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Operational Modal Analysis of a Box Girder Bridge using Fast Fourier Transform and Stochastic Subspace Identification

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ABSTRACT

The A.P. Pettarani Flyover Bridge in Makassar serves as a critical infrastructure supporting community mobility and regional economic activities. With the increasing volume of traffic and the resulting structural loads, the implementation of a Structural Health Monitoring System (SHMS) becomes essential to ensure both the safety and maintenance efficiency of the bridge. This study aims to explore the application of Operational Modal Analysis (OMA) through the use of Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) methods to analyze the bridge's structural health by extracting natural frequencies and damping ratios from dynamic response data. Dynamic response data were obtained through permanently installed accelerometers, enabling continuous monitoring of the bridge's vibrational behavior due to traffic loads and environmental influences. The FFT analysis effectively identified the dominant frequency at 3.92 Hz, consistent with the results from SSI analyses both SSI Data and SSI Covariance methods which also yielded a natural frequency of 3.92 Hz. Additionally, other frequencies were observed in the range of 9.80 Hz to 9.81 Hz, with corresponding damping ratios varying between 1% and 3%. The consistency in natural frequency results from both methods highlights the reliability of OMA in capturing the modal characteristics crucial for structural health assessment. Harnessing modern sensor technology and advanced spectral and subspace identification techniques, this monitoring system facilitates early detection of potential damage before it evolves into more significant issues. The practical implications of this research include enhancing maintenance strategies toward more targeted and sustainable bridge management. Furthermore, the success of this study provides a valuable reference model for the continual development of SHMS for other bridges throughout Indonesia, ultimately promoting road user safety and the longevity of national infrastructure.

1. Introduction

The A.P. Pettarani Elevated Toll Bridge in Makassar is a concrete box girder bridge comprising several spans, one of which measures 40 metres in length. This bridge is a critical piece of infrastructure that supports mobility and economic growth in the region. As traffic volume and the loads borne by the bridge increase, it is essential to ensure that this structure remains in good condition and safe for use. Therefore, the implementation of a Structural Health Monitoring System (SHMS) is of paramount importance. In the modern era, bridges serve not only as transportation means but also as vital infrastructure that requires special attention. To ensure the long-term functionality and safety of the bridge, the adoption of SHMS is a strategic and necessary step [1]. The Structural Health Monitoring System (SHMS) serves to continuously monitor the health condition of bridge structures through the utilisation of various analytical methods. One such method is Operational Modal Analysis (OMA), which integrates techniques such as Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) [2].

The Fast Fourier Transform (FFT) method is a fundamental technique in operational modal analysis that is employed to extract critical information from the vibration signals produced by bridges. The FFT

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facilitates the transformation of signals from the time domain to the frequency domain, thereby simplifying the identification of the natural frequencies and damping ratios of the structure [3]. By employing this technique, data collected from sensors installed on bridges can be effectively analysed. This provides a clear depiction of the dynamic behaviour of the bridge under various loading conditions. It is important to note that the natural frequency of a structure may change over time due to factors such as material wear, environmental changes, and structural damage [4].

Furthermore, the SSI method offers a more sophisticated approach to modal analysis. SSI facilitates the identification of modal shapes and the frequency response of structures without necessitating knowledge of the excitation styles applied [5]. The Stochastic Subspace Identification (SSI) method is a prominent time-domain approach for Operational Modal Analysis (OMA) that estimates stochastic state-space models solely from stationary output data. This method is recognised for its high parameter estimation accuracy and computational efficiency in comparison to other OMA techniques [6].

By gathering vibration data from various points on the bridge, the Stochastic Subspace Identification (SSI) method can provide accurate information regarding the structural condition of the bridge. This facilitates early detection of potential damage. For instance, if there is a significant change in the modal shapes identified through SSI, this may indicate that there is damage that requires further investigation. Therefore, the selection of the Fast Fourier Transform (FFT) and SSI methods in this study is based not only on their popularity but also on the ability of both methods to deliver accurate and relevant results within the context of structural health monitoring of bridges.

The integration of Operational Modal Analysis (OMA) methods into the Structural Health Monitoring (SHM) system of the A.P. Pettarani Toll Bridge not only enhances operational safety but also provides long-term benefits in terms of maintenance efficiency. Through continuous monitoring, the maintenance team can undertake preventive measures before damage escalates into more serious issues, thereby reducing potential repair costs arising from undetected damage. Research indicates that the implementation of SHM can lead to a reduction in maintenance costs by up to 30% by providing accurate data for informed decision-making [7].

The utilisation of advanced sensor technology within Structural Health Monitoring (SHM) systems significantly contributes to the effectiveness of monitoring. Modern sensors installed on bridges are capable of measuring a variety of parameters, including vibration, temperature, and deformation, in real-time. This data is subsequently analysed to provide a comprehensive assessment of the bridge's health [8]. With accurate and real-time information, the authorities can take the necessary measures to ensure that the A.P. Pettarani Toll Bridge remains safe and reliable for public use.

This research aims to explore the application of Operational Modal Analysis (OMA) using Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) methods on the A.P. Pettarani Toll Bridge in Makassar, as shown in Figure 1. Through this analysis, a comprehensive understanding of the bridge’s structural health is expected to be obtained, along with an evaluation of the effectiveness of the two methods employed. Furthermore, this study is expected to contribute to the development of bridge structural health monitoring systems in Indonesia and serve as a reference for future research in the field of Structural Health Monitoring Systems (SHMS).

Figure 1. The Location of A.P. Pettarani Toll Bridge, Makassar.

2. Methods

This research employs a comparative method that integrates data analysis from accelerometer sensors using the Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) approaches. By utilising accelerometer sensors that are permanently installed at 1/4, 1/2, and 3/4 of the bridge span, dynamic response data of the bridge during vehicle transit can be accessed via the internet, facilitated by Structural Health Monitoring (SHM) technology. As illustrated in Figure 2, during the operational period, the sensors installed on the bridge will automatically record dynamic response data. The data obtained from the sensors consists of acceleration measurements (m/s²).

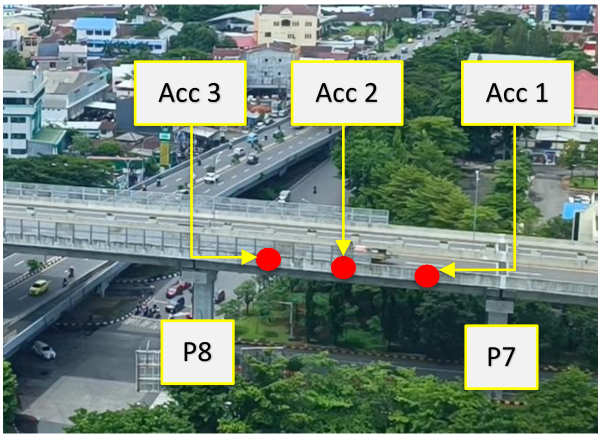

Figure 2. Three accelerometer sensors (Acc 1, Acc 2, and Acc 3) were installed on the bridge span between pier P7 and pier P8.

Data collection was conducted over a specified period to ensure that variations in traffic conditions could be adequately covered. In this study, data were collected at various times and under real-time traffic conditions. This is crucial for obtaining a more comprehensive understanding of the bridge's response to different excitations. According to previous research, consistent and repeated data collection can enhance the accuracy of modal analysis [9].

Following the data collection, the next step involves conducting an analysis using the Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) methods. This process will be carried out using Python software, utilising the available modules within the software such as NumPy and SciPy.signal. The purpose of the FFT analysis is to convert the data from the time domain into the frequency domain [10], In order to identify the natural frequencies of the bridge, we must undertake a process that includes filtering the data to minimise noise and clarify the relevant signals. The results obtained from the Fast Fourier Transform (FFT) analysis will provide information regarding the natural frequencies of the bridge, based on the dominant peak frequencies within the frequency spectrum. This information is utilised to ascertain the first mode shape[11] [12].

Mathematically, the FFT method is expressed as the discrete transformation of the time-domain signal *x(n)* into the frequency domain *X(k)* by Equation 1.

$$X(k) = \sum_{n=0}^{N-1} x(n).e^{-j\frac{2\pi}{N}kn} \tag{1}$$

where *X(k)* represents the spectrum value at the k^{th} frequency bin, *x(n)* is the input signal at sample *n*, *N* is the total number of samples, and *j* is the imaginary unit. This formula enables the decomposition of the time-domain signal into its constituent frequency components, facilitating the identification of dominant frequencies that characterize the natural vibration behavior of the bridge structure.

Subsequently, the analysis was continued using the SSI method implemented in Python with the Pyoma module. Pyoma employs data-driven algorithms (SSI-Data) as well as covariance methods (SSI-Cov) within its framework. The SSI-Cov method is particularly noted for its computational efficiency, leveraging block Hankel matrices obtained from data correlation analysis [6]. In general, the SSI procedure begins by forming a Hankel block matrix from the y(k) output data:

$$H_{i,j} = \begin{bmatrix} y(i) & y(i+1) & \cdots & y(i+j-1) \\ y(i+1) & y(i+2) & \cdots & y(i+j) \\ \vdots & \vdots & \ddots & \vdots \\ y(i+r-1) & y(i+r) & \cdots & y(i+r+j-2) \end{bmatrix} \tag{2}$$

where (*r*) is the window size and j is the depth of the stack (number of block rows). This matrix is outlined with Singular Value Decomposition (SVD):

$$H_{i,j} = U\Sigma V^T \tag{3}$$

Overall, the integration of the SSI method within the Pyoma module enhances the capability for structural health monitoring by facilitating efficient and accurate modal parameter estimation derived solely from output data [6]. Moreover, SSI is recognised for its effectiveness in addressing noise issues that frequently impact the results of modal analysis [13]. Subsequently, the results of the analysis from both methods will undergo validation against previous research that has been conducted on the topic of Comparing the Dynamic Properties of 1D, 2D, and 3D Models for a 40-metre

Span Box-Girder Concrete Bridge. The analysis was performed using numerical methods with Midas Civil software [14]

Finally, the outcomes of both methods will be compared to evaluate the consistency and accuracy of each approach. By employing a comparative method, this research aims to provide deeper insights into the effectiveness of FFT and SSI in the structural health monitoring of bridges. The results of the analysis are expected to offer recommendations for the enhancement of Structural Health Monitoring Systems (SHMS) in Indonesia.

3. Results and Discussion

3.1. Data from the Accelerometer Sensor Recordings

Based on the data that has been collected for analysis, information on acceleration in meters per second squared (m/s^2) was successfully obtained using a sampling frequency of 100 Hz. This acceleration measurement was carried out using a three-dimensional (3D) accelerometer permanently installed on the bridge structure. This tool allows data collection in three main directions, namely along the X, Y, and Z axes. Each sensor produces three data components that collectively describe the dynamic response of the bridge to the excitation load. In the context of this study, the main focus will be given to the acceleration data component on the Z axis, because this axis is considered the most representative of the bridge's response to the excitation force generated by vehicle activity crossing the A.P. Pettarani Toll Bridge in Makassar. To provide a clear picture of this acceleration pattern, data from the Z axis will be presented visually in the form of a graph in the time domain. The purpose of this presentation is to make it easier for readers to understand the characteristics of the dynamic response that occurs on the bridge, as illustrated in Figure 4 to Figure 6 that accompany this discussion.

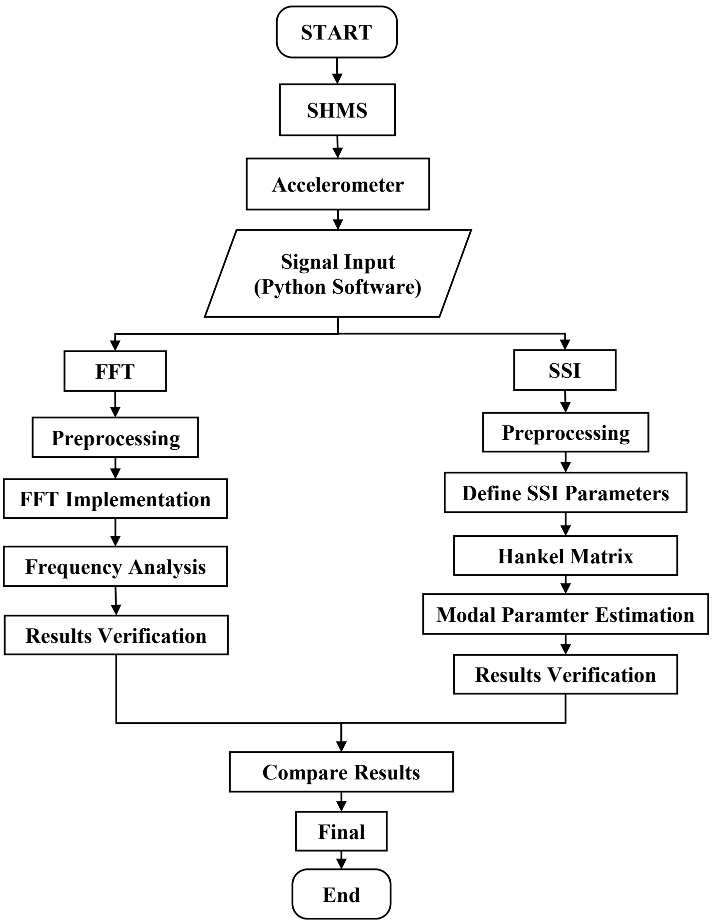

Figure 3. Research method flow chart

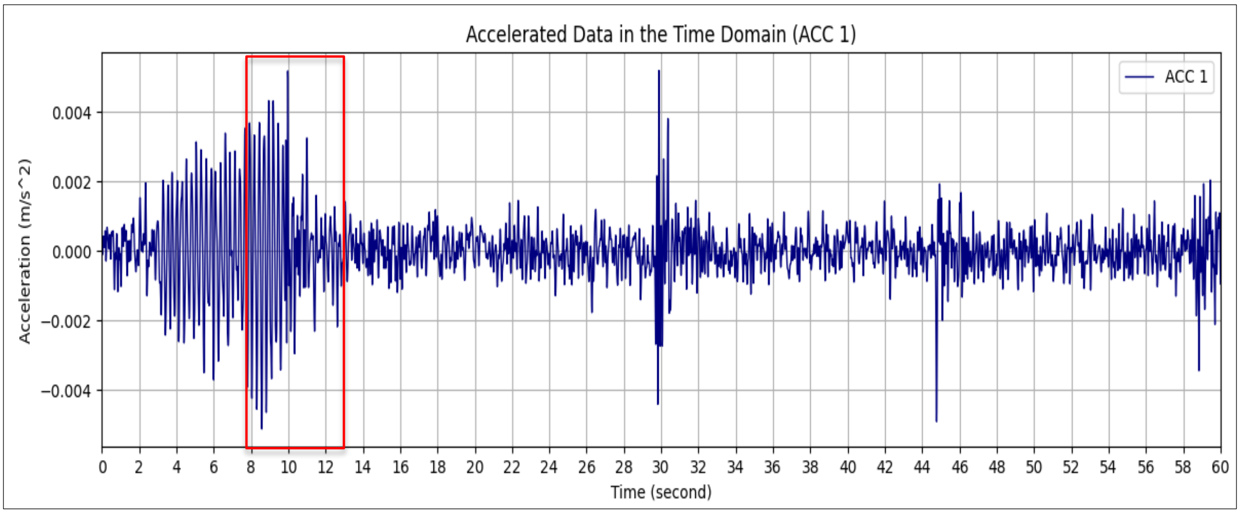

Figure 4. Sensor data ACC 2 in 1/4 of the bridge span

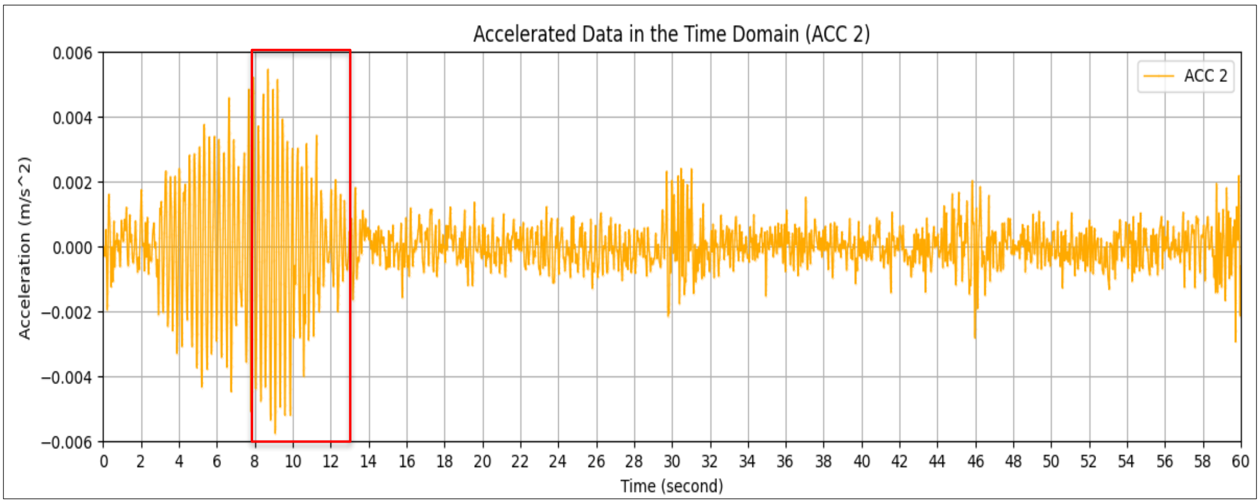

Figure 5. Sensor data ACC 2 in 1/2 of the bridge span.

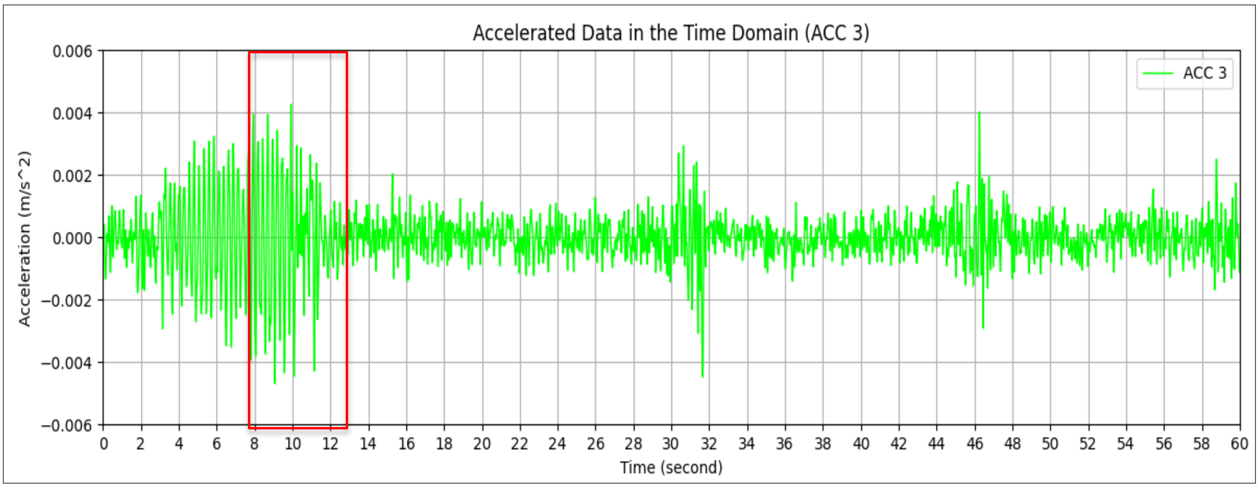

Figure 6. Sensor data ACC 3 in 3/4 of the bridge span.

Figure 4 to Figure 6 present the acceleration data obtained from the accelerometer sensors ACC 1, ACC 2, and ACC 3 installed on the bridge span. Each sensor recorded the structural vibration response with a data acquisition duration of 60 seconds. The measured data were subsequently analysed using the Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) methods to identify the modal parameters of the structure.

3.2. Data Analysis using FFT

The frequency spectrum analysis results are presented using the Fast Fourier Transform (FFT) method on three recorded signal channels. Each graph visualizes the frequency spectrum of the respective channels, where the horizontal axis (X) represents the frequency in Hertz (Hz), and the vertical axis (Y) denotes the amplitude or intensity of the signal at those frequencies. The spectral analysis is focused on the time interval between 8 and 13 seconds from the sensor data recording, representing the period of excitation force activity acting on the bridge structure. The FFT results show that all three channels exhibit highly consistent dominant peak frequencies, namely 3.91 Hz for the first channel, 3.94 Hz for the second channel, and again 3.91 Hz for the third channel. The consistency of these peak frequencies indicates the presence of a dominant vibration mode responding to dynamic loads such as vehicular traffic during the observation period. This finding is significant in the context of modal analysis and structural health monitoring, where the dominant frequency can be used as a primary parameter to detect changes in the dynamic characteristics of the bridge, potentially indicating damage or structural degradation. Visualization of the FFT results for the three channels can be seen in Figure 7 to Figure 9, supporting the conducted analysis.

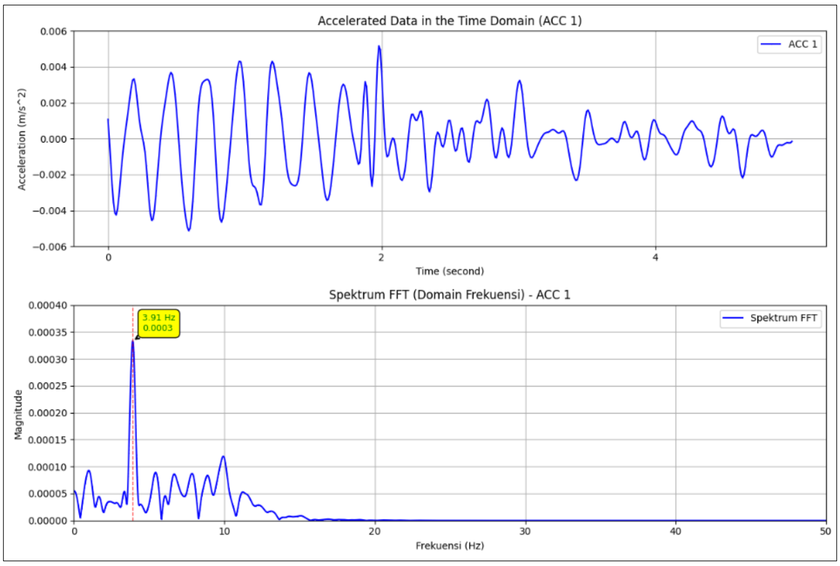

Figure 7. Graph of FFT Analysis Results for Channels 1

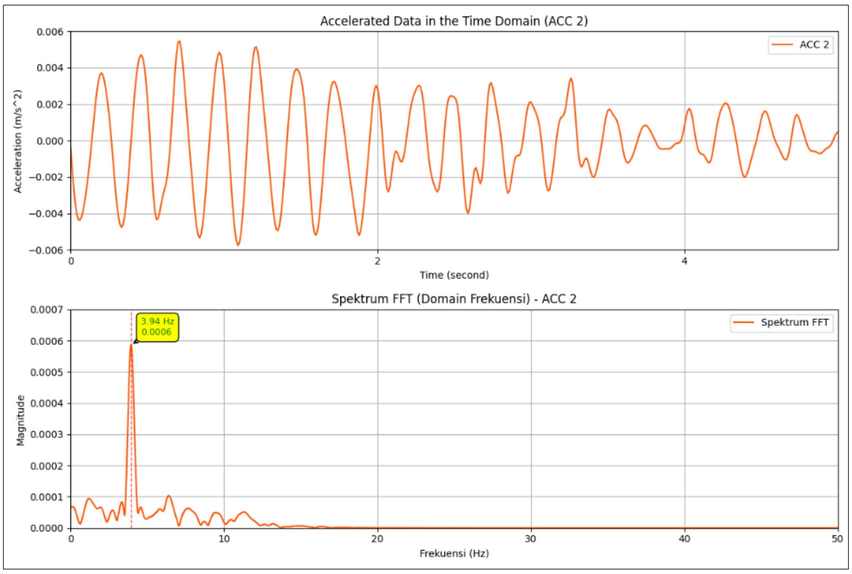

Figure 8. Graph of FFT Analysis Results for Channels 2

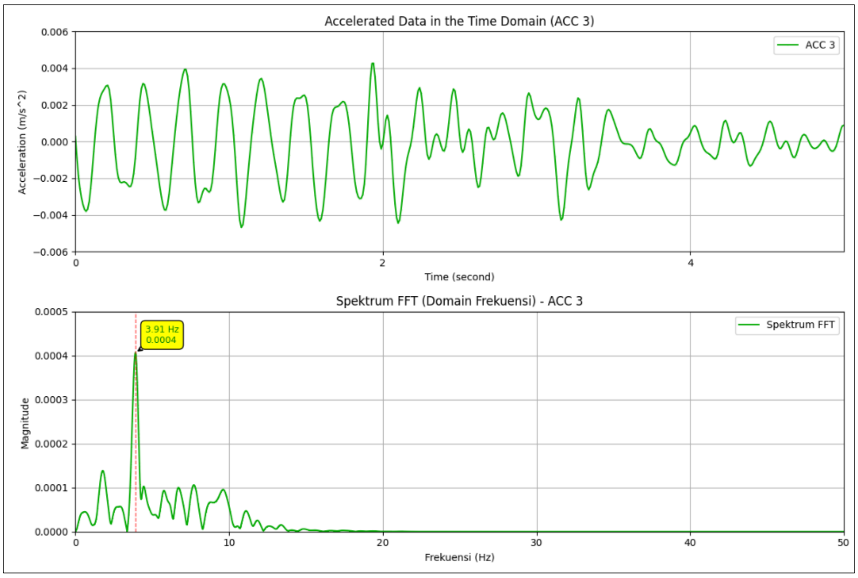

Figure 9. Graph of FFT Analysis Results for Channels 3

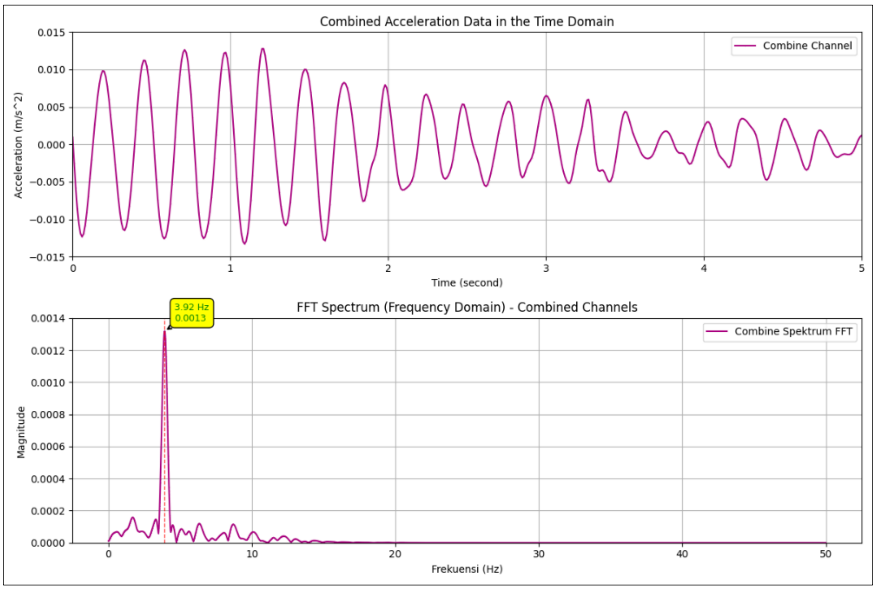

Figure 10. Combined FFT Analysis Results Graph.

Table 1. Dominant Frequency Values from FFT Analysis

Sensor	Frequency FFT (Hz)
Accelometer 1	3.91
Accelometer 2	3.94
Accelometer 3	3.91
Combination	3.92

Subsequently, a simultaneous FFT analysis was conducted on all available data. The result is a composite FFT graph, which can be utilised as a reference for determining the natural frequency of the bridge, based on the most dominant frequency of 3.92 Hz. This is illustrated in the FFT graph presented in Figure 10.

From the entire frequency data generated through FFT analysis, both those acquired from separate analyses for each channel and those that are combined, are presented in Table 1.

3.3 Data Analysis using SSI

The analysis conducted using the SSI data and SSI covariance methods was performed with the aid of the Python software module Pyoma, which facilitates the processing of the collected data to yield accurate and reliable results. The analytical process commenced with the gathering of the requisite data, which was subsequently processed employing the SSI data and SSI covariance methodologies. With the assistance of the Python program and the Pyoma module, this process can be executed swiftly and efficiently [6]. The results of the analysis are then represented in stabilization diagrams, as illustrated in Figure 11 and Figure 12. These stabilization diagrams provide valuable information for comprehending the data patterns present within the analysis dataset. The inclusion of several labels on the stabilization diagrams serves as a reference point for identifying data ranging from the least stable to the most stable, in accordance with the established order of the labels.

Based on the stabilization diagram obtained from the analysis using the SSI data and SSI covariance methods, the first modal frequency was identified at a value of around 3.92 Hz. As for the second mode, the frequencies obtained were 9.80 Hz and 9.81 Hz, respectively, indicating the consistency of the results from the two approaches. In addition, the damping ratio value was also obtained which shows the level of damping in each mode, with the first mode having a damping ratio of around 1.3% and 1.4%, while the second mode showed a damping ratio of 2.1% and 2.5%. These data confirm the dynamic characteristics of the structure being analyzed and provide important information regarding the structure's ability to dampen vibrations due to dynamic excitation. To provide a clearer and more comprehensive picture, the results are summarized in Table 2 and Table 3.

3.4. Combined Analysis of FFT and SSI

The structural vibration data of the bridge were analyzed simultaneously using two complementary approaches Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI). These methods were chosen due to their well-established capability in extracting dynamic parameters from output-only measurements, particularly under ambient excitation conditions, which is common in operational modal analysis (OMA) for in-service bridge structures. The results from both methods are presented through frequency spectrum plots and stabilization diagrams, providing a multi-perspective characterization of the bridge's dynamic behavior. Specifically, FFT serves as a powerful spectral tool to highlight dominant frequency content, while SSI offers a more advanced state space based framework for estimating natural frequencies, damping ratios, and mode shapes.

Findings from both analyses exhibit a strong correlation, with dominant peaks identified via FFT aligning closely with the stable frequency markers detected in the SSI stabilization diagrams. This alignment confirms the consistency of both methods in capturing fundamental modal properties, a conclusion that is also supported by previous studies which emphasized the synergistic use of FFT and SSI for enhanced modal parameter identification [11][15]. Such agreement is visually represented in Figure 13 and Figure 14, where both techniques reveal an almost identical frequency range. This congruence not only validates the reliability of the signal processing but also underscores the suitability of both methods for structural health monitoring (SHM) applications.

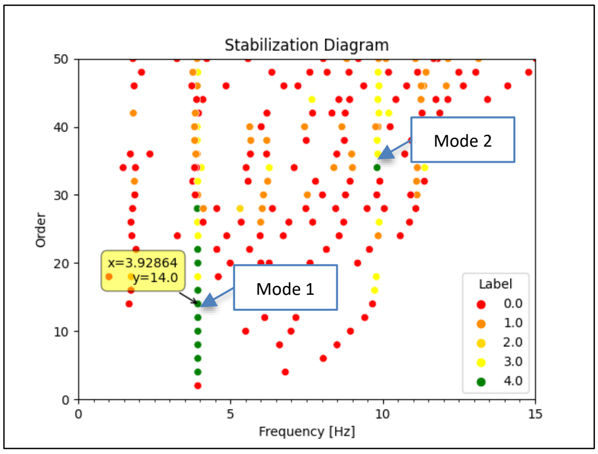

Figure 11. Stabilization Diagram of the Analysis Results of the SSI Method Data.

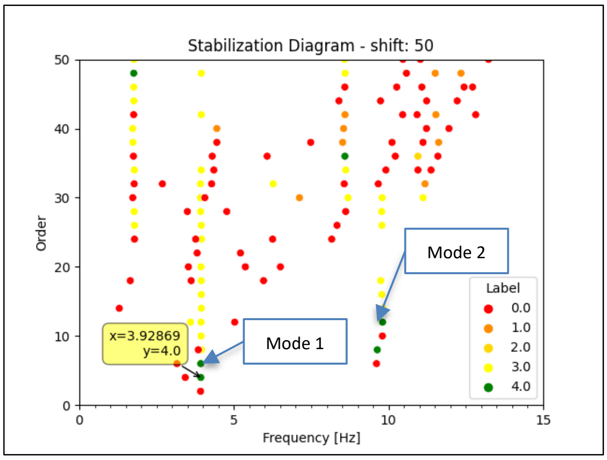

Figure 12. Stabilization Diagram of the SSI Covariance Analysis Results.

Table 2. Natural Frequency Values from SSI Analysis.

Mode Shape	SSI DATA	SSI COV
	Natural Frequency	
1	3.92	3.92
2	9.80	9.81

Table 3. Damping Ratio Values from SSI Analysis.

Mode Shape	SSI DATA	SSI COV
	Damping Ratio	
1	0.013	0.014
2	0.021	0.025

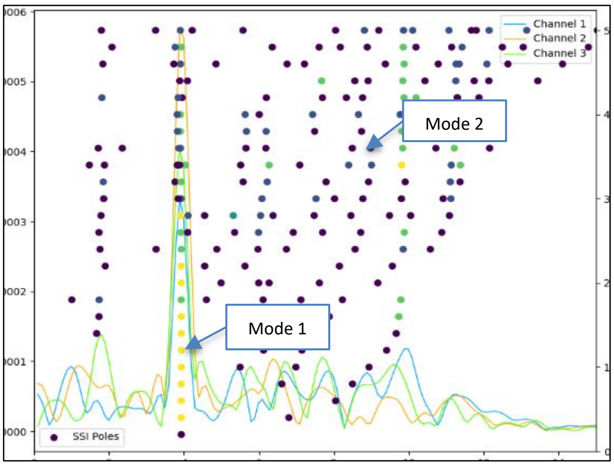

Figure 13. Stabilization Diagram of FFT Analysis Results Using the SSI Data Method.

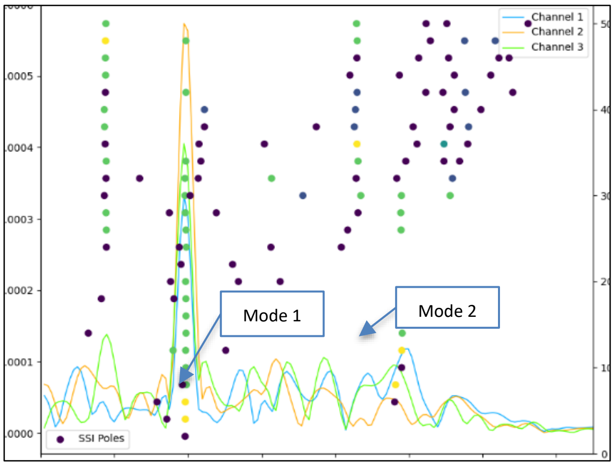

Figure 14. Stabilization Diagram of FFT Analysis Results Using the SSI Covariance Method.

Furthermore, the SSI analysis demonstrates an additional advantage by successfully identifying subtle mode shapes at frequencies around 9.80 Hz and 9.81 Hz—modes which were not clearly observable using FFT alone. This highlights one of the inherent strengths of the SSI algorithm, particularly the covariance-based variant (SSI-Cov), which leverages statistical correlations in the measured response and is less susceptible to noise contamination. This robustness to measurement noise, as emphasized by Pérez-Ramírez et al. [16], becomes critically important in field applications where environmental and operational variability is inevitable.

The integration of FFT and SSI provides a more holistic and cross-validated estimation of the structure's dynamic characteristics. Beyond basic frequency identification, this combination allows for deeper interpretation of vibration modes and damping behavior, improving confidence in the results and enabling better-informed engineering decisions. In the context of SHM, such an integrative methodology is highly beneficial not only for condition assessment and validation of numerical models but also for early damage detection, maintenance prioritization, and ensuring long-term safety and performance of bridge structures. Consequently, the dual application of FFT and SSI stands as a robust and practical strategy for high-fidelity modal analysis, offering both theoretical rigor and practical relevance in modern bridge diagnostics.

4. Conclusions

Based on the analysis conducted using the Fast Fourier Transform (FFT) method, the identified natural frequency is 3.92 Hz. This result indicates the primary mode of vibration that may occur in the bridge structure when subjected to dynamic excitation, such as that produced by passing vehicles. This natural frequency is crucial to ascertain, as it is directly related to the bridge's response to loading. Meanwhile, the analysis employing the Stochastic Subspace Identification (SSI) Data method yielded a frequency of 3.92 Hz, whereas the SSI Covariance method also indicated a frequency of 3.92 Hz. The results from both methods demonstrate their effectiveness in analysing the natural frequency of the bridge from vehicle excitation data.

As an illustration, on the A.P. Pettarani Toll Bridge, which has been studied through numerical methods in two-dimensional (2D) and three-dimensional (3D) modeling using MIDAS Civil software, frequencies of 3.77 Hz and 3.98 Hz were obtained. Meanwhile, the results from the bridge testing report showed a frequency value of 3.91 Hz [13]. Furthermore, referring to the natural frequency graph based on the span of the bridge [14][15], the analysis results indicate that the difference in frequency values obtained is not significant, with a relatively small difference between the analysis results in this study and some previous references. This indicates that both methods show consistency in measuring and identifying the modal characteristics of the bridge.

In the analysis of damping, the results obtained from the SSI-Data method indicate values of 1.3% and 2.1%. Damping is a crucial parameter that describes the ability of a structure to reduce the amplitude of vibrations, thereby mitigating the potential for damage caused by dynamic loads. Meanwhile, the analysis employing the SSI-Cov method yields values of 1.4% and 2.5%. These values suggest that the damping ratio of the bridge falls within the expected range, which is generally 2% to 5% for reinforced concrete structures [17][18]. While according to another reference, namely Eurocode 1: Actions on Structures - Part 2: Traffic Loads on Bridges, the minimum damping ratio based on the type of bridge and the span length of L ≥ 20 metres is 1% [19] . In other words, this bridge demonstrates a commendable capacity to control vibrations induced by dynamic loads, which is a vital factor in ensuring the safety and reliability of the structure.

Furthermore, the comparison between the results obtained from the FFT and SSI methods indicates that both methodologies yield complementary findings. Although there are slight discrepancies in the frequency values produced, both methods successfully identify the same modal characteristics. However, the analysis results also demonstrate that the SSI method is capable of verifying additional mode shapes. This suggests that the combination of both methods can provide a more comprehensive and accurate analysis. Previous research has also indicated that employing multiple analytical methods can enhance the reliability of the results [9]. Thus, this multi-method approach not only enriches the data obtained but also offers a deeper insight into the dynamic behaviour of the bridge.

In the context of bridge maintenance, the results of this analysis can be applied to formulate more effective maintenance strategies. For example, by understanding the natural frequency and damping ratio, we can design a more timely maintenance program, thus preventing more serious damage in the future. The use of natural frequency data in preventive maintenance has been shown to be effective in detecting changes in the dynamic behavior of bridges that may be caused by external factors such as increased traffic loads, structural weathering, or material degradation [15]. Studies by Hasani & Freddi [20] show that small changes in the value of modal parameters especially frequency and damping can be an early indicator of internal damage that are not visually detectable, making them particularly useful in condition-based maintenance approaches.

In addition, the research of Ao et al. shows that the natural frequency downward trend triggered by environmental influences and dynamic loads can be statistically analyzed to distinguish between operational effects and early indications of structural damage [21]. This information is crucial in determining the most appropriate time and method to conduct follow-up inspections or technical interventions, as described in a systematic review of vibration-based damage detection techniques on civil structures [22]. Experimental studies by Gong et al. on cable bridges showed that periodically identified variations in damping ratios could provide additional information regarding changes in local stiffness or damage to connection elements and bearings [23]. Therefore, the integration of the results of the capital analysis into the bridge maintenance system not only improves the efficiency of monitoring, but also extends the service life of the structure through early detection and proactive handling of potential damage [24].

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