Chapter 10
Operational Modal Analysis of the Bear Mountain Bridge and Comparisons with Finite Element Model

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Abstract The Bear Mountain Bridge is a historic suspension bridge that spans the width of the Hudson River in New York State. A wired sensor network of six uniaxial accelerometers was installed along the south side of the main suspended span to collect vibration data for use in operational modal analysis. This paper analyzes recently collected data to experimentally identify operational modes of the suspension bridge. Cross-validation of results from the system identification methods SSI-COV, ERA-NExT, and AFDD is used to determine modal frequencies. Stabilization diagrams from SSI-COV and ERA-NExT are compared to validate estimates of modal frequencies and mode shapes within individual datasets. Analysis of the identified modal frequencies, in conjunction with comparisons of associated mode shapes, found nine vertical modes for the bridge below 2.5 Hz. These results are then compared with estimates computed by a detailed finite element model of the bridge. This comparison shows good agreement between the experimentally identified modes and computationally identified modes.

Keywords System identification · Bridge · Modal properties · Sensor network · Structural health monitoring

Introduction

In recent decades, various vibration-based structural health monitoring techniques have been developed to identify dynamic properties in attempts to assess structural health. Ambient modal analysis involves recording structural vibrations during normal operation and analyzing these data to estimate modal properties [1]. There are a variety of well-established system identification methods capable of estimating structural modal properties based on ambient vibration data. Output-only system identification methods have been used historically to identify modes of large bridges based on the structure's dynamic response. For instance, modal analysis of the Golden Gate Bridge using an Autoregressive model accurately identified 67 different modes of the structure between 0 and 5 Hz [12]. These insights are highly valuable for calibration of physics-based models, damage detection, condition evaluation, and other applications [2].

Opened in 1924, the Bear Mountain Bridge has served as a landmark of cultural and economic value to New York State's lower Hudson Valley [3]. Its construction as a suspension bridge allows many comparisons to be made with other long-span, cable-supported structures, such as the Golden Gate Bridge, where analyses have previously been conducted [3][4]. In this study, accelerometer data is used to estimate the bridge's vertical and torsional modal frequencies, as well as its mode shapes. These modal characteristics establish a baseline that enables the detection of future structural changes. To improve

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accuracy, this baseline must be adjusted for environmental influences, such that variations in structural behavior can be more confidently attributed to shifts in the bridge's structural health.

Acquisition of Data

Modal identification in this study is based on the measurements of a network of six accelerometers installed on a main girder on the south side of the bridge, as shown in Figure 1. Spread across the 1632-foot-long main span, the sensors capture spatial dynamics of the bridge [3]. The uniaxial accelerometers are clamped to a flange underneath catwalk-access panels on the sidewalk. All accelerometers were hard-wired to a base station data acquisition system on the West side of the bridge. Sensors were affixed to the girder using a combination of mounting adhesive and clamps and positioned in such a way to resist detrimental environmental conditions.

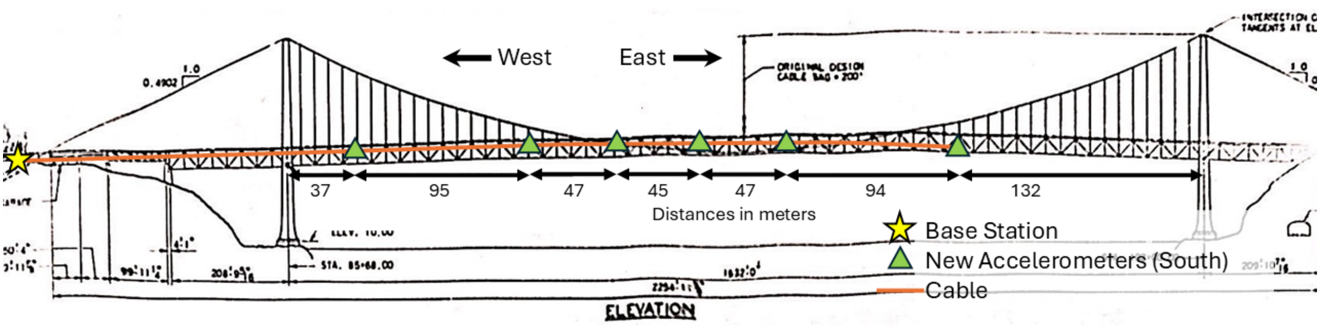

Fig. 1 Overview of Sensor Network Layout

Data collected from the "fixed" set of sensors requires on-site personnel to collect data, and so the data set was restricted to the bridge's working hours of 0800-1600. Initial datasets were collected in 2022 between the months of May and August with a previous sensor network. After the installation of this most recent network, data was collected in the months of November 2024, April 2025, and May 2025. The sensors are sensitive to a large band of low frequencies, including the expected range of 0-2.5 Hz for the relevant modal frequencies of the bridge.

Methods for Identification of Operational Modes

In order to conduct operational modal analysis on the Bear Mountain Bridge, output-only system identification methods are necessary. Prior analysis of the bridge identified three different output-only systems as appropriate for use with the data collection setup available. Automated Frequency Domain Decomposition (AFDD) [5], Eigensystem Realization Algorithm-Natural Excitation Techniques (ERA-NExT) [6], and Covariance-driven Stochastic Subspace Identification (SSI-COV) [7] are used as in past research to identify the operational modes of the bridge. The operational modal analysis of the structure uses stabilization diagrams with both SSI-COV and ERA-NExT to identify stable modes. Stabilization diagram results were further validated by comparing methods with representative datasets to ensure cooperating results. Technical issues with certain sensors required that some datasets be discarded altogether. In addition to output-only methods, a Finite Element Model (FEM) provided by an engineering firm was used to identify the modes of the model. Comparisons between these experimental and computational results were used to verify the accuracy of the Finite Element Model.

Stabilization Diagrams

Stabilization diagrams offer improved validation of results for operational modal analysis. Modes are initially identified through a base method—in this paper, SSI and ERA-NExT. Results are gathered for a range of model orders between 19 and 119; stable results exhibit similar frequencies (within 0.01 Hz), damping ratios (within 4%), and mode shapes (MAC value within 0.5%) across those multiple orders. These resulting stable poles are then clustered and averaged to identify a final frequency and mode shape. Stabilization diagrams also provide a visual guide for identifying the prominence of real modal frequencies. Vertical lines of results indicate a trend of stability for that frequency, indicating a high likelihood of real modes. This method reduces the risk of mischaracterizing computational artifacts as real modes, allowing for better validation of results. While a lack of access to precision accelerometers was a cause for a lack of results in the ultra-low frequency range, the available sensors proved sensitive enough to obtain a representative set of results at low frequencies.

Both SSI-COV and ERA-NExT were used to identify the operational modes of the Bear Mountain Bridge. The novelty of ERA-NExT is that it allows for output-only estimation of modes through an assumption of a uniform white-noise set of input parameters [8]. Frequencies and Mode Shapes at different model orders are identified by the eigenvalues and vectors evaluated through iteratively increasing Hankel Matrix size. The resulting modal frequencies, damping ratios, and mode shapes are then used to identify the stability of the pole and construct stabilization diagrams, as seen for a representative dataset in Figure 2. SSI-COV constructs a Toeplitz matrix of the covariance matrices of the structure's response, with singular value decomposition used to identify the modes [9]. Once again, the results are used to identify the stability of each pole and construct appropriate stabilization diagrams as seen in Figure 3.

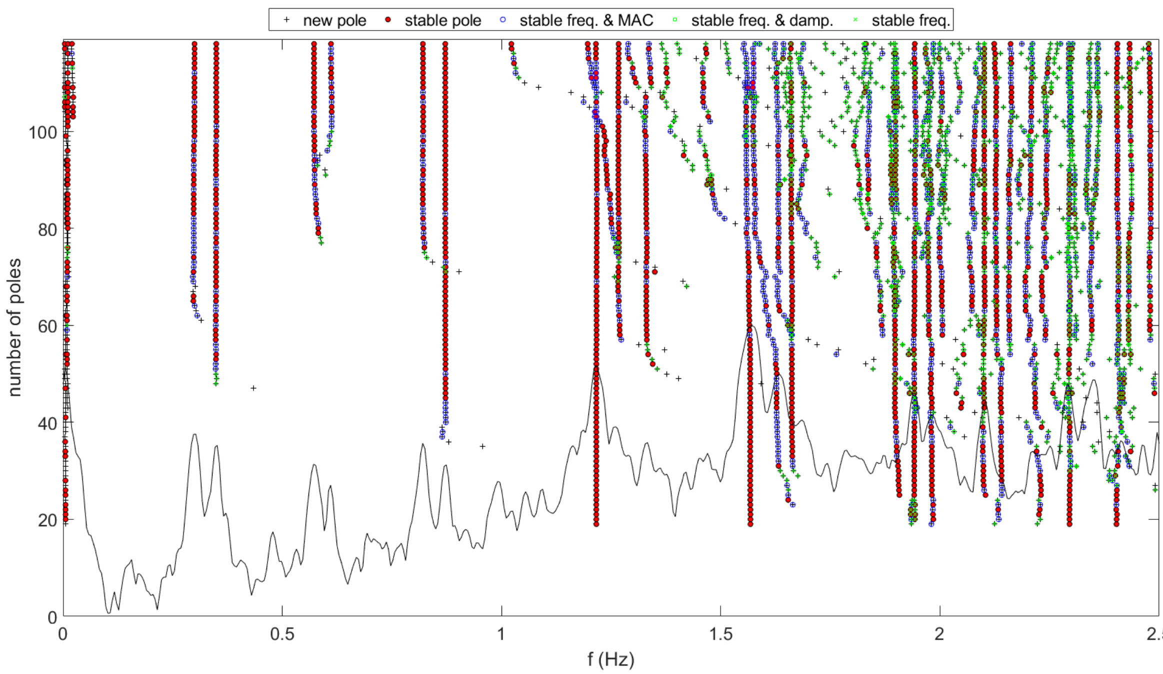

Fig. 2 Stabilization Diagram for ERA-NExT from a Representative Dataset (02MAY2025), Model orders 19 through 119

Finite Element Modeling of the Bridge

A three-dimensional global model of the suspended span of the Bear Mountain Bridge was developed in CSiBridge v24.2.0[17], as shown in Figure 4. The model includes the main cables, suspenders, towers, stiffening trusses, floor trusses, lateral bracings, stringers, concrete deck, tower saddles and other nonstructural components. Main cables and suspenders are modeled by cable elements that incorporate tension-stiffening and large-deflections nonlinearity in the element formulation. Towers, stiffening trusses, floor trusses, lateral bracings and stringers are modeled with beam elements. Shell elements are used for modeling decks, and link elements are used to simulate connections between the stiffening trusses and tower, as well as the stringer bearings. The main cables were anchored to the ground and modeled by pin support. At the top of the bridge tower, the main cable was supported through the tower saddles, joint constraints were defined for the main cable nodes and the tower saddle nodes. At the tower leg, the lateral only restraint provided by the tower to the upper and lower chord members of the stiffening truss were modeled by 1-D link elements. The entire model of the Bear Mountain Bridge consists of about 11,704 nodes, 7961 beam elements, 294 cable elements, 4224 shell elements and 1232 link elements.

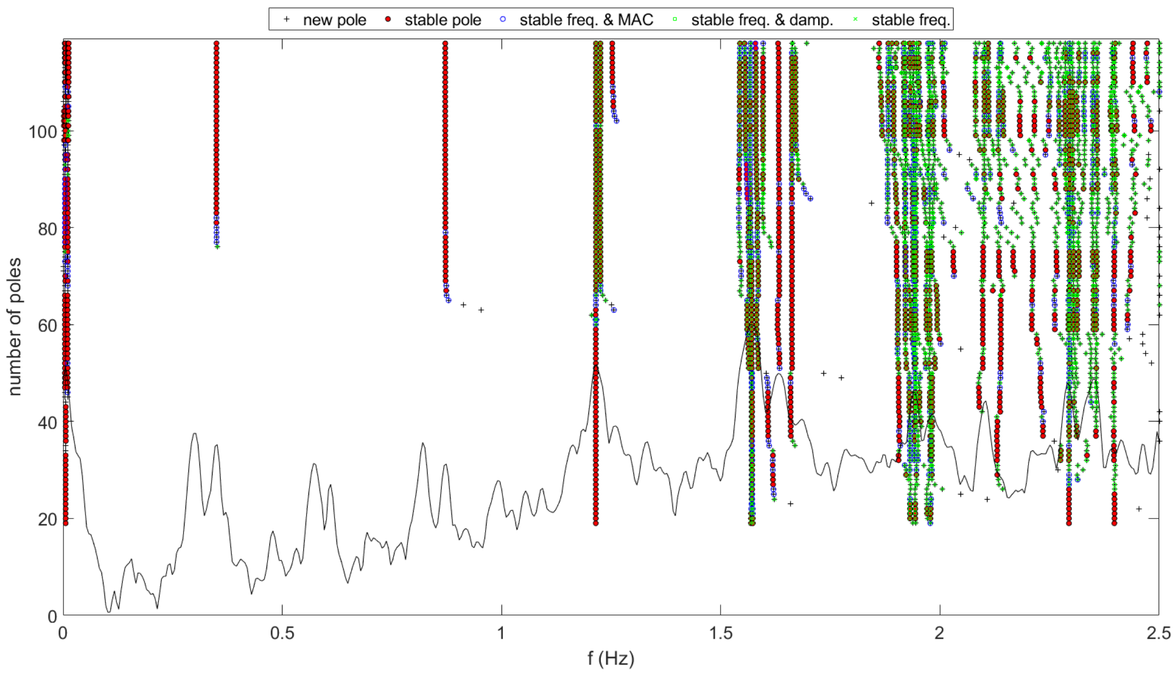

Fig. 3 Stabilization Diagram for SSI-COV from a Representative Dataset (02MAY2025), Model orders 19 through 119

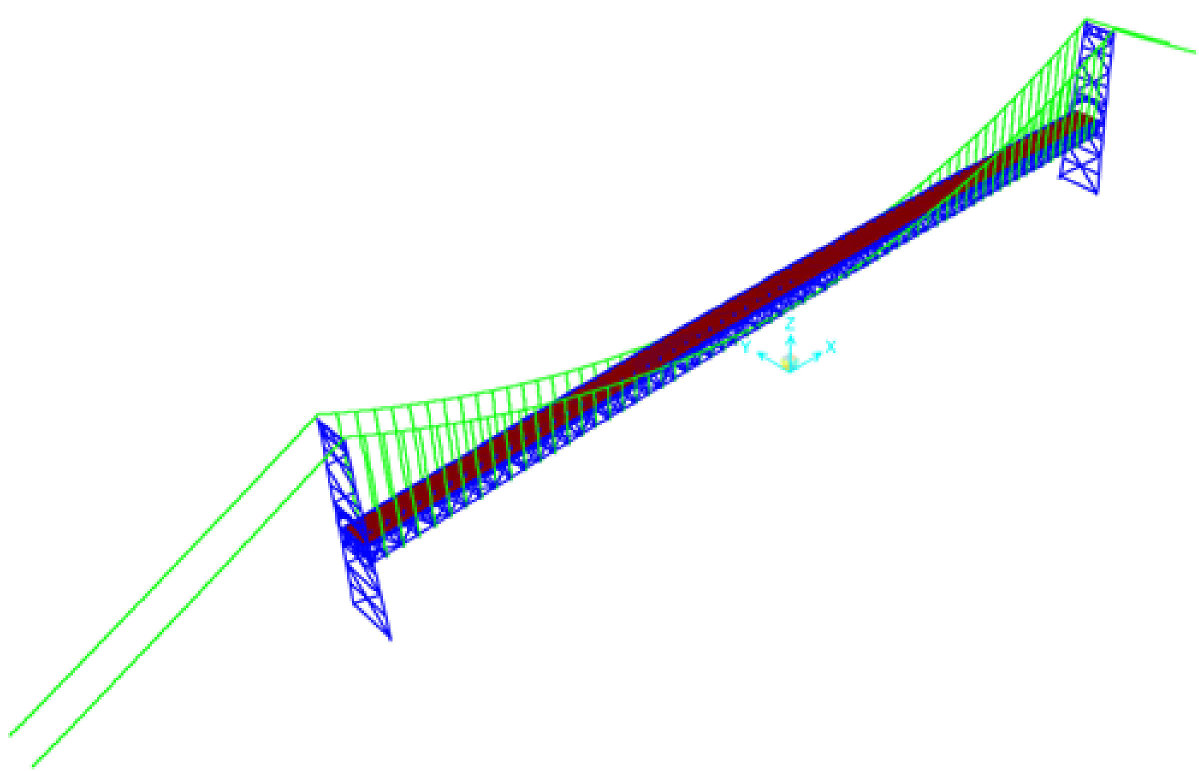

Fig. 4 The three-dimensional FEM model of the Bear Mountain Bridge

The modeling process began with a baseline model representing the bridge as it was originally constructed in the 1920s. Subsequently, a staged construction approach was adopted to simulate the deck replacement and strengthening undertaken in the 1970s, thereby representing the bridge's current existing condition. Model analysis was then conducted based on the stiffness at the end of nonlinear analysis of the dead load condition of the bridge in its current state.

Comparison of Results

The results from stabilization diagram analysis of the bridge are compared against the FEM-identified frequencies. For the Finite Element Model, the first 100 global modes of the bridge were extracted and compared with those identified from the field measurements. The corresponding mode shapes and frequencies obtained from the finite element model are presented in Figure 5 and Table 1. The results from the stabilization diagram come from a representative dataset. The stabilization diagram results for ERA-NExT identified 9 modes between 0 and 2.5 Hz, with the SSI-COV method identifying 5 modes, all of which align with the results from ERA-NExT. As shown in Table 1, the experimentally identified frequencies are in good agreement with the FEM results. Identifying concurring results with the results of the FEM model gives reasonable certainty that those modes are real modal frequencies. The concurring frequencies also lend credence to the accuracy of the FEM.

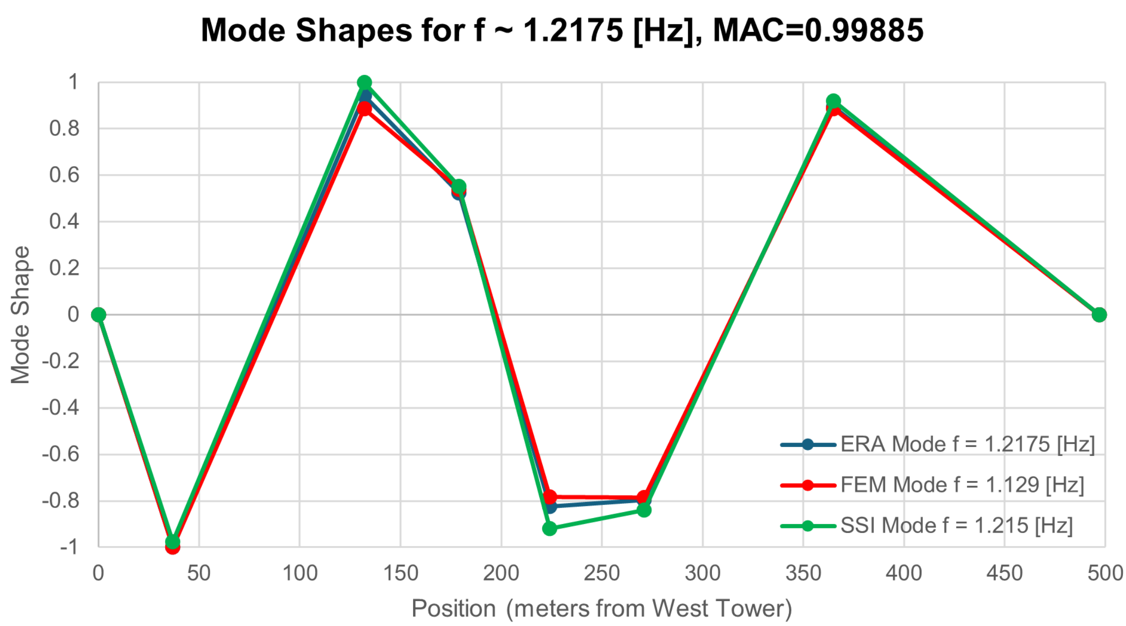

Fig. 5 Mode Shape Comparison for Mode 6

Once modal frequencies have been identified, their associated mode shapes can be analyzed. Comparisons of mode shapes from different methods at similar frequencies are used to validate the mode as a likely real mode. Modal Assurance Criterion or MAC values are computed for each pair of mode shapes from the three different methods and then averaged to give a quantitative evaluation of their correlation. MAC values close to 1 are indicative of concurrence between the different methods. For all nine identified modes, the average MAC values between the FEM, ERA-NExT, and SSI-COV methods remained close to 1, with mode shape concurrence decreasing as the modal frequencies increased. Due to high MAC values, reasonable certainty is gained that these identified modes are accurate, and that the mode shapes are representative of the dynamic response of the structure.

An example of the mode shape comparison is given in Figure 5 for Mode Six, a vertical mode, where the MAC value was computed to be 0.999. It is important to note the inherent limitation in spatial resolution of the estimated mode shape based on the limited number of fixed sensors. With six sensors, it is only possible to reconstruct mode shapes that have five or fewer points of inflection. Mode shape ordinates from the FEM model were selected at distances to match those of the sensors in order to demonstrate the concurrence between the mode shapes.

Table 1 Frequency Results from Stabilization Diagrams

Mode Number	Mode Type (V,T,?)	Modal Identification Results (02MAY25 Dataset)		FEM Results	Average MAC Values
		ERA-NExT	SSI-COV		
1	V	0.300	–	0.275	0.9988
2	?	0.349	0.350	0.340	0.9983
3*	?	0.572	–	0.526	0.9893
4	V	0.821	–	0.719	0.9989
5*	?	0.872	0.872	0.797	0.9995
6	V	1.217	1.215	1.129	0.9989
7	V	1.943	–	1.832	0.9839
8	T	2.101	2.101	2.050	0.8730
9*	?	2.478	2.358	2.510	0.8239

V = vertical mode, T = torsional mode, ? = unverified mode type. * = New Modes identified by Stabilization Diagrams.

Conclusion

This paper presents a continued analysis of the modal properties of the Bear Mountain Bridge based on vibration measurements from a network of six accelerometers. Through the use of stabilization diagrams for multiple methods, operational modes were calculated and validated by cross-checking modal frequency values and mode shapes through MAC value analysis, with operational modes identified by stabilization diagrams compared to modes identified from a finite element model. A total of nine modes were identified by ERA-NExT with five of those modes also identified by SSI-COV. All nine modes from ERA-NExT were also identified by the FEM out of the first 100 global modes of the model. Modal frequencies ranged from 0.3 to 2.5 Hz.

Mode estimation of the Bear Mountain Bridge through the use of stabilization diagrams further validates previously identified modes and establishes the usability of stabilization diagrams for future structural health monitoring. The strong concurrence between experimental results and FEM results highlights the accuracy of the FEM developed. With the Bear Mountain Bridge undergoing major renovations in 2026, this baseline modal analysis for the existing structure also offers the opportunity to identify in the future the impact of changing the bridge deck on its modal properties.

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