Dynamic monitoring of bridges: accelerometer Vs microwave radar interferometry (IBIS-S)

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Abstract. Dynamic monitoring of bridge structures require an innovative technique which could potentially be used for rapid damage assessment and provide reliable information. This paper presents a comparison study on bridge dynamic monitoring using accelerometer and microwave radar interferometry (IBIS-S) for bridge health assessment. In particular, this study describes the advantages and disadvantages of the measurement used in the recent studies. The results of study will provide preliminary information for selecting of the appropriate methods related to dynamic monitoring of bridges.

1. Introduction
There are around 2.5 million bridges world-wide which many of them are rated structurally deficient. For example, there are approximately 595,000 bridges in the USA and 28% of them are rated deficient in 2005 [1]. In Indonesia, it is estimated the number of bridges is around 89,000 with majority of them being over 50 years. It indicates that some of bridges in Indonesia may be deteriorated due to the ageing condition.

Bridges are generally imposed to the growing rate of progressive deterioration (e.g., traffic loads) and dramatic structural degradation (e.g., earthquake). It was reported that demand from heavy freight transports show rapidly on the rise. For example, around 80 percent of Indonesian freight transport still dominated by road transport [2]. In fact, projection of the total heavy freight task increased at a rate of 3.7% in 2016 led to significant effect in the number of heavy trucks required undertaking the future freight task [3]. Structural deterioration of ageing bridge infrastructures could be accelerated under increased demand of heavy trucks loads. Further, this effect can be very large as it can reduce the service life of bridge structures [4][5][6]. Therefore, monitoring and assessing bridge structural health is essential for operation and maintenance of bridges.

Structural health monitoring (SHM) can be described as inspection techniques used for detecting damages and so asset managers could decide maintenance strategies on structures [7]. In particular, the SHM systems are aimed at implementing rapid damage identification and providing reliable information on the integrity of structures. It consists of observing and collecting data on a system during a particular time using sensors, extracting damage-sensitive conditions from these observations, and generating statistical approach for the measured data to determine the current condition of the system’s health [8]. Structural health monitoring and assessment of bridges generally involves: acquisition works, validating data, analysis, prognosis and management of the system [9].

Extensive researches on techniques and methods for monitoring structural health, in particular on bridge structures have been investigated by researchers. These methods can be divided into [10]: (1)
Visual inspections, (2) SHM using destructive techniques, and (3) SHM using non-destructive techniques.

Visual inspection is recognized as a conventional bridge inspection method and the most common technique used for preliminary assessment of structural health. However, this method has some limitations such as it cannot detect some types of small damages within a structure. The accuracy of measurements depends on the visibility of human eyes, and therefore several inconsistencies between inspectors can be seen after the completed routine inspection [11]. Destructive techniques monitoring systems have quickly gained popularity after their introduction mainly because of its relatively low cost as well as higher reliability compared to the traditional inspection methods. Accelerometers and strain gauges are examples of contact sensor devices [12].

Unlike destructive tests which are destructive in nature, non-destructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without causing damage to the tested structure. Modern NDT techniques are widely used in forensic engineering, mechanical engineering, petroleum engineering, electrical engineering, civil engineering, systems engineering, aeronautical engineering, medicine, and arts. These advanced features of method have several advantages over destructive tests and visual inspection techniques such as portability, fast installation and operation, operating both day-night in all weather conditions, being more accurate as well as providing both static and dynamic measurements[12][13]. This paper presents an overview of the recent advanced SHM technique for monitoring of structural movements and deformations (e.g., accelerometer and IBIS-S). The advantages and disadvantages of this method are summarized.

2. Method

2.1. Accelerometer sensing technique

Accelerometers have been widely used for the analysis of a broad range of experiment in monitoring dynamic behavior of bridges under operational condition. It has capability of determining time histories of acceleration at a particular time. Accelerometer sensors can sample vibration at high frequencies to produce high resolution acceleration time. Figure 1 shows a typical accelerometer sensor consists of a sensor module, a microprocessor, memory, a radio transceiver, an antenna, a battery, and an electronic PC board that interconnects these components.

![Figure 1](image-url) Details of accelerometer components [14].

The working principle of an accelerometer is by creating a force in the sensor and generating a small change in the current. When the mass and force of a structure are known, the acceleration can be
measured. Such acceleration values can be transformed into velocities and relative displacements by numerical integration using the following equation,

$$S(t) = S_0 + V_0 t + \int_0^t \left( \int_0^t a(t') \, dt' \right) \, dt$$

(1)

where \(S(t)\) is the displacement at a particular time \(t\), \(S_0\) is the initial position, and \(V_0\) is the initial velocity and \(a(t)\) is the acceleration at a particular time \(t\). The drift of an accelerometer can be removed by applying high filter of low frequencies in time series (e.g., moving average filter). Frequency characteristics of the system are determined by spectral analysis methods. In practise, the Fourier transformation is most commonly used. The Fourier transformation is a method for converting signals from a time domain to a frequency domain by using the following equation,

$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t) e^{i\omega t} \, dt$$

(2)

A power spectral density is usually computed by Fast Fourier Transform (FFT) algorithm with application of Hamming spectral window function. FFT can be described as algorithm for Discrete Fourier Transform (DFT) solving, which is based on transformation of discrete measurements from time domain to frequency domain [8]. DFT can be determined by,

$$X_K = \sum_{j=0}^{N-1} y_j w(j) e^{\frac{2\pi ijk}{N}}$$

(3)

Where \(y\) is measured data and \(w\) is window function. In spectral analysis methods, significant frequencies from the discrete frequency spectrum can be estimated by known statistical test of periodicity (e.g., the Fisher’s asymmetric test). A flow chart describing steps of an accelerometer data processing is shown in Figure 2.

**Figure 2.** A flow chart showing an accelerometer data processing.

2.2. IBIS-S interferometric radar technology

2.2.1. Background of microwave radar interferometry technique. IBIS-S or Image By Interferometric Survey of Structures was developed by Ingegneria Dei Sistemi (IDS) Georadar of Pisa, Italy, in collaboration with the Department of Electronics and Telecommunications of Florence University, mainly in the framework of the Project Parnaso-Mater (2001-2004), and funded by the Italian Government [13][15]. A typical IBIS-S system which primarily consists of three parts: a sensor module, a user-control PC, and a power supply provided by 12V battery units (Figure 3). The sensor module is a coherent radar which consist of two horn antennas and is supported by a rotating head tripod. The sensor generates, transmits, and receives the electromagnetic signals from targets [15][16].
A sensor module has a mass of 12 kg. The horn antenna has the following characteristics:

- Maximum gain of 23.5 dBi.
- Horizontal antenna beam width at -3dB; 11 deg.
- Vertical antenna beam width at -3dB; 10 deg.

![Figure 3. View of IBIS-S components [17].](image)

During data acquisition, the sensor module, which has a USB interface, is connected to the control PC (i.e. Panasonic Toughbook CF-19) to configure the acquisition parameters, store the acquired signals, process the data, and view the initial results in real time via software packages, such as IBIS Surveyor and IBIS data viewer [13][18].

The IBIS-S radar sensor uses interferometric radar technology for imaging of structural vibrations from a distance up to 1km. Frequencies of structures can be measured from 0-100 Hz. In measurements, IBIS-S enables the displacement measurement with an accuracy of 0.01mm (e.g., for a distance less than 500m), a range resolution of 0.5m and a sampling rate up to 200Hz. However, 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. The radar system operates based on Ku-band frequency (17.1-17.3GHz and wavelength of 17.2-17.4mm) with a maximum bandwidth of 200MHz. In order to make distinguish the source of the reflected signal, the stepwise frequency ranging from 17.1-17.3GHz is divided into 256 intervals with linear increment frequency and the distance is divided into several bins with a length of 0.5m [19][20]. In typical measurements, the target point may be located 10–1000 m from the instrument. The image captured radar image is divided into pixel, and such pixel distinguishability is obtained when the change of distance is 0.50–0.75 m and azimuth is 4.5 mrad.

It should be noted that large civil engineering structures (e.g., bridges, buildings and towers) usually have a typical natural frequency within the range 0-20Hz. Therefore, the maximum sampling rate of the scenario of 200Hz is an excellent performance to capture the appropriate level of data required. In practice, using the sampling interval $\Delta t = 0.005s$ is sufficient to provide a good waveform definition of the acquired signals.
2.2.2. Principle and Operation of Radar Interferometry. The operating system of IBIS-S for remotely monitoring dynamic behavior of a structure is based on the combination of two well-known radar techniques (e.g., the stepped-frequency continuous wave (SF-CW) and the interferometry techniques). The radar has only 1D imaging capabilities. Different targets are only distinguished based on their distance from the sensor. Thus, measurement errors may occur from the multiplicity of contributions to the same range bin, coming from different points located at the same distance from the sensors [13].

The SF-CW technique enables to detect the position of different target points located along the route of the line-of-sight of radar measurement. This technique has capability of determining the range resolution using the short time duration pulses. When the shorter the pulse transmitted, the more accurate the measurement is. Thus, to achieve high range resolution, the IBIS-S transmits short time duration (τ) pulses which is the minimum distance between two targets on the structure that can be detected individually. The range resolution (ΔR) and the short time duration (τ) pulses can be expressed mathematically as,

\[ \Delta R = \frac{c \tau}{2} \]  

where \( c \) is speed of light in free space, and \( \tau \) is short-time duration (\( \tau = 1/B \)). Thus, the range resolution can be rewritten as,

\[ \Delta R = \frac{c}{2B} \]  

Observing Equations 4 and 5, a better range resolution can be achieved by either increasing \( B \) or decreasing \( \tau \). The SF-CW technique transmits a burst of \( N_p \) monochromatic pulses with identical, and increasing frequency (e.g., with set frequency step of \( \Delta f \)) rather than transmitting a short time pulse duration with a large bandwidth in frequency domain to attain a large effective bandwidth \( B \),

\[ B = (N_p - 1)\Delta f \]  

where \( \Delta f \) is the fixed frequency step.

It should be noted that signal sources of SF-CW radar dwells at each frequency for a sufficient duration to allow the echoes to be received back to each receiver. Therefore, the time required for every single pulse (\( T_{\text{pulse}} \)) indicates the observed maximum measured distance (\( R_{\text{max}} \)) in the scenario,

\[ T_{\text{pulse}} \geq \frac{2R_{\text{max}}}{c} \]  

Then, the number \( N_t \) of tones composing each burst are given by:

\[ N_t \geq \frac{2R_{\text{max}}}{\Delta r} \]  

To achieve an unambiguous target range, the range of the targets should be closer than the maximum measured distance (\( R_{\text{max}} \)), which is given by,

\[ R_{\text{max}} = \frac{c}{2\Delta f} \]
The maximum sampling frequency rate depends on the maximum measured distance ($R_{\text{max}}$) and range resolution ($\Delta R$). Thus, the maximum sampling frequency rate ($f_{\text{max}}$) can be obtained by substituting Equation 4 and Equation 7 into Equation 9 as follows,

$$f_{\text{max}} = \frac{c\Delta R}{4R_{\text{max}}^2}$$

(10)

Figure 4 shows an ideal model of range profile is obtained when the radar transmitting beam illuminates a succession of targets at different distances and angles from the system. The peaks identified in Figure 4 show several measurement points with good electromagnetic reflected signals (i.e., signal-to-noise ratio). The sensor can be used to simultaneously detect the displacement or the transient response of these points. If the image of the scenario illuminated by radar beam has been determined, the amplitude of the Inverse Discrete Fourier Transform (IDFT) at each sampling interval provides the position of the targets points and the phase difference between two consecutive IDFTs provide the deflection of each range bin.

In the interferometry technique, a measurement of the line-of-sight displacement or the radial displacement ($d_r$) of all the reflectors on the structure were illuminated by the antenna beam simultaneously that are more than 0.5m apart. If $\Delta \theta$ is the phase shift of the electromagnetic waves reflected by the object in various time intervals and $\lambda$ is the wavelength of the electromagnetic signal, the radial displacement ($d_r$) is given by,

$$d_r = -\frac{\lambda}{4\pi} \Delta \theta$$

(11)

If the radial displacement has been measured, the actual displacement of the measured points can be easily calculated by applying a simple geometric projection as shown in Figure 5.
The natural frequency of a structure can be determined by using the Frequency Domain Decomposition (FDD) technique in the frequency domain. Then, the Power Spectral Density (PSD) function matrix is decomposed into a set of auto spectral density functions by using Singular Value Decomposition (SVD), with each function corresponding to an individual frequency mode [23][24].

Assuming a linear dynamic system, the response spectral density matrix subjected to a white-noise random excitation is given by,

\[ G(f) = \Phi G_q q(f) \Phi^H \]  

(12)

where \( \Phi \) and \( G_q q(f) \) are the modal shapes matrix and the spectral matrix of the modal coordinates, respectively. The superscript \( H \) indicates the complex conjugate matrix transpose. In the spectral density matrix, the diagonal terms represent the auto-spectral densities while the other terms are the cross-spectral densities. The output PSD \( G(f) \) is obtained by taking the SVD at each frequency,

\[ G(f) = U(f) \Sigma(f) U^H(f) \]  

(13)

Where \( U \) is a unitary matrix of the singular vector \( u_{ij} \), \( \Sigma \) contains a diagonal matrix of the real positive singular scalar values in descending order. In the case of modal shapes are orthogonal, there will be only one term in Equation (13). Therefore, the spectral matrix can be determined by a rank-one matrix,

\[ G(f_r) \approx \sigma_1(f_r) u_1(f_r) u_1^H(f_r) \]  

(14)

It can be seen in Equation (14), the first singular vector \( u_1(f_r) \) is an estimation of the mode shape while the first singular scalar value \( \sigma_1(f) \) at each frequency represents the strength of the dominating vibration mode. Further, the first singular function can be used as a modal indication function to estimate natural frequencies. The remaining singular values may contain either noise or modes close to the dominant mode.

3. Discussion

Monitoring dynamic behavior of full-scale structures under operational conditions is becoming more popular in recent years and hundreds of bridges have been tested worldwide [13]. Such dynamic tests are generally performed using piezoelectric sensors or accelerometers since these sensors are relatively inexpensive but accurate. However, the use of accelerometers are generally laborious, time-consuming, and often resulting in accessibility problems. For example, accelerometers are unable to provide a direct measurement of bridge displacement and have to be installed at selected locations [15][25][27]. Further, the capture of the dynamic behavior of a bridge requires a large number of accelerometers [27]. In addition, other bridge monitoring technique, such as laser sensor technology, also has limitation in detecting the overall deformation of a bridge and is very sensitive to the dust and other environmental conditions [12].

The new innovative development radar sensors with interferometric technique (e.g. IBIS-S) overcome these limitations due to their capability of remotely monitoring the dynamic behavior of a bridge with high accuracy in a convenient and efficient way by using two well-known radar techniques (i.e. the stepped-frequency continuous wave technique and interferometry technique) [4][5][22]. The IBIS-S radar sensor is designed for interferometric imaging of fast-changing movements and vibrations of the structures. It has capabilities of remote sensing at distance up to 1km with the accuracy of 0.1mm and 0.01mm in dynamic and static mode respectively, real-time simultaneous mapping of deformations, fast installation and operation, structural vibration sampling, analyzing up to 200 Hz for model testing, and operating day-night in all weather conditions. In addition, the major advantage of IBIS-S is non-contact monitoring of road infrastructures without disturbing the flow of traffic [12][13][24].
The IBIS-S uses radar interferometry, which is a new technology for remote monitoring of structural movements and deformations. The name of radar is derived from radio detecting and ranging technology, however, a new radar system with interferometric capability provides more information about the target than its name that would be implied. Most importantly, it is able to simultaneously detecting the range (e.g., the position) and deflection of different targets placed at different distances from the sensors by measuring the time for the radar signal to propagate, to the target, and reflect back. Thus, to detect two or more targets illuminated by the radar, there must be at least two different antenna echoes reflected from the targets. The range resolution of a radar sensor is defined as a measure of the minimum distance between two targets that can still be detected individually. The range resolution or distance resolution can also be described as the minimum separation between two targets that can be detected along the line of sight of radar measurement. The range resolution area is usually called as range bin.

In field applications, most structures have enough natural source of reflection of the electromagnetic waves (e.g., the "corner zones" corresponding to the intersection of girders and cross-beams in the deck of bridges) to make it possible to perform a measurement without the installation of corner reflectors. However, the use of corner reflectors is recommended when the target points are not sufficiently reflective to electromagnetic waves or when displacement of specific points on the structure should be measured [15].

4. Conclusion
Monitoring dynamic behavior of bridges under operational conditions is becoming more popular worldwide. However, selecting of sensor techniques and methods is essential because it greatly affects the overall methodology in analyzing the data and performances of the systems. There are several methods and equipment available in monitoring dynamic behavior of bridges and each of the method chosen might be limited by the bridge accessibility, time and budgets. Although accelerometer has been considered as a conventional way in monitoring dynamic behavior of bridges, these sensors are relatively cheap but accurate. However, the use of accelerometers has limitations such as laborious, time-consuming, and often resulting in accessibility problems. Also, accelerometers are unable to provide a direct measurement of bridge displacement and have to be installed at selected locations. Although it is relatively expensive, the recent advanced features of IBIS-S technique could overcome the limitations in the conventional way of monitoring dynamic behavior of bridges such as portability, fast installation and operation, operating both day-night in all weather conditions, being more accurate as well as providing both static and dynamic measurements.

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