Dynamic Monitoring of Tall Buildings

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Abstract - **There has been an increasing demand on tall and high-rise buildings. In response, structural engineers have become more interested in improving the design of these newly constructed buildings as well as extending the life of the existing and aging ones. Field dynamic monitoring is the best method that engineers can rely on to measure the current performance of tall buildings in order to make critical decisions regarding the improvement of their designs or regarding the planning of their retrofitting and maintenance. Radar interferometry is a novel remote monitoring technique that has appeared to be exceptionally suitable for monitoring of tall buildings. However, the performance and capabilities of this system relative to other conventional sensors in not fully understood. This paper reviews the radar system and other commonly used sensors with a focus on their current status and application. A model for evaluating the relative performance of the different sensors for tall buildings is constructed and it demonstrates that the radar has unmatched capabilities for monitoring of high-rise buildings, The comparative case study on the Soul Tower, which is the first of its kind on such high-rise building, further confirms this conclusion.. Consequently, engineers are advised to always consider employing the interferometric radar for dynamic monitoring of tall buildings.**

Index Terms: **Interferometric radar, Real Aperture Radar (RAR), Structural Health Monitoring (SHM), dynamic monitoring, accelerometers.**

I. INTRODUCTION

There has been a worldwide rapid growth in the construction of tall and high-rise buildings thanks to the recent improvement in design and analysis technique and evolution of materials. Understanding the real behaviour and performance of such complex structures is an imperative part in structural engineering in order to deliver a cost-effective design solution that satisfies the requirements of safety, serviceability and comfort for their occupants [1].

Nevertheless, there is still substantial uncertainty in regards to the actual performance of these structures relative to the one predicted by analytical models [1] or the scaled experimental models such as the ones used in wind tunnel testing.

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In response to this need and driven by the advancement in instrumentation and data processing capabilities, dynamic testing of actual structures has evolved rapidly in the last four decades [2]. In this regard, Experimental Modal Analysis (EMA) provides the most effective way to verify and improve the current design practice and theoretical modelling approaches. Indeed, dynamic monitoring has matured to the point where it has often become an integrated part in long-term Structural Health Monitoring (SHM) programs such as the one described in Burj Khalifa Project [3] and Shanghai tower [4]. Such programs not only confirm the structural behaviour of buildings, but also provide real-time monitoring of their current status as they become subject to more severe loading events and deterioration over their service life.

Dynamic testing which is often referred to as experimental modal analysis consists of an acquisition phase and an analysis phase. The whole process aims to identify modal characteristics of the structure under test, namely natural frequencies, modal masses, modal damping ratios, and mode shapes which can be also estimated from analytical models. In the acquisition phase a variety of instruments (electro-mechanical, optical, radar, etc.) and techniques (single, multi-point monitoring) can be used to record the raw physical parameters of a structure over finite time such as acceleration, velocities, displacements, strains and forces [5].

Based on their method of application, sensors can be categorized into traditional contact sensors and remote (non-contact) sensors. Accelerometers have been by far the most traditional and popular instruments employed in the dynamic testing of buildings [6]. The recent development of wireless communication has eliminated the effort associated with their wiring when they are used in a network to capture the global behaviour of structures. However, their mounting process still involves considerable difficulty that can be a prohibitive factor in some cases.

For this reason, the innovative remote sensing devices, which do not rely on physical contact with the structure, have appeared as better options to use [6]. There is a variety of noncontact devices that employ different techniques to dynamically measure the response of structures. Some devices are (a): Laser based such as Scanning Laser Doppler Vibrometer (SLDV), Velocimeters and Light Distance and Ranging device

(LiDAR); (b): vision based such as Digital Image Correlation (DIC) and dynamic photogrammetry; (c): microwave based as in the interferometer radar.

Application testings have demonstrated that the aforementioned devices have varied level of applicability for tall buildings. Limitations include their point wise approach of measurements, insufficiently short range, poor measurement resolution and the dependence on weather conditions. Moreover, most of these devices require a special surface preparation or installation of reflectors which subsequently negate the benefit of their remote use [7]. In contrast, interferometer radar seems not to suffer from all these limitations and appears to be an exceptionally suitable measurement system in this field. This monitoring instrument, which has recently emerged and become commercially available, has a great potential of being widely adopted as civil engineering tool in the future. The aim of this research is to evaluate the performance and applicability of the interferometer radar in comparison with other sensors that are commonly adapted for monitoring of tall buildings.

II. LITERATURE REVIEW

High-quality measurements represent the first elementary step for a successful dynamic monitoring. High precision sensors are preferred as they can effectively monitor the dynamic response of a structure with less excitation force. Here we review the principals, application and factors affecting the performance of the different monitoring systems; namely accelerometers, inclinometer, GPS and the interferometric radar when used for high buildings. The review does not extend into quantifying financial factors but it is focused on the practical and technical aspects.

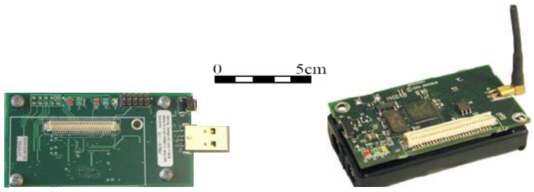
A. Accelerometers

Accelerometers are the most traditionally used vibration sensors in many fields including civil engineering due to their relatively low cost and high sensitivity [8] . Their conventional modal testing setup (Figure 1) consists of a number of transducers wired to a data acquisition device which is in turn connected to a computer that record and process data. The transducers are usually biaxial or tri-axial accelerometers to monitor vibrations in more than one direction and each axis represents a channel.

Recent advancement in digital circuitry has led to the emergence of MEMS (Micro Electro-Mechanical Systems); a new generation of accelerometers that are designed to collect, analyse and store or transfer dynamic data as one unit [9]. The integration of MEMS with wireless communication to form a Smart Wireless Sensor (Figure 2) was first realised in 1999. These sensors can remotely and simultaneously connect to a base station to form Wireless Sensor Network (WSN).

(a) System setup (b) Accelerometer (c) Data acquisition

Figure 1. Conventional (wired) Accelerometer System and its Components [8]



(a) Individual USB (b) Smart wireless sensor

Figure 2. MEMS Based Accelerometers [10]

Buildings and civil structures in general are characterised by limited frequency range (as low as 0.1Hz) which translates into low amplitude of acceleration specially if the vibration was under low ambient loads [11]. Consequently, high-sensitivity accelerometers with exceptional low frequency characteristics such as piezoelectric and servo transducers are the ideal choice [12]. Low level of vibration (in terms of micro-g) can currently be measured by the high-end wired accelerometers that are characterised by higher size, weight and cost. However, one should bear in mind that the monitoring quality not only depends on the resolution of the transducers, but also on the mechanical and electrical noise from the whole instrumentation chain including cables, amplifiers an data acquisition system, and undesired ambient interference including thermal, acoustic, electromagnetic and motion noise [13].

In regards to MEMS and WSN accelerometers, most of their commercial models have serious limitations to be used for buildings as reported by Velez [8], Haritos [14] and Nagayama & Jr [11]. Their transducer's low resolution is the biggest issue that limits their use to vibrations over 20mg which is improbable to occur in buildings. Another factor that contributes to their low resolution is the embedded Analog Digital Converter (ADC). Velez [8] developed a prototype of tri-axial MEM accelerometer that addresses all these issues. With a minimum resolution between 1 and 0.1mg they demonstrate successful application in moderate to low vibration scenarios in buildings.

B. Inclinometers and GPS

Commercially available inclinometers measure tilt angle of a mounted sensor relative to the horizon by opt-electronic means. The inclination measurements are simultaneously taken in dual-axes with an accuracy down to micro-radian precision (0.001mm/m) and sampling frequency of 10 Hz while connected to computer [15]. These measurements can be converted into dynamic displacements with sub-millimetre levels of accuracy based on structural models or by relating it with other displacement sensors such as GPS [16].

Figure 3. Inclinometer - Leica Nivel 210

(a) Reference station (b) Roving receiver

Figure 4. GPS Components [17]

Global Positioning System (GPS) has long been used for static monitoring of civil engineering structures that are subject to settlement, thermal expansion and other long-term displacement trends. The advent of real-time kinematic (RTK) surveying technique has made GPS usable for dynamic monitoring. RTK technique utilizes a reference station (Figure 4) and the phase of signal carrier's wave to pinpoint, correct and fast track the 3D coordinates of a roving receiver [18]. Current technology is able to measure the dynamic displacement at sampling rate of 20Hz or more. In best cases it has ±10mm accuracy while the best estimate of its resolution is about 3mm in the horizontal plane [19].

In the last decade, many researchers have investigated the quality and feasibility of using GPS for continuous dynamic monitoring applications of high-rise buildings and they had varied outcomes as found in the literature [16], [20]–[25]. Major issues includes limited displacement resolution, particularly when good satellite geometry is not available, communication issues with base station and most importantly signal noise due to the multi-path effect in urban areas.. Nevertheless, all reports confirm that GPS is accurate enough for monitoring response of high-rise buildings when displacement amplitude is adequately high (as during major earthquake and windstorm events).

The greatest advantage of the GPS resides in its capability to measure the static and quasi-static components of structure's response to wind which cannot be otherwise recovered by accelerometers or inclinometer [22]. This explains why GPS was deployed on the rooftop of several high-rise buildings in combination with other precise sensors such as accelerometers and inclinometers. For example three towers of the Chicago Full-Scale Monitoring Program were instrumented with GPS and accelerometers [26], while Shanghai tower incorporated inclinometer as well for its in-construction and in-service SHM [4].

C. *Real aperture radar*

The application of radar in the field of civil engineering was first demonstrated on a bridge by Farrar, Darling, Migliori and Baker [27]. The technique was based on the interferometry principle, measuring the dynamic displacement by detecting phase shift of the backscattered microwaves by a novel coherent radar sensor. In 2004 Pieraccini et al. [28] tested an improved system that utilises another principle, namely Stepped Frequency Continuous Waveform (SF-CW). Henceforth, such system is frequently called coherent Real Aperture Radar (RAR). The improved system provided the radar with a range resolution that makes it capable of measuring the response of several targets simultaneously. The new technology was developed by the Italian company IDS in collaboration with the University of Florence and was named IBIS-S (Image By Interferometric Survey of Structures) [29]

The most prominent advantage of the interferometer radar underlies in its remote monitoring capability. The device can reliably perform its remote measurements without a reflector in almost all cases, thus saving a great amount of time and cost associated with the mounting of the alternative contact sensors. Furthermore, the capability of the device to simultaneously monitor more than one point in its field of view makes it useful in capturing the overall behaviour of a large structure [30].

In addition, rather than deriving displacements from acceleration data which often come with considerable errors [31], the RAR provides a direct measurement of this interesting engineering parameter. Interestingly, the measured displacement has an accuracy in orders of sub-millimetre regardless of the monitoring distance and weather conditions while the range can cover up to several centimetres allowing to monitor structures with varied degree of flexibility.

The radar (shown in Figure 5) is commercially implemented as portable equipment supported by a tripod and powered by a battery pack. The management of the device is facilitated by system management software preinstalled in an auxiliary portable computer. The software is also capable of showing real time response and performing modal analysis on stored data. Table 1 lists the key operational characteristics of the radar.

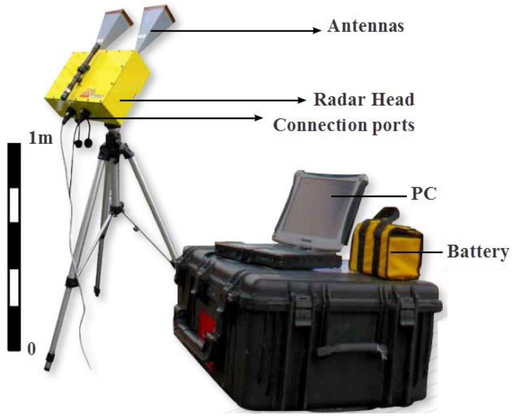


Figure 5. IBIS-S Microwave Interferometer [32]

Table 1. Main Characteristics of IBIS-S

Operating frequency	17.2 GHz (Ku band)
Max. operating distance (Rmax) (@ 40 Hz sampling frequency)	500 m
Radiofrequency bandwidth (B)	300 MHz
Nominal displacement sensitivity dLOS	0.01 mm
Max. sampling frequency Sampling interval Δt	200 Hz 5 ms
Weight of the whole system	12 kg
Max sampling window	5 mins
Max range resolution (ΔR)	0.5m
Antennas half power beam-width (Pyramidal horns)	0.18 rad ($3m^2$ at 10m)

The elementary sampling volume of a radar measurement is called a radar bin and it is related to the field of view (FOV) of the antennas and to the radar range resolution [33]. Basically any two objects located in the same bin cannot be individually distinguished. The radar identifies objects on the basis of their measured range rather than their angles. Similarly, only displacements along the line of sight (d_{LOS}) can be measured.

The monitoring procedure of an ordinary building using the RAR involves positioning the radar in the front of the investigated structure and orientating it towards the top of the building. The radar then generates a signal-to-noise ratio (SNR) profile for the range bins. From there the user can select multiple points with the highest SNR values to record their displacement-time history. Later this recorded data undergoes modal analysis so that modal characteristics of the building under testing can be estimated.

The literature review has revealed a number of interesting recent studies to evaluate the radar's performance on buildings, bridges, chimneys, masts and wind turbines as summarised by Massimiliano Pieraccini [34]. The height of observed buildings in the evaluation campaign ranges from 20 meters [6] to 94 meters [35]. In some cases, other conventional sensors were deployed together to evaluate the accuracy of the radar results [33], [36]. All filed tests confirmed the applicability and accuracy of the RAR.

Luzi, Monserrat, & Crosetto [37] suggested that SNR of 70dB or more is required in order to measure vibration amplitude in the order of 0.01mm. The SNR received back from an illuminated area of a building is strongly related to its geometry and the dielectric characteristics of its surface [38]. As illustrated in Figure 6, the presence of geometric discontinuities can improve the level of reflected echo at higher observation angles; however the SNR is still expected to be lower than the ones obtained at lower observation angles. It should be highlighted that the best monitoring scenario for a building usually involves its upper part as this part exhibits much greater displacement response and hence should be the easiest to measure. However, another complication of the higher observation angles is that the radial component of displacement (d_{LOS}) can be too small to detect. In this respect, Luzi et al. [6] showed that an observation angle up to 70 degrees was satisfactory in the close radar range for certain buildings.

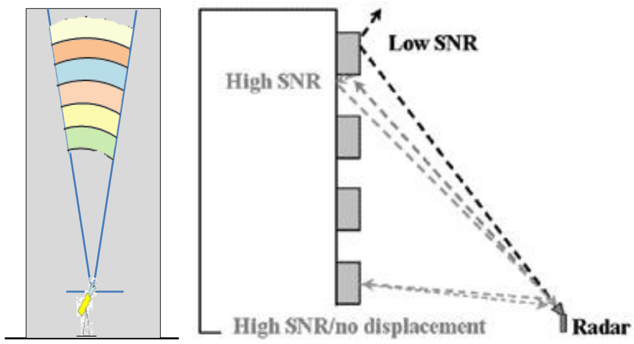


Figure 6. SNR Strength and FOV of the Radar

The SNR measured by the device is called thermal SNR as it pertains only to the instrumental noise and does not include the clutter generated by other vibrating object in the same radar bin [29]. Therefore, façade elements that vibrate autonomously rather than coherently with the building would have their contribution blended with the selected bins causing a dramatic distortion of the sampling quality. Therefore, high thermal SNR values do not always guarantee high quality of vibration monitoring for the object of interest. The presence of unwanted spurious vibrating targets can drastically affect the monitoring results as was reported by Pieraccini, Dei, Mecatti, & Parrini [39] when they failed to monitor the San Gimignano Tower due to vegetation growth on its walls.

III. METHODOLOGY

The literature review has identified some existing gaps. Engineers are often faced with the task of selecting an appropriate dynamic monitoring instrumentation scheme for tall buildings. The selection of sensors is often based on experience and applicability aspects. The performance aspect of sensors, however, can be very critical yet not fully understood due to the different dynamic parameters of the sensors used.

Higher performance sensors are capable of extracting dynamic properties of a monitored structure under lower excitation. This is particularly important for EMA of constructed buildings, as monitoring is often performed under AVT and wind speed has to be adequately high for sensors to detect buildings response. To put this into perspective, these measured responses such as accelerations and displacements are approximately proportional to the cube of the wind speed [40]. This illustrates the great influence wind speed can have on the success of EMA.

The objective here is to develop full understanding of the performance of all monitoring systems reviewed earlier with respect to the height of tall building using a theoretical approach. In addition and similar to the approach widely adopted in the literature, an experimental case study of high-rise building monitored by different system will be presented for evaluation.

A. Theoretical model

Accelerations measured by accelerometers are not homogenous with the units measured by displacement-based sensors such as RAR and GPS, neither with the tilt angles measured by inclinometer. Therefore, we need to find an approximate relationship between all these units based on theories of structural dynamics. The minimum amplitude of acceleration that can be appropriately detected by accelerometers needs to be defined based on an extensive examination of the available literature and products specifications.

According to Li [22] the main components of a structure's displacement response to wind are the static component caused by mean wind force and the resonant component which corresponds to structure's natural vibration mode. Figure 7 illustrates this on a building of height (H) being subject to dynamic wind loads ($F_{(t)}$). For the resonant component the structure can be simplified into a single-degree of freedom model that vibrates in its first transitional mode. The relationship between displacement amplitude (U) and acceleration amplitude (A) of the top floor is:

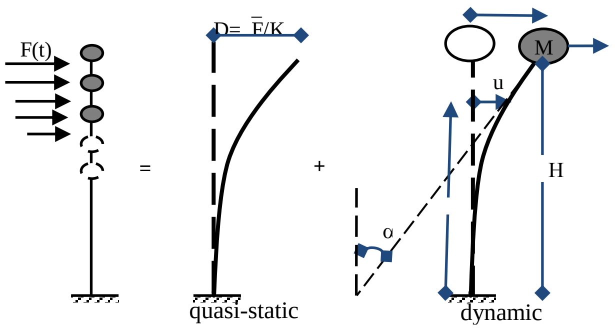


Figure 7. Wind Response Mode

$$|A| = \omega_1^2 U \text{ ---- eq (1)}$$

Where: $\omega_1 = 2\pi f_1$ = fundamental angular frequency of the structure

There are several empirical formulas to roughly estimate the fundamental natural frequency (f_1). The Australian and New Zealand Standard AS/NZS 170.2 formula can be used:

$$f_1 = \frac{46}{H} \text{ --- eq (2)}$$

Where: H = building height in meters

f_1 is expressed in (sec^{-1})

The displacement amplitude along building's height $u(y)$ can be approximately estimated using eq (3):

$$u = U\left(\frac{y}{H}\right)^{\xi} \text{ ---eq (3)} \quad [41]$$

Where: y= floor height

ξ=1.5-2 for cantilever buildings (such as ones with shear cores)

The relationship between displacement amplitude in the top floor (U) and the corresponding tilt amplitude (α) can be found by taking derivative of eq (3) using the lower boundary ξ=1.5 :

$$\alpha = u'(H) = 1.5\frac{U}{H} \text{ ----eq (4)}$$

B. Case study

The best case for dynamic monitoring of high-rise buildings was found in the Soul tower described by Barnes, Lee, & Papworth [42]. The tower is located in the Gold Coast and comprises of 77 storeys. It was monitored with multiple dynamic sensors during its construction in late 2010 as it was approaching 200m height. Verifying the dynamic properties of the tower was critical at that stage due to its exposure to coastal winds and the strict habitability requirements for its residents. Figure 8 and Figure 9 illustrate the monitoring scheme on the building.

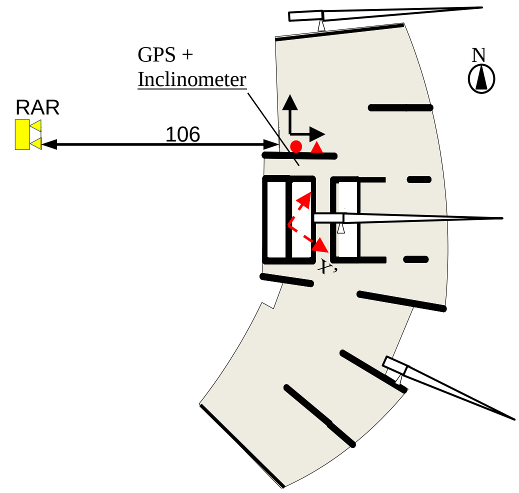


Figure 8. Building Monitoring Scheme

Figure 9. View from the Observation Point

Instead of relying on ambient wind, the test was carried out with forced excitation utilizing the three erected tower cranes by performing a start-stop loading sequence with various combinations of weights, positions and timings to capture all major vibration modes of the building. **Error! Reference source not found.** shows the adopted excitation and monitoring scheme. Remote monitoring was taken by RAR at106.8m positioned at the west side of the building. The biaxial inclination sensor Leica Nivel 220 and Leica GPS rover were mounted on the tip of the shear walls at 182.8m above the ground.

All data were supplied in form of graphs as measurements were processed into the frequency domain. The classical frequency domain peak-picking method is to be applied to extract modal frequencies from each measurement for comparison. The method is based on the theory that the amplitude spectra of a structure have peaks at its natural frequencies and the assumption is that the structure is excited with a broadband white noise (random excitation frequencies).

IV. RESULTE, ANALYSIS AND FINDINGS

A. Theoretical model

A defined precision applicable to common accelerometers can be established based on the experimental research carried out by Foss [43] and Velez [8]. Those experiments were part of two separate researches to establish the noise floor and relationship between resolution and detectable acceleration for most common accelerometers. Here we adopt 0.04mg and 1mg as the lowest detectable amplitude of acceleration for conventional accelerometers and MEMS based accelerometers correspondingly.

It is also useful to put these minimum detectable acceleration amplitudes into perspective with the upper boundaries expected in tall buildings. Motion perception at top occupied floors is a design parameter that often governs the design for high rise buildings [40], [44]. Examining the design practice [44] the lowest perception threshold for is found to be 5mg of peak acceleration (with less than 10% probability of being exceeded in any given year).

All acceleration amplitudes can be approximately converted into equivalent displacements using eq (1) and eq (2). The results are function of building height. For tilt angles, the detectable amplitude for Leica Nivel 220 is found to be around 0.005mrad with a resolution of 0.001mrad. Using eq (4) one can obtain the equivalent detectable displacement as a function of height. In addition 10mm and 0.2mm amplitude of displacements can be adequately monitored by GPS and RAR respectively.

Figure 10 shows the developed graph model. For any given building height, sensors that are lower in the graph are expected to perform better under the same conditions.

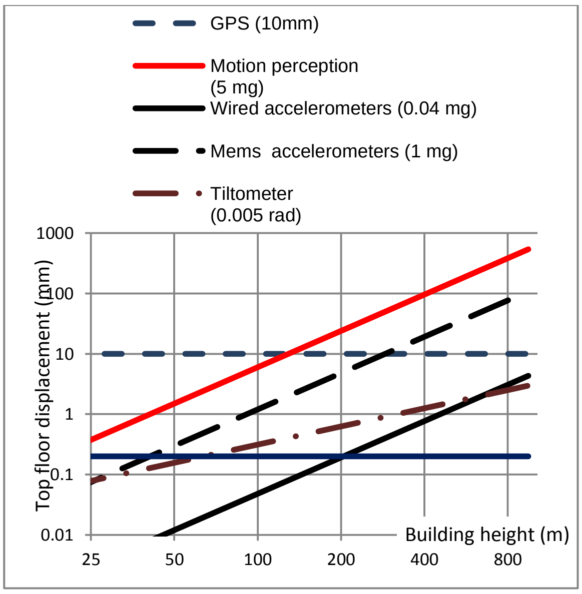


Figure 10. Sensors Performance Model

It can be seen that inclinometer and RAR most often perform better than MEMS based accelerometers. Low noise wired accelerometers only outperform RAR if building height is less than 200m. Another remark is that GPS is only useful for dynamic monitoring of buildings higher than 200m and they can outperform MEMS accelerometers for buildings higher than 400m.

B. Case study

For the radar observation 6 bins with high SNR and interesting range are selected for analysis. By considering the observation geometry and their range, each bin can be associated with a building height (*y).* Bins vibration measurements are already transferred into the frequency domain and some peaks corresponding to natural frequencies of the building can be clearly identified from the peaks.

Unlike RAR, which only measures response in its direction, these biaxial sensors provide more information about the directional components of vibration modes. Due to the complex plan shape of the building we can observe coupled transitional and rotational modes. The identified modal frequencies obtained from each sensor are presented in table 2. There are good agreements between all sensors with discrepancies less than 5%.

Table 2. Modal frequencies Obtained from Inclinometer, GPS and RAR

Natural frequency (Hz)			Mode shape
Inclinometer	GPS	RAR (Y)	
0.26 (X+Y)			1st torsional
0.29 (X+Y)	0.29 (X+Y)	0.3	1 transitional (X')
0.32 (X+Y)			2nd torsional
0.37 (Y+X)		0.38	1st transitional (Y')
0.61 (Y)			2nd transitional (Y)
0.67 (X)		0.64	2nd transitional X
0.75 (Y)			2nd transitional Y

The GPS overall performance was below expectation in this test. Only the first transitional mode of vibration in the transverse direction (x') could be identified due to the system's low resolution. On the other hand, the dual-axis inclinometer was able to capture all modes of vibration detected by other sensors. RAR performs relatively well as it was able to capture all vibration modes in its direction. Capturing the other transitional modes requires setting the radar in the other side of the building.

V. CONCLUSION

The interferometric radar is a pioneering remote dynamic monitoring instrument that can potentially save a great time and effort associated with the installation of conventional contact sensors. In this research, we have evaluated the potential of this technology for application to the modal identification of tall buildings. Extensive investigation into the performance of this displacement-based device and other conventional sensors has enabled us to create a comprehensive sensor performance model with respect to tall buildings. The model demonstrates that besides its ease of use, the radar is exceptionally powerful for taller buildings and can easily outmatch the performance of all other commonly used sensors for buildings over 200 meters. The comparative case study on the Soul Tower has supported the theoretical model and confirmed the accuracy of this instrument.

The high performance of the real aperture radar is conditional on high echo signal and this requires a careful setup of the observation geometry with a minimum offset space. In addition, spurious vibrating elements in the same view range should be avoided. With respect to dual-axis sensors, the only shortcoming identified in the radar is the need to reposition the device to monitor the building in the other direction and the difficulty in identifying torsional modes. Nevertheless, the interferometric radar should always be considered as the first option for dynamic monitoring. Other contact and invasive sensors might only be more suitable for long term structural health monitoring.

RESOURCES

The IBIS-S interferometric radar and its management software is supplied by industry partner organisations (IDS Ingegneria Dei Sistemi) in collaboration with the Department of Geomatics at the University of Melbourne. All data and observation graphs for Soul Tower were obtained from the experimental study of Barnes et al., [42].

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