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Evaluation of Structural Dynamic Parameters of the Old Truss Bridges Using Smartphone-Embedded Sensors

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Abstract: Bridges are critical components of transportation infrastructure that experience continuous dynamic loading from traffic and environmental factors, leading to gradual deterioration of structural performance. Conventional Structural Health Monitoring (SHM) systems are often constrained by high cost and operational complexity. This study evaluates the application of smartphone-embedded accelerometers combined with the Ambient Vibration Test (AVT) method to identify the dynamic parameters of old steel truss bridges in Ketapang, West Kalimantan. A non-destructive and cost-effective approach was employed by utilizing daily traffic as a natural excitation source. Several bridges were selected based on service age, visible deterioration, and operational condition. Vibration data were collected using the Resonance Android application, which records acceleration and processes it into frequency spectra. Dominant frequencies and damping ratios were extracted and analyzed to assess the dynamic response of the structures. Field measurements on the Pawan 1 and Pawan 2 bridges revealed that several parameters—such as natural frequency, displacement, and damping ratio—exceeded standard thresholds, indicating potential structural degradation. These findings demonstrate that smartphone-based monitoring can serve as an effective preliminary diagnostic tool, providing valuable insights to support maintenance decisions and guide further detailed structural assessments.

Keywords: Structural Health Monitoring, Ambient Vibration Test, Smartphone Accelerometer, Damping Ratio, Bridge Inspection

1. Introduction

Bridges are critical components of transportation infrastructure, enabling regional connectivity, economic activity, and social mobility. A large number of existing bridges, particularly steel truss bridges constructed several decades ago, are currently operating beyond their originally intended service life. Continuous exposure to traffic loading, environmental effects, and material aging can lead to progressive deterioration such as stiffness reduction, fatigue damage, corrosion, and connection degradation. These forms of damage often develop internally and may not be detected through routine visual inspections, thereby increasing the risk of unexpected structural performance degradation.

Dynamic response–based assessment provides an effective means of evaluating the structural condition of bridges. Key dynamic parameters, including natural frequencies, damping ratios, and mode shapes, are directly related to the stiffness, mass, and energy dissipation mechanisms of a structure. Changes in these parameters can therefore serve as early indicators of structural degradation or damage [1,2]. However, conventional vibration-based Structural Health Monitoring (SHM) systems typically rely on high-precision sensors, wired data acquisition systems, and specialized expertise. The associated costs, installation complexity, and operational requirements often limit their application to a small number of critical bridges.

These challenges are particularly pronounced in rural and remote regions of developing countries, where aging bridges remain in active service but resources for advanced monitoring are limited. In such contexts, bridge management practices rely heavily on periodic visual inspections, which may fail to capture subtle changes in structural behavior. Consequently, there is a growing need for monitoring approaches that are technically reliable, economically feasible, and easily deployable without disrupting traffic operations.

Recent advances in consumer electronics have introduced new opportunities for low-cost structural monitoring. Modern smartphones are equipped with embedded accelerometers capable of recording vibration responses within the frequency range relevant to many bridge structures. When combined with appropriate signal processing techniques and ambient excitation sources, these sensors offer a promising alternative to conventional instrumentation. Ambient Vibration Testing (AVT), which utilizes natural excitations such as traffic-induced vibrations, enables non-destructive and in-service evaluation without the need for artificial loading.

Motivated by these considerations, this study aims to evaluate the feasibility of using Android smartphone accelerometers in combination with the AVT method to identify the dynamic parameters of old steel truss bridges in Ketapang Regency, West Kalimantan, Indonesia. By leveraging normal traffic as the excitation source, the proposed approach seeks to provide a practical and low-cost solution for dynamic assessment of aging bridges in remote areas, supporting more sustainable and accessible bridge maintenance strategies.

2. Literature Review

Vibration-based structural health monitoring has been widely adopted for bridge condition assessment due to the sensitivity of dynamic parameters to changes in stiffness, mass distribution, and energy dissipation mechanisms. Numerous studies have demonstrated that damage such as cracking, corrosion, or connection loosening can cause measurable variations in natural frequencies, damping ratios, and mode shapes, making modal identification a valuable tool for early damage detection [1,2].

Traditional modal testing techniques commonly employ high-precision accelerometers and laser-based measurement systems, which can achieve high accuracy in identifying dynamic characteristics. However, these systems require extensive cabling, complex installation procedures, and skilled operators, resulting in high costs and limited scalability for routine or large-scale monitoring applications.

To address these limitations, recent research has explored the use of low-cost sensing technologies, particularly smartphone-embedded accelerometers. Smartphone-based vibration monitoring has been shown to capture bridge response data suitable for modal identification when appropriate sampling rates and signal processing techniques are applied [3]. Despite their advantages in affordability and accessibility, smartphone sensors are more susceptible to noise and may exhibit reduced accuracy when identifying higher vibration modes under low-amplitude excitation conditions.

Comparative studies between smartphone sensors and ded icated Internet of Things (IoT) accelerometers have further examined the capabilities of low-cost devices. Field measurements have demonstrated that both sensing platforms can accurately identify fundamental natural frequencies under ambient excitation, although limitations remain in terms of noise sensitivity and mode resolution [4].

Another emerging approach is drive-by or crowdsourced monitoring, in which vibration data are collected from vehicles traveling across bridges. Large volumes of vehicle-based data have been shown to enable the estimation of bridge modal parameters and support long-term performance assessment [5]. However, this approach depends strongly on traffic volume and data aggregation, which may restrict its applicability to bridges in low-traffic or rural environments.

To improve data efficiency, compressed sensing techniques have been introduced for vibration-based damage detection. Such approaches reduce data storage and transmission requirements while maintaining sensitivity to structural changes, although their implementation typically requires advanced signal processing expertise and careful calibration [6].

In parallel, automation and robotic technologies have been developed to enhance bridge inspection and monitoring practices. Robotic systems capable of performing visual inspections and vibration measurements can reduce human exposure to hazardous conditions and improve inspection coverage [7,8]. Nevertheless, the deployment of robotic platforms is often constrained by cost, operational complexity, and logistical challenges, particularly in remote regions [9].

Among dynamic parameters, damping remains one of the most difficult to estimate accurately due to its dependence on boundary conditions, material behavior, and connection characteristics. Reliable damping identification still relies primarily on field-based dynamic testing [1]. Recent review studies have highlighted that smartphone-based structural health monitoring methods, including vibration monitoring, vision-based deformation measurement, and drive-by analysis, represent a promising and sustainable direction for future bridge assessment [10].

Despite these advances, most existing studies have focused on modern bridge types or controlled experimental settings. Limited attention has been given to old steel truss bridges operating under real traffic conditions, particularly using Android-based smartphone accelerometers in conjunction with ambient vibration testing. This research gap provides the motivation for the present study.

3. Methodology

This research adopts a quantitative experimental field approach aimed at identifying the dynamic parameters of old steel truss bridges using built-in accelerometer sensors embedded in Android smartphones. The ambient vibration test (AVT) method was employed to measure the dynamic response of the structures without artificial excitation. Instead, ambient vibrations induced by normal vehicular traffic were utilized as the primary excitation source. This approach is non-destructive, cost-efficient, and capable of capturing representative structural behavior under real operational conditions.

The study focused on several old steel truss bridges located in Ketapang Regency, West Kalimantan, Indonesia. Bridge selection was conducted using a purposive sampling method based on engineering considerations to ensure representativeness and data reliability. The selected bridges satisfied the following criteria: (1) a service life exceeding 10 years, (2) a primary load-bearing system consisting of bolted steel trusses, (3) visible minor structural deterioration observed during preliminary inspections, (4) noticeable reductions in user comfort, such as increased vibration perception during vehicle passage, and (5) sufficient functional safety to allow field testing without interrupting traffic flow.

Dynamic response data were acquired using the Resonance Android application, which records real-time acceleration data through the smartphone's internal accelerometer. Two Android-based smartphones were used simultaneously as vibration sensors. Each device recorded acceleration data for a duration of 120 s per measurement session. The sensors were mounted at the midspan of the bridge using transparent adhesive tape, as this location is expected to experience the maximum displacement under traffic loading.

Two measurement points were selected at each bridge segment: the sidewalk or deck element, denoted as Tr, and the diagonal web member of the truss, denoted as Dg. Both sensors were activated several seconds before a heavy vehicle crossed the bridge to ensure that the vibration response during loading and subsequent free vibration was fully captured. After completing measurements at the first segment, the sensors were repositioned to the second segment, and the same procedure was repeated to obtain consistent data along the span.

The Resonance application automatically transformed the recorded acceleration signals into frequency spectra using the Fast Fourier Transform (FFT) algorithm. Dominant peaks identified in the frequency domain were interpreted as the natural frequencies of the structure. Displacement responses were obtained through double integration of the acceleration signals, which was performed automatically by the application.

Damping estimation was conducted using the free-vibration response following vehicle passage. The logarithmic decrement method was applied to evaluate the decay of successive vibration amplitudes. The logarithmic decrement, δ, was calculated using

$$\delta = \frac{1}{n} ln \left(\frac{x(t)}{x(t+nT)} \right) \tag{1}$$

where *x(t)* is the vibration amplitude at the first peak, *x(t+nT)* is the amplitude after *n* oscillation cycles, *T* is the vibration period, and *n* is the number of cycles considered. In this study, *n* was selected between one and three to reduce the influence of noise.

Once δ was obtained, the damping ratio, ζ, was determined using

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{2}$$

where ζ represents the damping ratio and π is the mathematical constant. The resulting parameters—including natural frequency, damping ratio, and maximum displacement—were used to evaluate the dynamic characteristics of the investigated bridges.

4. Result and Discussion

Field measurements were conducted on two steel truss bridges—Pawan 1 (as shown in Figure 1 and Figure 2) and Pawan 2 (as Shown in Figure 3 and Figure 4)—located in Ketapang Regency, West Kalimantan. Both bridges are critical links within the regional transportation network and have been in service for more than three decades, with Pawan 1 operating for approximately 37 years and Pawan 2 for 32 years. The dynamic response of the structures was evaluated using smartphone-embedded accelerometers through the ambient vibration test method, employing regular vehicular traffic as a natural source of excitation. Two sensors were positioned at the midspan of each bridge, one on the sidewalk deck (Tr) and another on the diagonal web member (Dg), where maximum displacement was expected. Data were recorded for 120 seconds per segment, and the measured accelerations were transformed into frequency spectra using the Fast Fourier Transform (FFT) algorithm within the Resonance Android application. The result of dynamic parameters is shown in table 1.

Table 1. *Dynamic Parameters of the Bridge Measured at Midspan.*

Bridge Technical Information	Measurement Location	Frequency (Hz)			Displacement (mm)			Damping ratio (%)
		x	y	z	x	y	z	
Pawan 1	Segmen 1 (Dg 1)	34,1	2,3	27,2	30,7	26,7	34,6	8,2
• Service age:	Segmen 1 (Tr 1)	14,1	18	2,3	3,9	0,3	6	3,2
37 years	Segmen 2 (Dg 2)	2,3	2,2	14,4	1,6	9,3	40,7	7,2
• Total length:	Segmen 2 (Tr 2)	9,2	2,3	14,5	14,8	3,4	66	11,3
240 m	Segmen 3 (Dg 3)	9	2,2	17,4	14	10	22,3	3,1
• Width: 7 m	Segmen 3 (Tr 3)	3,5	2,3	2,2	12,9	11,2	45,6	5,7
• Height: 5 m	Segmen 4 (Dg 4)	42,4	2,3	17,9	22,1	5,9	53,2	2,9
	Segmen 4 (Tr 4)	14,5	16,9	2,3	0,4	7	27,1	5,9
Pawan 2	Segmen 1 (Dg 1)	4,3	3,3	47	12,9	103,5	3,1	7,2
• Service age:	Segmen 1 (Tr 1)	25,3	17	3,3	7,9	0,6	25,6	5,7
32 years	Segmen 2 (Dg 2)	27,5	3,1	17,3	1,2	29,3	40,3	7,1
• Total length:	Segmen 2 (Tr 2)	21,7	15,9	16,4	5,3	11,3	66,5	7,9
240 m	Segmen 3 (Dg 3)	31,3	2,2	25,5	9,7	1,2	24,4	4,4
• Width: 7 m	Segmen 3 (Tr 3)	12,1	13,1	2,2	0,7	2,3	46,2	8,5
• Height: 5 m								

Figure 1. *Overview of Pawan 1 Bridge*

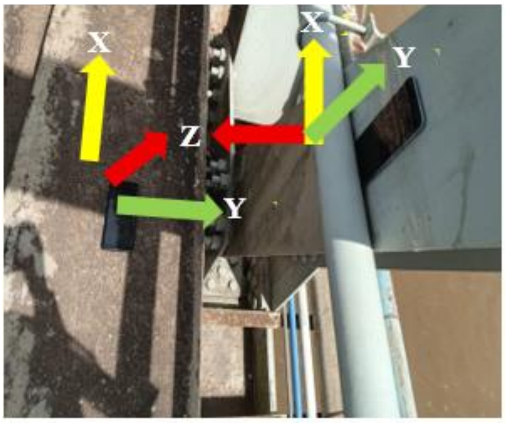

Figure 2. *Sensor installation layout on Pawan 1 Bridge*

Figure 3. *Overview of Pawan 2 Bridge*

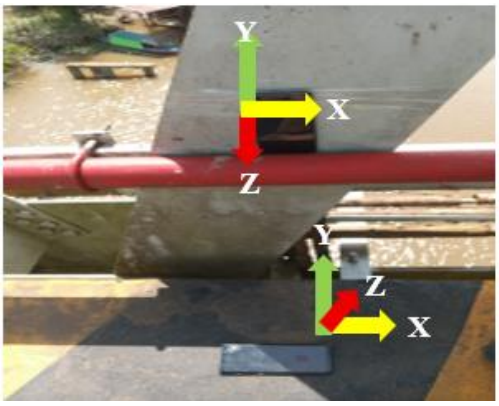

Figure 4. *Sensor installation layout on Pawan 2 Bridge*

The recorded dynamic responses reveal substantial variability in natural frequencies, displacement amplitudes, and damping ratios across different structural elements and measurement segments. For the Pawan 1 Bridge, the identified natural frequencies range from 2.2 Hz to 42.4 Hz, with estimated displacement amplitudes between 0.3 mm and 66 mm and damping ratios reaching 11.3%. Similarly, the Pawan 2 Bridge exhibits natural frequencies between 2.2 Hz and 47 Hz, estimated displacement amplitudes ranging from 0.6 mm to 103.5 mm, and damping ratios as high as 8.5%. These wide ranges indicate non-uniform dynamic behavior along the bridge span, reflecting differences between global structural response and localized member vibrations, as well as potential stiffness degradation associated with long-term service and environmental exposure.

In accordance with SNI 1725:2016 [11], the dominant natural frequency of typical medium-span bridges subjected to traffic excitation generally lies within the range of 2–5 Hz, corresponding to the global bending or vertical flexural modes of the structure. In this study, several measured frequencies exceed 10 Hz, which are unlikely to represent global bridge behavior. Instead, these higher-frequency components are interpreted as local vibration modes associated with individual structural elements—such as truss members, bracing components, or deck panels—particularly when sensors are mounted directly on these elements. Conversely, frequencies observed in the range of 2.2–3.5 Hz, consistently identified in Segments 2 and 3 of both bridges, are considered representative of the global structural modes and therefore provide the most meaningful indicators of overall bridge stiffness and integrity. The coexistence of global and localized modes, along with their spatial variability, suggests an irregular stiffness distribution, potentially caused by localized corrosion, fatigue damage, or loosening of bolted connections.

Regarding energy dissipation characteristics, Eurocode 8 (EN 1998-1:2004) recommends that the equivalent viscous damping ratio for steel structures under normal operating conditions should generally not exceed 5% of critical damping [12]. The measured damping ratios for both bridges frequently exceed this range, with several segments exhibiting values between 6% and 11%. While relatively high, such damping ratios are physically plausible for aging steel truss bridges, where nonlinear energy dissipation mechanisms—including friction at loosened joints, micro-slip at corroded interfaces, and localized damage at connections—become increasingly significant. The damping ratios were estimated using the logarithmic decrement method derived from free-vibration decay, and the corresponding formulation has been clarified and consistently applied in the analysis.

Dynamic displacement responses were further evaluated with reference to the AASHTO LRFD Bridge Design Specifications, which limit live-load deflection for steel bridges under urban service conditions to L/1000 [13]. For the Pawan 1 Bridge, with a total length of 240 m divided into four 60 m segments, the allowable displacement per segment is 60 mm. For the Pawan 2 Bridge, comprising three 80 m segments, the corresponding allowable limit is 80 mm.

Most estimated dynamic displacement amplitudes for both bridges remain within these limits; however, localized exceedances were observed. In the Pawan 1 Bridge, a truss element at Segment 2 (Tr2) recorded an estimated peak displacement of 66 mm, slightly exceeding the allowable limit (approximately 110%). In the Pawan 2 Bridge, the deck element at Segment 1 (Dg1) exhibited an estimated displacement of 103.5 mm, corresponding to approximately 129% of the allowable limit and representing the largest response in the dataset. It is important to note that these displacement values were obtained through double numerical integration of acceleration data from smartphone sensors, which are susceptible to low-frequency drift. Consequently, the absolute displacement amplitudes—particularly the largest values—may be overestimated. Nonetheless, the relative differences between segments remain informative and consistently highlight locations with reduced stiffness and increased flexibility.

Estimated displacement amplitudes exceeding 50 mm, observed in multiple segments of both bridges, may contribute to serviceability concerns and user discomfort, even if the absolute values are conservatively interpreted. The concentration of larger vibration responses in deck components and truss web members supports the presence of localized stiffness loss, likely resulting from long-term fatigue effects, connection slippage, and corrosion-induced deterioration accumulated over decades of operation.

Overall, the combined evaluation of natural frequencies, damping ratios, and displacement responses indicates that both bridges have experienced measurable degradation in dynamic performance. Elevated damping ratios, irregular frequency distributions, and relatively large vibration amplitudes—when interpreted with appropriate caution—collectively suggest progressive deterioration of specific structural components. These findings are consistent with field inspection observations, which identified corrosion at truss joints, coating deterioration, and minor deformations in connection plates, all of which are known to influence the modal characteristics and energy dissipation behavior of aging steel structures.

From a practical standpoint, the results demonstrate that smartphone-embedded accelerometers can effectively capture key dynamic features of bridge structures and provide early indications of stiffness loss or localized damage. Although the accuracy of such low-cost sensors is limited compared to professional instrumentation—particularly for displacement estimation—their affordability, accessibility, and ease of deployment make them suitable for preliminary structural health assessments, especially in remote or resource-limited regions. The extracted dynamic parameters can serve as baseline data for periodic monitoring and maintenance prioritization. Future research should focus on improving signal filtering techniques, integrating smartphone-based sensing with IoT platforms, and combining measured data with finite element modeling and long-term monitoring to enhance the reliability of bridge health monitoring systems in Indonesia.

5. Conclusion

This study evaluated the dynamic characteristics of two aging steel truss bridges—Pawan 1 and Pawan 2 in Ketapang, West Kalimantan—using smartphone-embedded accelerometers and the ambient vibration test method. The results confirm that, despite their low cost and limited precision, smartphone sensors can capture key dynamic parameters, including natural frequencies, displacement responses, and damping ratios, under ambient traffic excitation.

A wide range of frequencies was identified; however, frequencies within 2.2–3.5 Hz, consistently observed in Segments 2 and 3 of both bridges, are interpreted as the dominant global bending modes and represent the most reliable indicators of overall structural integrity. These global-mode frequencies fall within the typical 2–5 Hz range specified in SNI 1725:2016. Higher frequencies exceeding 10 Hz are attributed to localized member vibrations and are less representative of system-level behavior.

Both bridges exhibit irregular dynamic responses, indicating non-uniform stiffness distribution and aging-related degradation. Elevated damping ratios exceeding 5%, as referenced in Eurocode 8 (EN 1998-1:2004), suggest increased energy dissipation associated with corrosion, fatigue, and joint slippage. When assessed against the AASHTO LRFD deflection limit (L/1000), most estimated vibration amplitudes remained within allowable limits; however, localized exceedances—particularly at the Pawan 2 deck (103.5 mm) and Pawan 1 truss (66 mm)—indicate localized stiffness reduction and serviceability concerns, with potential implications for user comfort.

Overall, the results confirm measurable performance degradation consistent with the bridges' long service life. The study demonstrates that smartphone-based vibration monitoring is a feasible and non-destructive approach for preliminary structural health assessment, especially in regions with limited access to advanced instrumentation. Future work should integrate smartphone sensing with high-precision IoT or MEMS accelerometers and finite element model updating to enhance accuracy and support long-term monitoring and maintenance planning.

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