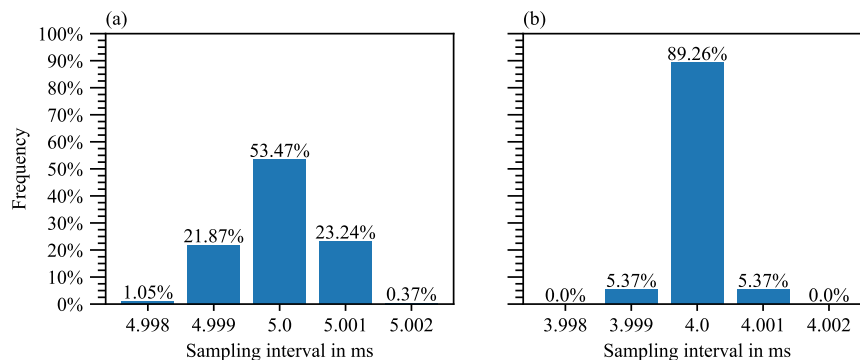


Figure 4. Jitter of sampling interval for (a) SHM system I and (b) SHM system II based on time stamps in the recorded data.

## RESULTS FROM DATA FUSION

Modal analysis imposes stringent requirements on the accuracy and quality of measurement data. In this context, the fusion of data from the two systems proves advantageous and serves as a demonstrative example. The monitoring task ‘ESD - extended structural dynamics’ is defined to investigate the bridge dynamics with increased spatial resolution. The new monitoring task doesn’t introduce additional sensors but combines the measurements from SHM System I monitoring task ‘DB - dynamic behavior’ and SHM System II monitoring task ‘SD - structural dynamics’, see TABLE II.

TABLE II. OVERVIEW OF FUSED MONITORING TASKS BASED ON THE SHM SYSTEMS I AND II MONITORING TASKS.

Origin of the data	Sensor type	Measurement variable	No. of sensors	Measurement frequency	Monitoring task
- DB (SHM system I) - SD (SHM system II)	- IEPE accelerometer - MEMS accelerometers	acceleration in the girder box	9	200 Hz (2 min at each hour)	ESD - extended structural dynamics

For the modal analysis in this case study, the measurements were taken from 12th December 2023 when the air temperatures were at around 10 °C and the concrete temperature of the structure at around 8 °C for the whole day. For validation, the identified modes are compared to a second dataset taken from the 21st May 2024 using the Modal Assurance Criterion (MAC), like in [4]. The fused accelerations over time as well as the singular values of spectral density (SVD) are plotted in

Figure 5. The time series shows the unfiltered excitation of the bridge induced by an approaching truck, which predominantly excites the structure at its first bending eigenfrequency. The bridge begins to vibrate as the vehicle approaches the bridge section coming from the approach bridge, typically reaching maximal vibration when passing the Gerber joint.

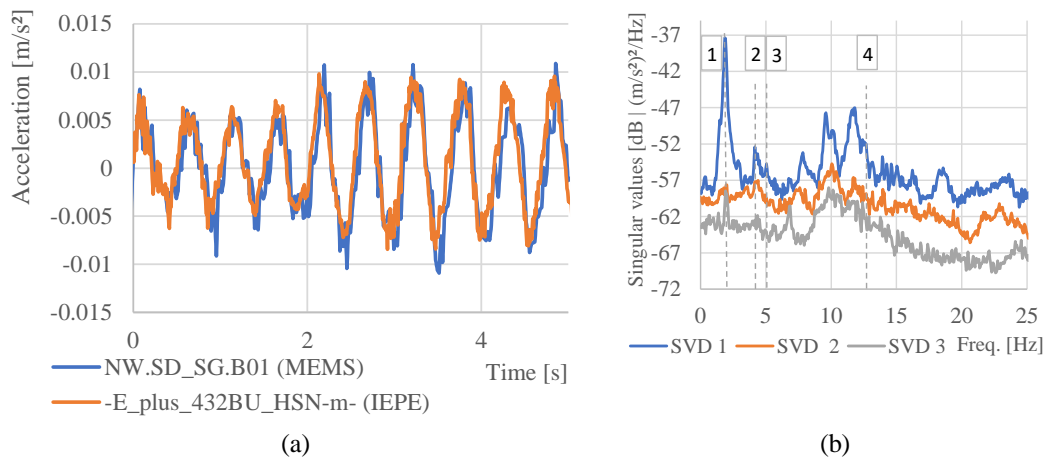


Figure 5. Fused acceleration time series from SHM System I and II for monitoring task ESD at the positions near the Gerber joint (a) and the according SVD plot (b).

The first bending eigenfrequency has been identified at 1.87 Hz using Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI), as shown in

Figure 5 and detailed in TABLE III. The phase shift between the IEPE sensors and the MEMS sensors is visible in the time series diagram (

Figure 5 (a)) and has been identified to be approximately  $15^\circ$  for this frequency. It can be explained by the phase shift of the MEMS sensors of  $-10^\circ$  and the IEPE sensors of  $+5^\circ$ . The phase shift is evident in the mode shapes, with one type of sensors moving off phase relative to the other type. The mode shapes corresponding to the identified vertical eigenfrequencies, achieved using the same methods, are presented in TABLE III:

TABLE III. IDENTIFIED VERTICAL EIGENFREQUENCIES OF NBW AND MODE SHAPES OF FUSED MONITORING TASK ESD, ARROWS MARK THE POSITION AND DIRECTION OF ACCELEROMETERS (PINK ARE PROJECTION CHANNELS, GREEN & ORANGE ARE REGULAR CHANNELS), LINEAR INTERPOLATION USED OF THE NEAREST MEASUREMENT FOR FREE NODES (GREEN DOTS), MEASUREMENT ON 12TH DECEMBER 2023.

No.	Frequency	Shape	Visualization
0	-	Undeformed Structure Model SHM system I (orange) SHM system II (green & pink)	
1	1.87 Hz	First Bending Eigenfrequency	
2	4.15 Hz	First Torsion Eigenfrequency	
3	5.03 Hz	Second Bending Eigenfrequency	
4	12.55 Hz	Third Bending Eigenfrequency	

The frequencies themselves remain unaffected by the phase shift, only the mode shapes are influenced. The first bending eigenfrequency was determined as 1.87 Hz, followed by the first torsion eigenfrequency at 4.15 Hz. The second and the third bending eigenfrequencies equal 5.03 Hz and 12.55 Hz, respectively. At these

frequencies, the effect of the phase delay becomes clearly visible, particularly where IEPE sensors and MEMS sensors are positioned adjacent to each other in the middle of the bridge.

## CONCLUSION AND OUTLOOK

The vibration measurements from the SHM System I can be used to extend the vibration sensor setup for modal analysis of SHM System II. It is evident that it is possible to perform a modal analysis of fused data of two SHM systems using two different types of sensors when the hardware is synchronized. However, the phase difference that depends on the frequency shall be addressed. One potential approach to address this issue in a next step is to apply the inverted transfer function identified for each single sensor or each sensor type according to [5]. Fusing data from different DAQ systems and sensor types to perform a modal analysis is a challenging task. Nevertheless, with increasing numbers of sensor positions along the structure, both the shape and the order of the mode shape can be accurately identified. It should be noted that, in our case, identifying the third bending eigenfrequencies mode shape was initially not possible without the fusion of SHM System I and SHM System II. Moreover, the temperature and environmental measurements in SHM System I are necessary for analysis together with the data of SHM System II.

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