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Mode Shape and Natural Frequency Identification of a Prestressed Box Girder Bridge in Nonthaburi, Bangkok

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ABSTRACT: *Gradual deterioration of structures leads the engineers towards the Structural Health Monitoring system to confirm the existing serviceability scenario, where modal properties are the indispensable part of the process. Modal properties like modal frequency and mode shape from the service providing structure are essential to adjust the numerical finite element model to make the model more like the existing structure. This study built up the mode shape and computed the natural frequency of a precast box girder bridge to compare with numerical model. The selected bridge for this study is situated close to Bangkok city known as canal crossing bridge. A finite element model was developed based on as built drawing, and then, the model was updated with the existing structure's modulus of elasticity. The ultrasonic pulse velocity test was conducted to obtain modulus of elasticity data. Then accelerometers data were collected under ambient vibration situation from each predefine station to find the modal properties. The study found that mode shape and natural frequency for first mode are similar for both calculated from acceleration data and numerical model.*

KEYWORDS: structural health monitoring, modal parameters, mode shape, natural frequency.

1. Introduction

Bridges, the horizontal structures, are inseparable part of transportation system, and residential or commercial buildings, the vertical structures, have significantly ameliorated the people living standard on which society vigorously relies upon (Medhi, Dandautiya, & Raheja, 2019). Deterioration on serviceability, performance and durability of bridges start just after the construction due to continuous variable traffic loading, outrageous weather conditions, and effects from earthquake and wind. Moreover, deterioration process starts during the construction phases as well, while structural integrity needs to be confirmed between design numerical model and as-built condition, where assessment of the structural behaviors become obvious (Lantsoght, van der Veen, de Boer, & Hordijk, 2017). So, Structural Health Monitoring (SHM) system is highly needed to confirm the level of performance and durability of the bridge structures (Wenzel, 2009), where modal properties need to extract from the real structures.

Modal properties, like mode shape and modal frequency under ambient vibration condition, help to improvise the numerical modeling. Moreover, damage detection and localization of damage can be done by using mode shape and curvature of mode (Nayek, Mukhopadhyay, & Narasimhan, 2018). Numerous numbers of approaches are available to identify the modal parameters of structure such as conventional model-based approaches; neural networks and genetic algorithms approaches; Chaos theory; multi-paradigm approaches; signal processing approaches of vibration test, etc., recently, signal processing approach becomes the more popular technique (Su, Le, Huang, & Lin, 2018). In signal processing technique, to ensure the collection of desire signal or responses from the structure requires predefine field conditions, which generate the vibration on in-service structure with specific loading condition.

Identification of modal properties is very common under control environment and loading condition in the laboratory (Mohanty & Rixen, 2005). Several loading conditions; like impact vibration, forced vibration and ambient vibration were considered to induce dynamic behaviors of bridge to extract the modal parameters from the acquired signal of in-situ structures (Yang & Yang, 2018). Force induce excitation which generated by introducing artificial loading on structures, and free vibration excitation is developed with the help of sudden impact force on structures, for both cases operation of the structures, are needed to be postponed. Moreover, conventional forced vibration technique, like force induce excitation, is needed a loaded moving-vehicle which often generate quasi impact vibration of flexural torsion mode or may induce excitation parallel to the road. On the other hand, ambient vibration responses can be measured with regular activities of structures, and which can be demonstrated as a cost-effective and convenient technique to verify the global responses in terms of modal behaviors of a bridge. Generally, forced vibration is more effective compared with ambient excitation responses but ambient vibration does not need any special arrangement. In addition, since excitation in ambient conditions is a recurrence event, with the help of limited sensor devices high resolution data collection is achievable (Ehhq, Sorlwlqj, Phdvxuhphqw, & Wkh, 2018; Lamonaca et al., 2019; Rao, Gubbi, Ngo, Mendis, & Palaniswami, 2016; Xie & Cai, 2015). Most of the recent output-only model of signal processing under ambient vibration responses are sophisticated to confirm precise and consistent dynamic parameters (Rent & Zong, 2004; Sabamehr, Lim, & Bagchi, 2018)

Finding the modal properties under ambient situation are getting more priority to compare with finite element model and it has to be adjusted the numerical model to make more analogous model with existing structure. Extraction of modal parameters under the operational condition of structure has some obstacles such as recorded signal need to be apposite condition to consider stationary white noise signal, and sometimes magnitude of the output signal are very small with noise. Peak picking technique where power spectral densities function is used (Julius S. Bendat, 1995), and stochastic subspace identification method (Peeters & De Roeck, 2000) are more popular in practice to adjust the challenge of stationary signal with white noise and low magnitude signal from ambient vibration. This study followed the peak picking technique to find the natural

frequency and to construct the mode shape, afterward compared with the numerical model data.

A good number of studies have conducted experiments with accelerometer to find the modal parameters like frequency, damping and mode shape of the structure in under-construction, newly completed or fully operational conditions and even after damage (Aasim, Karimi, Tomiyama, & Aydan, 2020; Drygala, Polak, & Dulinska, 2019; Gara, Nicoletti, Carbonari, Ragni, & Dall'Asta, 2020; Marcheggiani, Clementi, & Formisano, 2020; Scozzese, Ragni, Tubaldi, & Gara, 2019). This paper has focused to develop the mode shape and calculated the natural frequency of a box girder cantilever precast segmental bridge, which is located near Bangkok and known as canal crossing bridge of Ratchaphruek road in Nonthaburi. Finally, authors compared the modal responses of in-situ structure with numerical model parameters.

2. Method

2.1 Study Area

The study has been done on Bangkok-Noi canal crossing bridge of Ratchaphruek road in Nonthaburi. Total length of the bridge is 210m, which has three spans, mid span is 90m and two side spans are 60m each. This bridge is post-tensioned box girder with variation in depth of the box girder, which consists of 2 traffic lanes and one walkway. An adjacent cantilever slab of 1.6m width was constructed after the construction of box girder to facilitate the walkway. Riverbank support of the side spans are abutment type, and fixed pier supports have been constructed in the river for mid span. The side section view of the west side of the bridge is shown in Fig.1.

2.2 Development of Model

Numerical model of Bangkok-Noi canal crossing bridge was developed with a commercial software CSI-BRIDGE, version 20.2.0, and the model was analyzed as 3D FEM model for dynamic analysis. The box girders of the bridge, segmental type, were

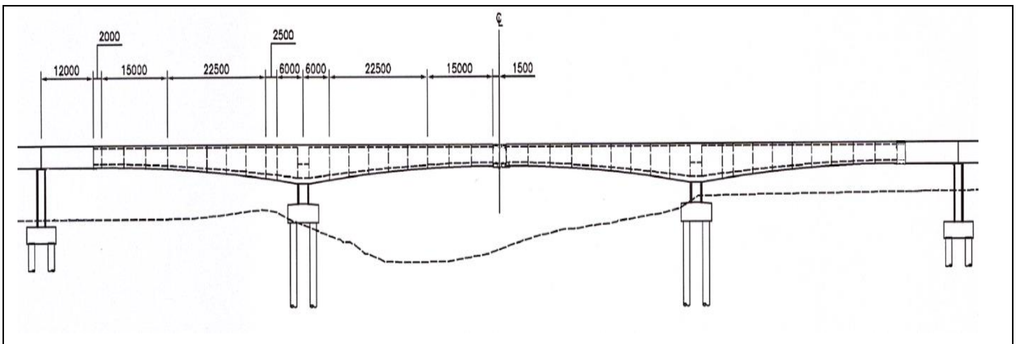

Figure-1: Side section view, West side of the Bridge considered as shell elements, and total 44 numbers of box girders were included in the model. Both ends support of the bridge are pot bearing, which were placed in between

box girder and abutment, and modeled them as sliding pin bearing system. On the other hand, the column having thick dimension of 2.4m x 3.7m, and foundation were assumed as solid elements. Two piers in the river were constructed as a fix support between the column and the girder. Since, half of the column and the pile cap both are covered by ground soil, and the pile cap was considered as fixed with ground. All the properties of materials were collected from as-built drawing of the project, where 35MPa compressive strength was suggested for the girders, abutments, columns, and footings based on 28 days standard.

After conducting the ultrasonic pulse velocity test (UPV), current condition modulus was calculated, and later the as built drawing model was updated with calculated modulus. Later, the mode shapes were compared with constructed mode shape from ambient vibration test which was done by using accelerometer. From the UPV test data on bridge, modulus of elasticity values of individual box girder was replaced with the calculated values. The updated model showed very small difference in natural frequency, which is not significant to change the of strain location. However, first mode shape showed opposite phase shift, and other mode shapes were found similar with as built drawing model and patterns, mentioned in Table-1, remained same. So, no significant change of natural frequencies was found. The comparison of modal properties for built-in drawing model and updated model are shown in Table 1.

Built-in drawing model			Updated model		
Mode No.	Period (sec.)	Natural Frequency (cyc/sec)	Period (sec.)	Natural Frequency (cyc/sec)	Patterns
1	0.5993	1.6685	0.6027	1.6591	Bending
2	0.5675	1.7623	0.5604	1.7843	Bending
3	0.4687	2.1337	0.4636	2.2418	Torsion
4	0.4497	2.2235	0.4461	2.2417	Bending
5	0.3164	3.1604	0.3090	3.2357	Torsion

Table 1: Comparison of modal properties from numerical models

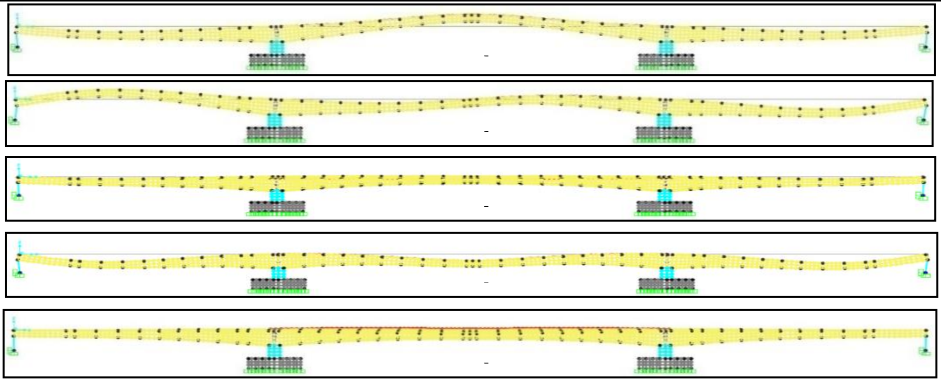

Figure-2: Mode shapes from the updated model.

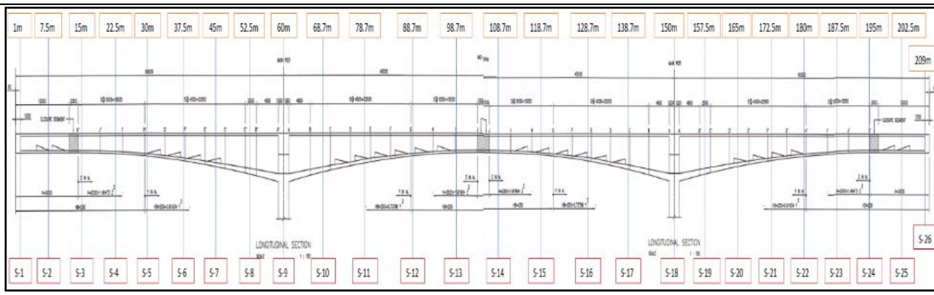

Figure-3: Location of moving station of accelerometer in longitudinal direction of bridge.

After updating the built-in drawing model by in-service modulus of elasticity, it was found no change in mode shape and mode pattern like flexure and torsion. The determined mode shapes from updated model are shown in Fig.2. Among first five modes, 1st, 2nd, and 4th modes occurred due to bending moment with translation in Z axis (vertical axis) while 3rd and 5th mode showed torsion. For regular structures, it is expected and found, first few modes occur due to bending and higher modes develop torsional stress

Ambient vibration test (AVT) was conducted to confirm the mode shape and the natural frequency of the structure with numerical model. To perform the test, 26 moving stations and one reference station were considered for collecting the desired signal, shown in Fig.3. The reference station was chosen near to L/3 distance, 28.7m from the

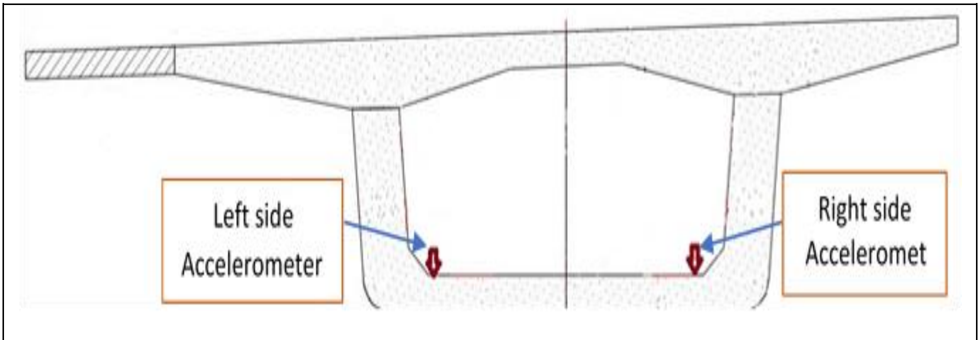

Figure-4: Location of accelerometer on both side girders

pier E2 on mid-span. And the moving station distance were selected on the side spans and mid span, which are 7.5m and 10m interval, respectively, except the stations S-1, -10, S-18 and S-26.

Each of the moving station data was recorded for 5 minutes with the sampling rate of 100 Hz. Reference station accelerometer was fixed throughout the whole testing period, whereas moving station accelerometer was shifted along the longitudinal direction of the bridge from station 1 to 26. Accelerometer were placed web's left and right sides of the box girder in longitudinal direction of pier E1 to E4, shown in Fig. 4

2.3 Instrumentation for Accelerometer Data

To conduct the AVT, a good number of electronics equipment; Accelerometer, datalogger, laptop, time synchronizer and power cell were used in the testing. Total two uniaxial vertical acceleration measuring SN420 accelerometers, with different maximum capacities, were used in the test. Capacity of the reference station accelerometer was ±0.5g, and for moving station was ±0.25g. With help of bidirectional water leveling, level of the accelerometer was confirmed before starting the data recording.

Individually, reference station and moving station were set-up with one laptop, one datalogger and commonly connected with time trigger, which help to synchronize the time between two laptops. Lab-View software was used as a helping tool to recorder data in data logger and transfers the recorded file to laptop. The recorded data is voltage difference from accelerometer with respect to time. The Fig. 5 is showing the data collection arrangement of reference station and moving station separately.

2.4 Data processing

Data from AVT with accelerometer were collected on both side of the box girder separately. Mode shape can be developed by using power spectral density function either "pwelch" from MATLAB or using fast Fourier transform "fft" function. The schematic diagram of the mode shape development is shown in Fig. 6. In the beginning, recall all the captured acceleration responses from reference station and moving station recorded at the same time. To confirm the same starting time of reference signal

(a) Reference station | (b) Moving station

Figure 5: Station arrangement for data collection

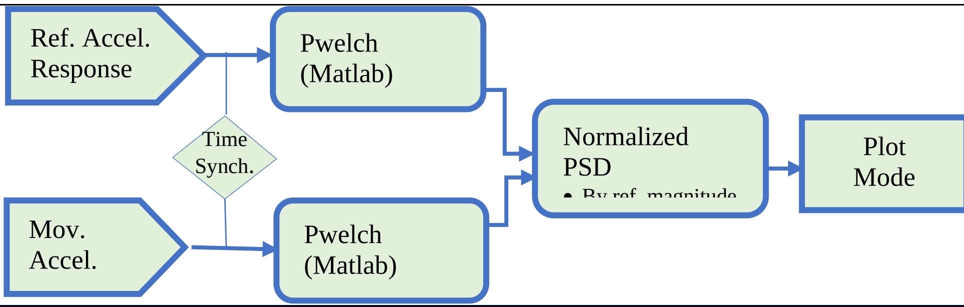

Figure 6: Schematic diagram of mode shape development

segment and the moving station signal of ith station, time difference needs to calculate from the time trigger signal. After the adjustment of time differences, both the signals of time domain from reference and moving station were transform into frequency domain by "pwelch" function. Natural frequency of each mode was identified, and the Fourier magnitude of the corresponding modal frequency of every station was recorded. Each moving station magnitude was normalized by the value from reference station, and all the value normalized by the maximum normalized value to get height displacement to be one for each mode. For "pwelch" function, the

magnitudes need to do square root due to power spectrum. Similar process needs to continue to find all the stations value throughout the bridge length. With the help of

FFT phase shift values directions of the mode were confirmed to get the actual shape of the mode.

3. Results and Discussions

Acceleration response from reference station, which has a sampling rate of 100 under ambient vibration condition, which is shown in Fig. 7. Individual moving station data recording time was synchronized with time to find the reference data of same time.

Reference station triggered value and individual station triggered value were selected manually. For example, shown in Fig. 8, reference station time period is 698.8 to 998.8 sec for the time of 300 sec of moving station 2, which confirm the same starting and ending time of on-site signal that collected from reference and rover station. Since the acceleration data were collected from the both sides of the box girder, left side is East and right side is West direction, similarity of natural frequency of the was checked. Natural frequencies from both sides' reference stations were found very close, 1.61Hz. and 1.62 Hz, which is shown in Fig.9. To check the natural frequency total testing time was considered as time span of reference station.

Figure-9: Fn from refence station; (a) east side and (b) west side of box girder. Then, PSD amplitude (shown in Fig. 10) of each moving station and reference station were normalized to draw the mode shape of the bridge. It was noticed that, only first mode frequency value gave the clear peak magnitude for moving and reference station. That is why only first mode shape can be developed from the data after the normalization of peak magnitude of each moving station, mode shape was plotted along the length of bridge. To confirm the phase direction, FFT function of MATLAB was used. Fig.11 and Fig.12 show the mode shapes on both sides of the box girder are identical, and center of the mid span exhibits the highest mode shape value. Maximum mode shape value was scaled to unit value to easily identify the higher strain locations for the particular mode.

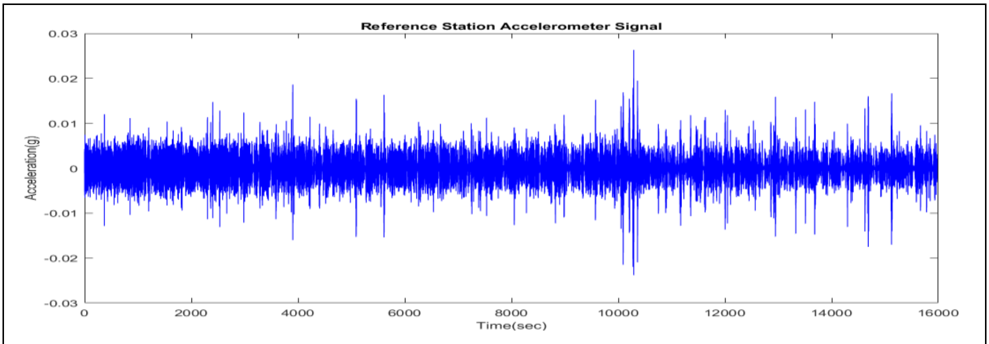

Figure-7: Acceleration data of reference station

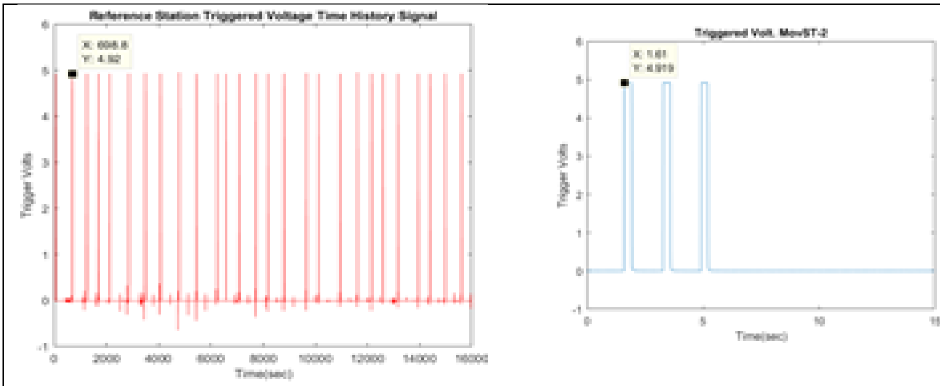

Figure-8: Time history of triggered voltage.

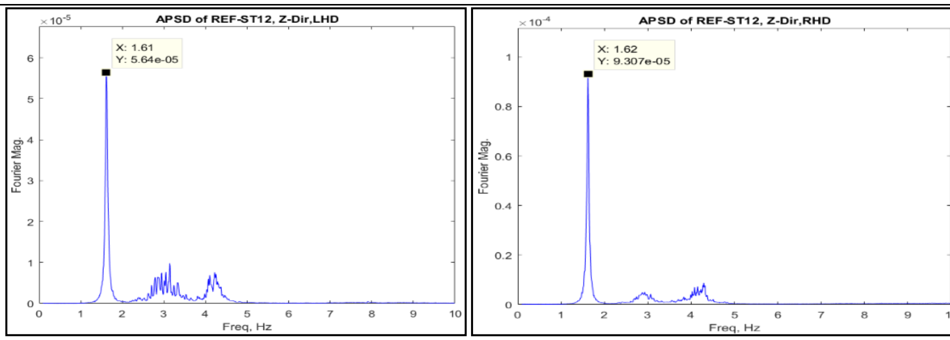

Figure-9: Fn from refence station; (a) east side and (b) west side of box girder

To. confirm the mode shape between numerical model and constructed one, both the shapes placed one after another with same scale. Fig.13 shows that mode shape of numerical model and developed one are almost same; however, numerical model mode shape is looking very smooth due higher number of data point from the model. For the first mode, it can be suggested that maximum and minimum stress concentrated area on the in-service bridge are similar with numerical model. As not much deviation is found between numerical and on-site data mode shape and modal frequency, the structure neither get more stiffness and rigidity from variable increased modulus of elasticity nor loss stiffness and rigidity due to service life, especially in global scale.

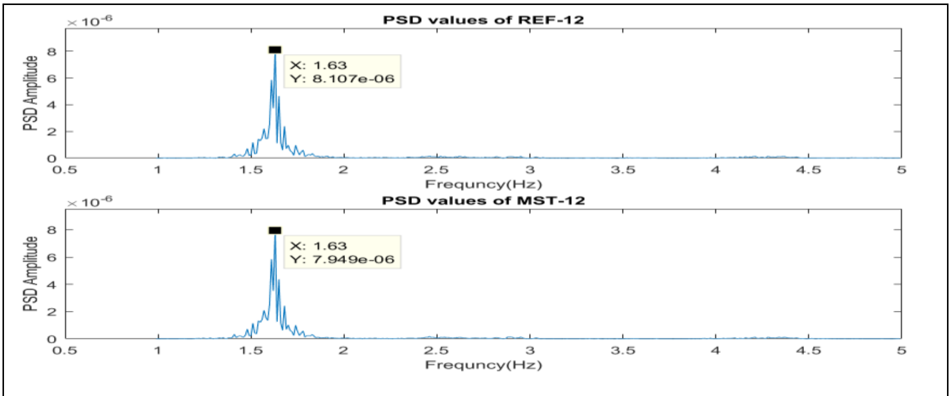

Figure 10: PSD amplitude of reference and moving station 12.

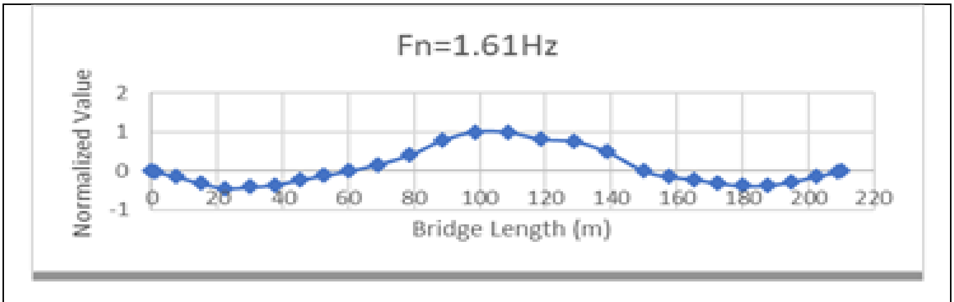

Figure-11: Mode shape for Fn-1.61Hz. from left (east) side data of the girder

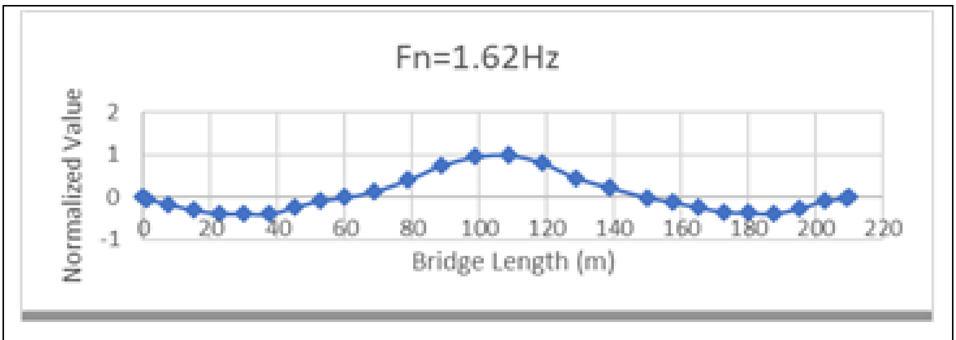

Figure-12: Mode shape for Fn-1.62Hz. from right (west) side data of the girder

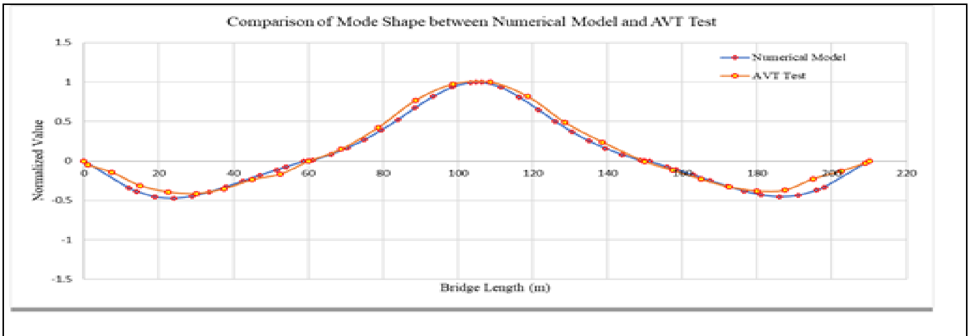

Figure 13: Comparison of mode shape-01 between numerical model and AVT test data

5. Conclusions

Initially developed numerical model did not show any significant change in mode shapes and natural frequencies after updating the model with UPV test data. Development mode shape for first mode was done and compared with the numerical model results. The study found that mode shape and its

pattern are very similar in first mode, govern by the flexural force, for numerical and measured data. Moreover, the magnitude of natural frequency of first mode from measured data is very close to the numerical model value. Natural frequency of first mode at every data collection station has shown clear peak at first mode, however, other modes frequency could not calculate by using peak picking method from ambient vibration data.

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