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Dynamic Behavior of Indonesian Bridges using Interferometric Radar Technology

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ABSTRACT: Structural deterioration of critical transport infrastructures (e.g., bridges) represents trillion dollars of transportation budget. Inspection and monitoring structural deterioration of bridge structures require an innovative method for an improved quality and accuracy of measurements. This paper presents and discusses the capabilities of the recent advanced interferomertic radar technique (IBIS-S) for remote monitoring structural vibations of bridges (e.g., displacement and natural frequency). Three case studies bridges in Indonesia were selected for field measurements. The research outcomes demonstrate the potential use of interferometric radar technology as an efficient way for structural health assessment and monitoring of bridges under operational condition.

KEYWORDS: Dynamic behavior, Bridge, IBIS-S, Displacement, Natural frequency.

1 INTRODUCTION

Bridges are critical infrastructure component in the transportation networks. Catastrophic failures of bridges may result in loss of life and economic consequences. For example, damage to access bridges in the seaports contributes to long-term economic loss due to the required downtime of the seaports for repairing the physical damage suffered by the port structures (Chang 2000). Therefore, the development of innovative strategies for monitoring dynamic behavior of critical bridges infrastructures is of paramount importance.

In Indonesia, the total sea road transports indicate rapidly on the rise. As reported from the Java integrated port, Tanjung Perak port Surabaya, container traffic has increased in recent years, with volume up to 8 percent from 2013-2014, and predicted continously to grow (Xiaolin 2015). The implication of these predictions is that the number of heavy trucks required undertaking the freight task would be increased. Significant increase in traffic load with trends towards heavier vehicles could considerably effect on accelerating rate of structural deterioration of bridges and ultimately the reduced service life of bridge structures. It was observed that 9 axles articulated trucks with an axle pattern 1-2-2-2-2 are the most common trucks used for transporting freights in the port.

Over the past few decades, monitoring dynamic behavior of bridges are required a large number of accelerometers (Malekjafarian et al. 2015). However, the use of these devices generally consists of localized measurements since only at preselected points information can be obtained. Although accelerometers have been extensively and successfully used, their performance for monitoring dynamic behavior of bridges may be limited by resources (e.g., accessibility, time and budgets) (Gentile 2010a, Pieraccini et al. 2007). When a remote monitoring of structural movements and deformations is required, a technique called Interferometric radar technology (IBIS-S) overcomes these limitations due to their capability of remotely monitoring the dynamic measurements of a bridge with high accuracy in a convenient and efficient way (Kafle et al. 2017, Maizuar et al. 2017, Zhang et al. 2016). This technique allows imaging of structural vibrations from a distance up to 1km. Vibration frequencies can be measured from 0-100 Hz. In typical testing conditions, IBIS-S enables the displacement measurement with an accuracy of 0.01mm, a range resolution of 0.5m and a sampling rate up to 200Hz. Further, the accuracy of the high frequency of emitted signal enables to detect displacements even the order of 1μm when the microwave reflectors which give an unambiguous reflection are used (Gentile and Bernardini 2010b, Guido Luzi et al. 2017).

Monitoring dynamic behavior of structures under operational conditions by using recent advances of interferometric radar technology are mainly initiated in Italy and have now become an increasingly popular technique for monitoring civil infrastructures worldwide. In this context, extensive researches using various large structures (e.g., buildings, bridges, chimneys, towers, etc.) have been tested and demonstrated the potential use of IBIS-S for vibration monitoring of structures (Atzeni et al. 2010, Gentile and Bernardini 2010a, G. Luzi et al. 2012, Pieraccini et al. 2008). However, the applications of this technique including various case studies were carried out mostly in Europe and US. Recently, some experimental works using IBIS-S has also been conducted in Indonesia for monitoring dynamic behavior of transport infrastructures. This paper presents and discusses dynamic behavior of three case studies bridges: monitoring the trestle bridges in Port of Tanjung Perak (Terminal Petikemas and Terminal Teluk Lamong), and highway bridge at Sumo tollway (the Waru I bridge) in Surabaya Indonesia.

The paper is organized as follows: An overview of interferometric radar technique is described in Section 2. A description of three case study bridges and field measurements are presented in Section 3. The results of the field measurements and major findings in this study are summarized in Section 4.

2 OVERVIEW OF INTERFEROMETRIC RADAR TECHNIQUE

The IBIS-S radar sensor has recently emerged as a new technology, specifically suitable to remotely measure the fast-changing movements and vibration response of various engineering structures. Detailed description of IBIS-S components has been reported in many literatures (Bernardini et al. 2007, Gentile et al. 2008). The IBIS-S instrument is capable of detecting of a structure by measuring the rotation, in the complex plane of the phasor related to the backscattered signal of a single resolution cell. In this case, the detected phasor is taken as the summation of all individual phasors related to each scatter in the resolution cell.

Since radar has only 1-dimensional range profile with distance resolution, the radar is able to distinguish object on distance basis only. In order to capture the overall structural vibration, it is strongly recommended to place the IBIS instrument in such a way that different zones of the structure appear at different ranges. Thus, for large structures with longitudinal extension such as bridges, it is necessary to configure the line of sight of radar view in an inclined position with respect to the structure itself. The length of the resolution cell is equivalent to the range resolution of the radar, while the antenna's lobe is used to constrain its angular width. Therefore, the displacement of the target projected along the line of sigh of radar is determined by the rotation angle of the summation phasor, only if the scatters of a single resolution cell carry out a rigid shift (Gentile 2010b).

The IBIS-S radar sensor technology is founded on the combined use of interferometric and wideband waveforms techniques. The interferometric sensor is basically a coherent radar generator which generates, transmits and receives the electromagnetic signals from targets based on the well-known principle of electromagnetic interference between coherent waves. The radar operates at microwave frequency transmitting a series of N continuous waves with a set of constant frequency step of Δf by using continuous-wave step-frequency (CWSF) technique to attain a large effective bandwidth $B=N\Delta f$. The working radar radiates at 16.75GHz centre frequency with band width around 400MHz. The measured vibration can be as high as 100Hz. In operational condition, the radar is suitable for measuring displacement of a structure with accuracy better than 0.01mm (Gentile and Bernardini 2010b).

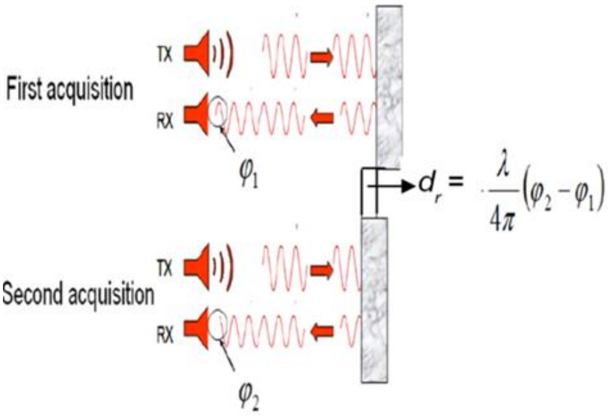

Figure 1. IBIS-S interferometric radar technique

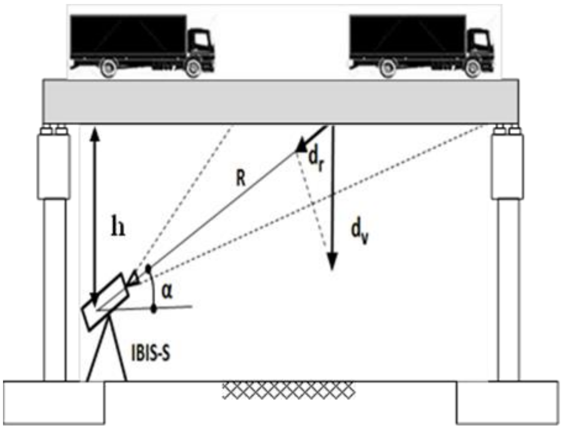

Figure 2. Measurement geometry of a bridge using IBIS-S

As the IBIS-S instrument is coherent radar, phase information of an object is preserved in different time periods. Therefore, the displacement along the radar line-of-sight is detected by comparing phase shift reflected waves from the object (Figure 1). This radar sensor is able to detect the displacement time history of the target projected along the sensor-target line of sight only (*e.g.*, the distance d_r).

$$d_r = -\frac{\lambda}{4\pi}\Delta\varphi \qquad (1)$$

where $\Delta\varphi$ is the phase shift of the electromagnetic waves reflected by the object in various time intervals and λ is the wavelength of the electromagnetic signal. To calculate the effective displacement, the knowledge on the acquisition geometry is required. By using simply geometry projection, the vertical displacement d_v can be computed as ratio between the distance from the radar R of the point where the displacement is detected and the height h of the same point with respect to the radar antenna horizontal plane (Figure 2).

To obtain unambiguous target range measurement, the range of the targets should closer than the maximum measured distance ($R_{\max}$),

$$R_{max} = \frac{c}{2\Delta f} \qquad (2)$$

where c is speed of light in free space and and Δf is a constant frequency step. The maximum sampling rate ($f_{\max}$) which depends on the maximum measured distance ($R_{\max}$) and range resolution (ΔR) is given by,

$$f_{max} = \frac{c\Delta R}{4R_{max}^2} \qquad (3)$$

Monitoring dynamic behavior of a bridge using IBIS-S involves the following steps:

- Place the IBIS-S instrument under the bridge allowing the lower part of the bridge deck to be illuminated by radar sensors. It is possible to put the radar sensors axis not parallel to displacements to be measured. It should be noted that when the displacements are not parallel to the axis of radar sensors, the angle between the direction of the radar sensors axis and the direction of displacements should not exceed 84^0 (Beben 2011).
- Determine the measurement points. To obtain natural reflectivity of the microwave signal, the position of radar sensors is projected to points at the corner of deck-girders zone. Otherwise, several corner reflectors should be installed.
- Configure the acquisition parameters by using the IBIS Surveyor software package in a control PC. The measurement types can be selected either static or dynamic.
- Determine the configuration parameters of the test. These parameters include: maximum range distance, sampling frequency, maximum distance resolution, and survey duration. The sampling frequency can be as high as 100Hz to ensure the appropriate level of data is captured in operational condition (Dei et al. 2009)
- Determine the geometry parameters of the tested structure. It consists of: structure length and angle, coordinate of IBIS-S, and vertical tilt (observation angle) of IBIS-S.
- Proceed the test for entire survey duration and save data when finish.
- Generate the results using the IBIS data viewer software in a control PC (*e.g.*, range profile of the bridge, response spectrum parameters, Frequency Domain Decomposition (FDD) analysis, and modal analysis).
- Analyse the results

3 CASE STUDIES

The outstanding performance of IBIS-S interferometric radars sensors described in the previous section was implemented to investigate the dynamic behavior of three case study bridges at Port of Tanjung Perak and Sumo Tollway in Indonesia. Port of Tanjung Perak is the second busiest sea port in Indonesia, located at Surabaya, East Java. The port has two container terminals; Terminal Petikemas and Terminal Teluk Lamong. The experimental work mainly focuses on measuring and comparing the vertical displacements and natural frequencies obtained using IBIS-S.

3.1 *Monitoring the trestle bridge at Terminal Petikemas*

The Terminal Petikemas is located in Port Tanjung Perak Surabaya Indonesia. This terminal provides services for domestic and international container berths which connected by the access bridge (trestle bridge) to the mainland. The trestle concrete bridge was constructed in 1984 and has 102 spans with each span length of 15m. The bridge deck is simply supported by nine normal T-girders. The carriageway has three lanes accommodating the outbound and inbound traffic lanes as well as the overtaking lane in the middle of the carriageway. The view of elevation and detailed of cross section of the bridge are shown in Figures 3.

As shown in Figure 4 the IBIS-S radar sensors were projected to cover a horizontal distance of 4.2m and a height of 0.3m with a distance resolution of 0.75m and a sampling frequency of 100Hz. It should be noted that the IBIS-S can only be projected to the outer beam becuase the distance between the girders and the ground less than 1m.

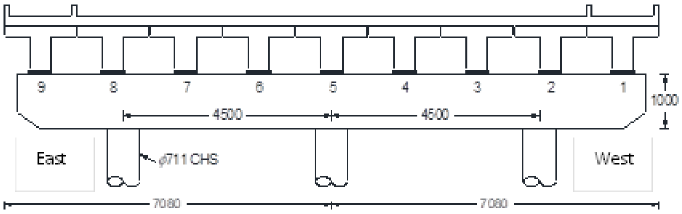

Figure 3. Cross section of trestle bridge at Terminal Petikemas

3.2 *Monitoring the trestle bridge at Terminal Teluk Lamong*

Due to reduce the delay in delivering freight in the Terminal Petikemas, the newest Terminal Teluk Lamong in Port of Tanjung Perak Surabaya was constructed and successfully operated since 2015. This multi purpose terminal is the first in the implementation of semi-automatic and green port in Indonesia. Similar to Terminal Peti Kemas, this terminal also connected by the trestle bridge to the the land in Java island (Figure 5). The bridge has 20 spans with each span length of 41.6m. The bridge deck is constructed on top of 6-longitudinal pre-stressed concrete I-girders.

Figure 4. Testing set up of IBIS-S in trestle bridge at Terminal Petikemas

Figure 6 shows the IBIS-S was configured to a horizontal distance of 6.7m and a height of 2.1m with a distance resolution of 0.75m and a sampling frequency of 100Hz.

Figure 5 View of trestle bridge at Terminal Teluk Lamong

3.3 *Monitoring the Waru I highway bridge at Sumo tollway*

The Waru I highway bridge is located in Sumo tollway (Figure 7). This overpass bridge was constructed in 2008 with a length of 62.3m and a width of 19.5m. The bridge deck is supported by ten prestressed concrete I-girders which are then connected on abutments at two extreme ends of the bridge and two internal piers. The Waru I bridge is a three span construction comprising of central span (30.1m) and external spans (16.1m). The traffic width includes three lanes of carriageways with an emergency stopping lane.

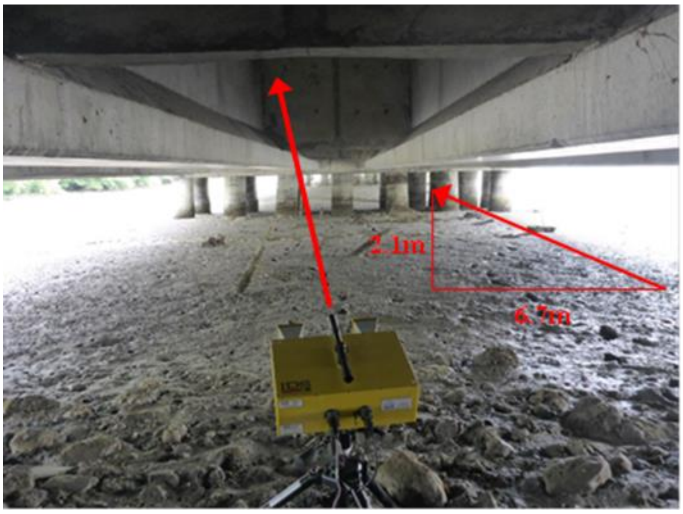

Figure 6. Testing set up of IBIS-S in trestle bridge at Terminal Teluk Lamong

Figure 7. View of the Waru I bridge

To capture the dynamic properties of girders supporting the outbound traffic loading, the sensors was pointed out to a horizontal distance of 9m and a height of 3.5m with a distance resolution of 0.75m and a sampling frequency of 100Hz as shown in Figure 8.

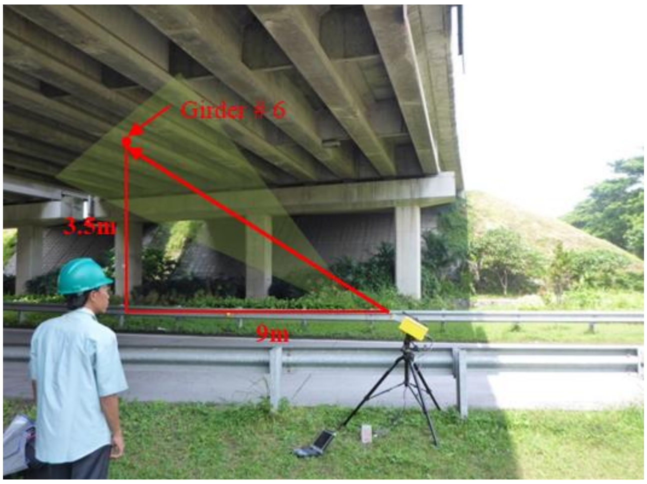

Figure 8. Testing set up of IBIS-S in the Waru I bridge

4 RESULTS AND DISCUSSION

4.1 *Range Profile of Bridges*

A typical range profile of the test scenario describes the qualitative measurement of the electromagnetic reflected signals by the radar sensors. As shown in Figures 9 to 11, the range profile of bridges plot the relative distance from the sensors with several peaks of measurement points (e.g., SNR). TP indicates target of measurement point. It can be seen that the electromagnetic reflected signals at target points were captured with excellent accuracy.

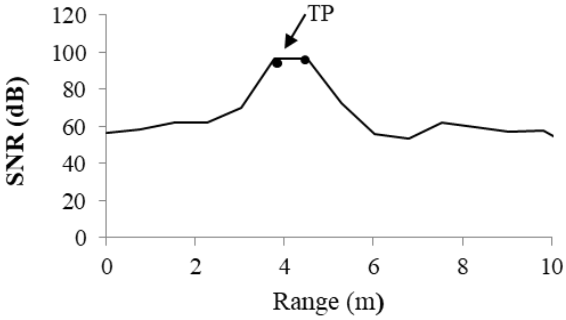

Figure 9. Range profile of trestle bridge at Terminal Petikemas

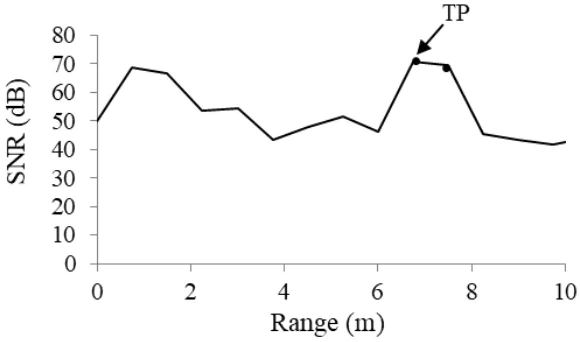

Figure 10. Range profile of trestle bridge at Terminal Teluk Lamong

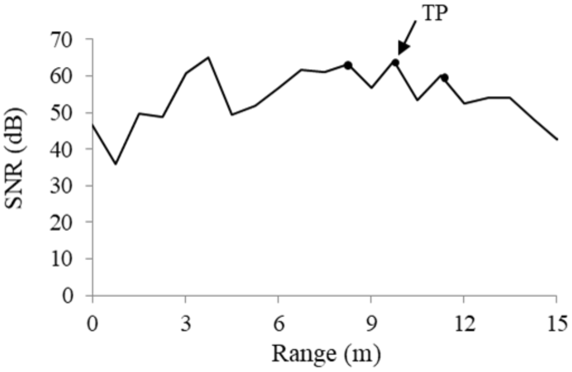

Figure 11. Range profile of the Waru I bridge

4.2 *Displacement time history*

The measurement performed at the case study bridges have been processed through IBIS data viewer software to extract dispalcement time history at various measurement points (range bins). Figures 12 to 14 show the vertical displacement time history of the bridge girders resulting from the passage of traffic loading over deck. It was observed that the maximum displacement at Terminal Petikemas, Terminal Teluk Lamong and Waru I bridges are 12mm, 6.5mm and 3mm, respectively. It can be seen that the maximum observed displacements are under the allowable serviceability state requirement of the bridges (e.g., L/480).

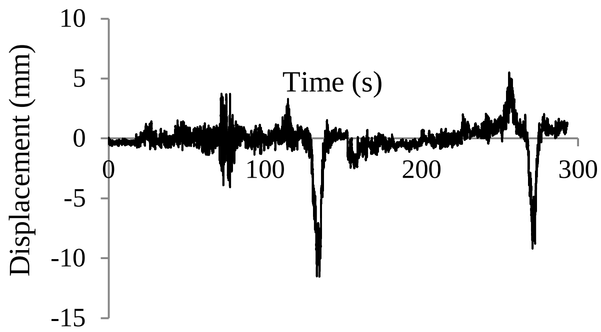

Figure 12. Displacement time history measured in trestle bridge at Terminal Petikemas. Maximum displacement observed is around 12mm.

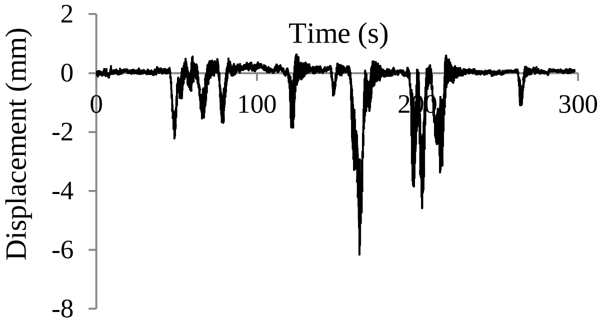

Figure 13. Displacement time history measured in trestle bridge at Terminal Teluk Lamong. Maximum displacement observed is around 6.5mm.

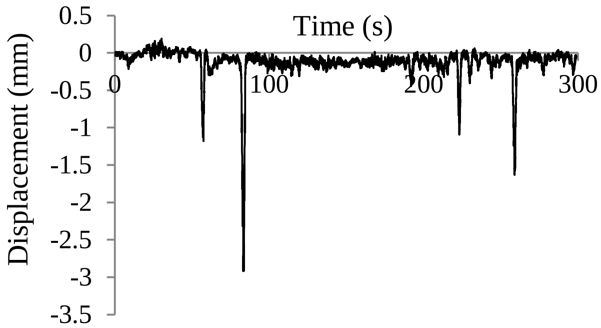

Figure 14. Displacement time history measured in the Waru I bridge. Maximum displacement observed is around 3mm.

4.3 *Natural frequency*

Another important characteristic related to the dynamic behavior of a bridge structure is its natural frequencies, which are sensitive to structural integrity. It has been found that an imposed frequency as a result of dynamic loading which is close to that of the structure can cause resonances which in turn results in dangerously large fatigue stress and even failure of the structure.

The IBIS-S data viewer software package has capability to generate frequency spectra for each measurement point (range bin). Through analysing the datasets acquired by IBIS-S using the displacement spectrum analysis in frequency domain, the natural frequency of the bridges are obtained. The frequency characterized by the peak points of the spectrum represents the natural frequency of the bridge. Figures 15 to 17 shows the natural frequencies of the bridges obtained at Terminal Petikemas, Terminal Teluk Lamong and Waru I bridges. These results are consistent with the available empirical formulae of natural frequency such as specified in the British Standard (BS EN 2003).

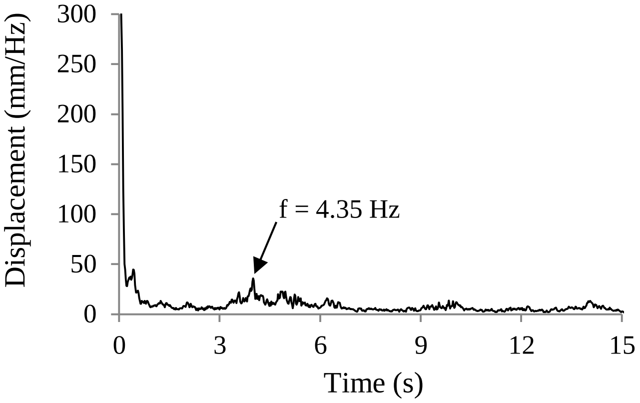

Figure 15. Natural frequency identified in trestle bridge at Terminal Petikemas

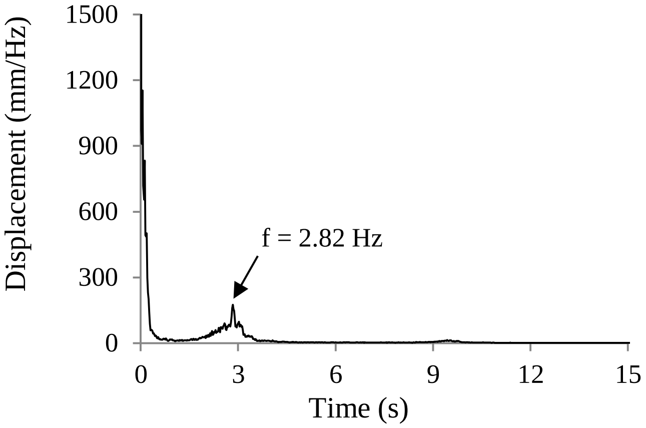

Figure 16. Natural frequency identified in trestle bridge at Terminal Teluk Lamong.

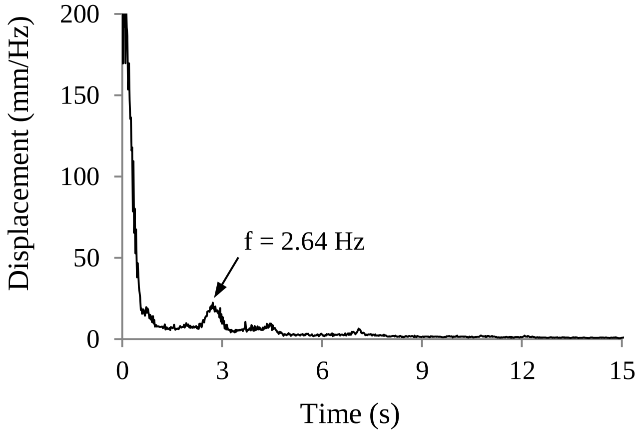

Figure 17. Natural frequency identified in the Waru I bridge

5 CONCLUSION

The application of interferometric radar technology using three case study bridges in Indonesia confirmed the outstanding performance of IBIS-S for monitoring dynamic behavior of bridges and the potential of the acquired datasets as the input for further life-cycle performance analysis of bridges. However, the IBIS-S measurements in seaport should consider the available clear distance between target points and the ground which is often insufficient for antennas beam to illuminate the part of bridges. In comparison to mainland, the measurements of bridges in seaport are also greatly affected by tide cycle time.

Through analysing the IBIS-S measurement results, it was concluded that the maximum vertical displacements were generally below 15mm at the test conditions. The natural frequencies of the bridges are between 2.6Hz and 4.4Hz which similar to other previous experimental results. The outcomes of the study demonstrate the potential use of interferometric radar technology for real-time monitoring of structural vibration and natural frequencies under operational condition.

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