Structural health monitoring on medium rise reinforced concrete building using ambient vibration method

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Abstract. Monitoring of structural health from initial stage of building construction to its serviceability is an ideal practise to assess for any structural defects or damages. Structural integrity could be intruded by natural destruction or structural deterioration, and worse if without remedy action on monitoring, building re-assessment or maintenance is taken. In this study the application of ambient vibration (AV) testing is utilized to evaluate the health of eighth stories medium rise reinforced concrete building in Universiti Tun Hussein Onn Malaysia (UTHM), based comparison made between the predominant frequency, fo, determined in year 2012 and 2017. For determination of fo, popular method of Fourier Amplitude Spectra (FAS) was used to transform the ambient vibration time series by using 1 Hz tri-axial seismometer sensors and CitySharkII data recorder. From the results, it shows the first mode frequencies from FAS curves indicate at 2.04 Hz in 2012 and 1.97 Hz in 2017 with only 3.14% of frequency reduction. However, steady state frequencies shown at the second and third modes frequencies of 2.42 Hz and 3.31 Hz by both years. Two translation mode shapes were found at the first and second mode frequencies in the North-South (NS-parallel to building transverse axis) and East-West (E,W-parallel to building longitudinal axis) components, and the torsional mode shape shows as the third mode frequency in both years. No excessive deformation amplitude was found at any selective floors based on comparison made between three mode shapes produced, that could bring to potential feature of structural deterioration. Low percentages of natural frequency disparity within five years of duration interval shown by the first mode frequencies under ambient vibration technique was considered in good health state, according to previous researchers recommendation at acceptable percentages below 5 to 10% over the years.

1. Introduction

Civil structures are prone to damage and deteriorate under structural aging, excessive forces, faulty material or structural design, unsuitable building configurations, failure of ground-structure
interaction etc. These vulnerabilities effects may influence the integrity of the structure throughout its serviceability without appropriate monitoring, maintenance or re-assessment technique is performed. Quantifying the damages and assessing their significance are important for both existing and new structures in order to protect safety and eventual losses. Thus, reliable maintenance, monitoring and re-assessment protocol through simple, quick and economic practise have attracted many attentions among researchers, especially for the purpose of early damage detection, decision making for remedy repair or rehabilitation requirement, safety preparedness, abandoned and demolished action.

Dynamic characterization can be used for modal identification and also provide a valuable help to calibrate numerical models to represent the behavior of the construction [1]. According to [2] which have been reported by [3], dynamic characteristics in terms of natural frequency (its inverse gives natural period), mode shape and damping ratios are important to predict the dynamic response of the structure at design or building re-assessment stage. According to [4], the use of natural period as diagnostic parameter has its basis on the assumption that this parameter has sensitive indicator against structural integrity. Ambient vibration method is widely used nowadays in site-structure dynamic characteristics investigation since it could be performed for quick data collection and analysis, even though with lack of structural design information and constraints in conducting destructive testing [5]. Besides, this ambient vibration technique is also applicable to be carried out to structures in low to high seismic regions, or also to new structures which nowadays are more focusing to new construction technologies and innovation such as lightweight, renewable materials, rapid constructions techniques etc. [6,7,8,9]. In this study, a simple ambient vibration monitoring approach has been performed on a medium rise reinforced concrete building in Universiti Tun Hussein Onn (UTHM), in order to investigate for any degradation and disparity on its dynamic characteristics in terms of natural frequencies and mode shapes, based on comparison of AV input motions which have been collected in year 2012 and 2017.

2. Methodology

Reinforced concrete moment resisting frame of Faculty of Civil and Environmental Engineering (FKAAS) building in UTHM is fully operated since 2011 (see figure 1). This FKAAS building has two towers. The highest tower has 8th stories (about 34 meter from the ground level to the roof top) and labelled as South tower in this paper, while the North tower has 6th stories. Both towers are constructed with two lift core, and staircases are provided at both wings that can be accessed from ground level to the top floor. For the purpose of structural health investigation using ambient vibration technique, the South tower has been chosen in this study. In this tower, all lecturer rooms are placed from 2nd to 7th floors. Meanwhile, light laboratories are placed on the first two levels (ground floor and 1st floor), and a studio is located on the 8th floor which can be fitted approximately up to 70 maximum audiences. At the West wing, the tower has been attached to three stories adjacent building. This adjacent building is connected from the first floor to the ground level.

In general, the first measurement of AV data collection was taken in year 2012 and subsequences fieldwork was performed in Mac 2017. All recorded ambient vibration time series was computed into Fourier spectrums for identification of predominant building frequencies with their respective mode shapes. A few filtering protocols were also applied to distinguish the origin natural frequencies of building and ground in this study. Comparison from both year findings of predominant building frequencies and their respective mode shapes were carried out for any dissimilarity in the end.

AV signals were measured in three main components i.e. vertical direction (UD) and horizontal directions (North-South: NS and East-West: EW). The AV instruments used in this study consist of four units Lennartz portable tri-axial seismometer of 1 Hz eigenfrequency sensors (S) and 400 V/m/s output voltage, CityShark II data logger up to 15 input channels, and 1 GB memory flash card data storage (see figure 2). The sensors were connected by geophone reinforced cable to the data logger. The data logger is operated under 12 volts of direct current. The data logger setup parameters were based on 100 Hz sampling rate frequency at optimum gain level applied along 15-minutes of recording length. All recorded measurements were automatically stored into a flash card. The AV record signals from data logger were manually transferred to a notebook for data processing.
Figure 1. (a) FKAAS building under construction works, (b) view of North and South towers and (c) South tower connected by adjacent building

Figure 2. Ambient vibration instruments

Figure 3 show an illustration of sensor positions on South tower. Orientation of seismometer sensors were placed in two alignments which were arranged horizontally and vertically. Four seismometers were placed, levelled and set to the transverse axis which was assigned as the reference axis (parallel to the North-South directions). In horizontal alignment, all sensors were arranged along longitudinal axis. Two sensors were positioned at both wings (East and West) and one sensor was placed in the middle (see table 1). Minimum of four measurements were arranged in vertically alignments at selective floors on both wings (see table 2). At respective wings from both vertical measurements, one sensor has been placed on the ground surface for the purpose of ground fundamental frequency determination. The details of ground AV measurements have been extracted into table 3. Similar sensor alignment and positions procedures were applied in Mac 2017 fieldwork.

Figure 3. Positions of sensor on South tower
Table 1. Breakdown of horizontal sensor arrangements and positions on building

| File Index | Year of Measurements | Time   | Sensor 1 (S1n), Ref. Point | Sensor 2 (S2n) | Sensor 3 (S3n) |
|------------|----------------------|--------|----------------------------|----------------|----------------|
| 533        | 2012                 | 02.19 pm | West wing (WW)             | Mid-span (MS)  | East wing (EW) |
| 55         | 2017                 | 11.21 am |                             |                |                |

Table 2. Breakdown of vertical sensor arrangements and positions at EW and WW of South Tower

| File Index (EW/WW) | Sensor 1 (S1v), Ref. Point | Sensor 2 (S2) | Sensor 3 (S3) | Sensor 4 (S4) |
|--------------------|-----------------------------|---------------|---------------|---------------|
| 2012               |                             |               |               |               |
| RT                 | 7                           | 5             | -             |               |
| RT                 | 7                           | 3             | -             |               |
| RT                 | 5                           | 3             | -             |               |
| RT                 | 5                           | 1             | -             |               |
| 2017               |                             |               |               |               |
| RT                 | 7                           | 5             | 3             | 3             |
| RT                 | 7                           | 5             | 3             | 1             |
| RT                 | 5                           | 5             | 1             | GF            |
| RT                 | 3                           | 1             | GS            |

Table 3. Details of AV measurements on ground surface (GS)

| File Index | Year of Measurements | Time   | Sensor No. | Position on FKAAS South Tower |
|------------|----------------------|--------|------------|-------------------------------|
| 544        | 2012                 | 04.29 pm | S3         | Close to EW                   |
| 539        |                      | 01.29 pm |            | Close to EW                   |
| 59         | 2017                 | 12.13 pm | S4         | Close to WW                   |
| 318        |                      | 15.45 pm |            | Close to WW                   |

FAS and HVSR (Horizontal to Vertical Spectral Ratio) spectrums were automatically computed by open source software of GEOPSY (Geophysical Signal Database for Noise Array Processing) [10]. Several computation parameters have been applied in FAS and HVSR analyses such as, 15 sec of windowing process, automated anti-triggering function, cosine taper of 5% on both sides of each window, and Konno and Ohmachi smoothing constant at 40 bandwidth. The ambient vibration time series from the NS, E, W and UD components of the building were transformed by using FFT (Fast Fourier Transform) algorithm. Each FFT spectrum obtained from respective component were then averaged to form FAS mean-curves in order to identify significant peak building frequencies. Similar procedures were applied in HVSR analysis. But those FAS spectrums from horizontal components (NS and E, W) were averaged and divided by the vertical spectrum, then followed by root mean square computation to form into HVSR curve. By identifying their respective peak origin frequencies that strongly presence, the ground and building natural frequencies (f_s and f_w) were distinguished from overlapping spectrums made between mean FAS and FAS_E,W curves on rooftop against HVSR curves on the ground surface [11]. Lastly, the normalised mode shapes were finally plotted based on respective building predominant frequencies obtained.

3. Results and Discussions

Significant peaks of FAS curves at three predominant modes frequencies are found between 1.95 to 2.03 Hz (in the 1st mode), 2.42 Hz (in the 2nd mode) and 3.31 Hz (in the 3rd mode) from the NS and E, W components in 2012 and 2017. Meanwhile, a single sharp peak of HVSR curves is obtained from the ground ambient vibration measurements at steady fundamental frequency of 1.40 Hz in both years. Both FAS and HVSR curves carried out in 2012 and 2017 are given in figure 4 and 5, and these building predominant frequencies are summarized in table 4.

Single sharp peak of ground natural frequency may explained to the existence of deep soil thickness with a large velocity contrast [12,13]. From the closest borehole data to study area (approximately 150 m away from study area), the SPT ‘N’ profile has almost met to this circumstance (see figure 6). It was also agreed with [14] and [15] which have been reported by [16], when at this
frequency (1.4 Hz or 0.72 sec of natural period) the ground was classified under dense to soft soil classification which could be found within 30 to 60 m depth.

**Table 4.** Comparison result of predominant frequencies identified in year 2012 and 2017

| Identified mode of frequency | Year of AV measurement | Natural frequency (Hz) | Disparity percentage |
|-----------------------------|------------------------|------------------------|---------------------|
| 1<sup>st</sup> mode of building frequency (translational) | 2012 | 2.03 | 3.14% - decreased |
| 2<sup>nd</sup> mode of building frequency (translational) | 2012 | 2.42 | 0% - maintained |
| 3<sup>rd</sup> mode of building frequency (torsional) | 2012 | 3.31 | 0% - maintained |
| Single peak of ground fundamental frequency | 2012 | 1.40 | 0% - maintained |

Consistent spectrum pattern and peak frequencies have been concluded to steady dynamic behaviour and characteristic experienced by building within five year duration. In facts, none of structural damage has been reported by the building owner or found from visible observation on FKAAS South tower to date. But, from the first mode frequencies finding at 2.03 Hz in 2012 have been slightly reduced to 3.14% in 2017, with the other two frequency modes are remained steadily (see table 4). Even no specific guideline is provided against specific allowable vulnerability percentage of frequency reduction between years, but according to [17], the natural frequencies of a
Building may slightly change within 5 to 10% over the years due to various factors namely weak/moderate motion, weather conditions such as temperature and moister in the walls, occupation of building, changes in nearby buildings etc. The authors have also added, under damage scenario, the frequency changes may drop between 30 to 50% depending on the degree of damages. Even though this percentage has not been exceeded from the finding of this study, but care should be taken to continuously monitor the degradation of frequencies in the subsequence years.

![Figure 6. Location of the closest borehole (BH) SPT blows count profile](image)

The deflections modes are almost alike from both finding in years 2012 and 2017. The horizontal deflection behaviour of South tower shows bigger displacement amplitude on the East wing compared to the West wing from the plan view in figure 7(a). At the West wing, it has been strengthened by two lift cores which significantly reduce the displacement amplitude. From vertical mode shapes, the deformation shows steadily increased from the third level to the roof top without excessive inter-storey displacement occurred at any floors (see Figure 7(b)). However, the deflection amplitudes are steeply reducing from the third level to the ground floor, due to the influence of adjacent building when the South tower has been attached and restrained from the first to the ground floors (see photograph in figure 1(c)). The illustration of the three dimensional mode shapes based on the first mode frequency attained, based on both characteristic of horizontal and vertical deflection mode shapes is illustrated in figure 7(c).

![Figure 7. Illustration of translational deformation by the first mode frequency obtained from NS direction (transverse axis) from (a) plan view, (b) side view and (c) 3D view](image)

Similar conditions indicate by the longitudinal axis deformation in 2012 and 2017 when the deformation shapes are almost identical as illustrated in figure 8. The second mode frequency occurring at 2.42 Hz has shown to steady deformation in horizontal as well as in vertical deformation mode shapes. The vertical deflection curvature is linearly decreased from the roof top to third level, but the amplitude is slightly changed from the third level to the ground floor. The torsional effect has been found from the third mode frequency occurring at 3.31Hz. From horizontal deformation shapes
shown in figure 9(a), both wings tended to swing in opposite directions but approaching to null amplitude when reaching to the centre of the building. Double curvature bending shape could be seen from the vertical mode shape as given in figure 9(b), when the inflection point is occurring at fifth floor. Figure 9(c) illustrates the torsional mode of South tower based on combination both horizontal and vertical mode shapes findings.

Figure 8. Illustration of translational deformation by the second mode frequency obtained from E,W direction (longitudinal axis) from (a) plan view, (b) side view and (c) 3D view

Figure 9. Illustration of torsional deformation by the third mode frequency obtained from NS direction from (a) plan view, (b) side view and (c) 3D view

4. Conclusion
Natural frequency can be utilized as a good parameter and indicator in order to monitor the health state of new or existing structures. It is believed the changes of natural frequency over the years could be used as benchmark and good practices in structural stiffness degradation monitoring. Investigation on FKAAS building using ambient vibration technique has found three predominant modes of frequencies, at acceptable frequencies disparity percentage after five years measurements interval. Only 3.14 % of discrepancy found from the first mode frequency (from 2.03 to 1.95 Hz), but the remaining frequencies are sustained at 2.42 Hz for the second and 3.31 Hz for third modes, in both AV measurement years of 2012 and 2017. Lastly, comparable mode shapes are illustrated under translational and torsional mode shapes without excessive inter-storey displacement detected at any floor levels.

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