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System Identification of Typical Truss Bridge Using VibSensor

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Abstract
Since bridges are of great importance to society and economy, system identification of bridge has very practical significance during its service life. This study explains the use of Smartphone accelerometers for extracting the model parameters of the truss bridge by operational modal analysis. Three major motorable truss bridges were taken for the study purpose. In this study we have used Samsung S6 as a Smartphone from which the vibration data of the truss bridges were collected by using the Vibsenor application. For this process we use the operational model analysis (OMA), where we use vehicle load as ambient vibration for actuating the bridge. The natural frequencies of the bridges are identified from operational modal analysis using the data obtained from Smartphone accelerometers at a single point and a peak picking technique. Then FEM modeling of the truss bridge has been done using SAP2000 and model parameter of the bridge is obtained. Finally these two results were compared. The result shows that the first three modal frequencies of the truss bridges can be accurately obtained using the data collected from Smartphone sensor and peak picking method.

Keywords
System Identification, Smartphone, Operational Modal Analysis

1. Introduction

System Identification (SI) is the process of modeling an unknown system based on a set of input–outputs and is employed in different fields of engineering. The system identification of structural system can be done in the form of (a) Identifying structural parameters such as stiffness, vibration signatures such as frequencies, mode shapes, and damping ratios, and stress and strain energies, or (b) Structural response. System Identification of the civil structure which is mostly based on structural vibration has become an major important research field due to the rapid advancement of computer and sensor technology[1]. Smartphone-based bridge system identification has advantages over the conventional monitoring techniques, such as low cost, ease of installation, and convenience[2]. Therefore, this study investigates the implementation Smartphone for system identification of major motorable single span truss bridge. This studies show the potential of using Smartphone to measure vibrations.

Vibration based technique using Smartphone have undergone significant development and been widely utilized on infrastructures, especially bridge structures. The structural elements of bridges must be visually inspected in order to identify cracks, excessive deformations, and reinforcements exposed to the naked eye. However, the elements are typically not readily accessible and although easy to perform, visual inspection is subjective because changes in the properties of the materials that compose the structural elements go unnoticed. This drawback is overcome by monitoring the structures with instrumentation, which allows inspections through the use of dynamic modal parameters. The dynamic behavior of the structural system can be understood and the need for maintenance determined by defining these parameters.

In Nepal structure health monitoring especially in bridge is rarely done. So this concept of structural health monitoring can be very advantageous in determining the health of structure. Vibration-based SHM has been explored for damage detection, model updating, performance assessment, and reliability estimation of civil engineering structures such as buildings and bridges, bringing new solutions to cope with aging and deteriorating urban infrastructure. Since bridges are of great economic as well as social valued structure, their structural health monitoring must be done. Truss bridges is a very popular bridge design that uses a diagonal mesh of most often triangle-shaped posts above the bridge to distribute forces across almost entire bridge structure.

The operational modal analysis (OMA) helps for identifying the bridge modal properties which is based the collected vibration data when the bridge is under the operating conditions. There is no initial excitation or known artificial excitation. Here the bridge natural frequencies, damping ratios and mode shapes are identified. Compared to modal analysis performed experimentally, operational modal analysis is a rapid process that does not interfere with the operation of the structure; i.e., the excitation source is already working in the system, and therefore the measured responses represent the actual operating conditions. The operational form represented the results of the entire system being analyzed; as such, this analysis is suitable for large and complex structures and can be used for the vibration control of structures and to identify damaged regions. Modal analysis can be performed via two processes. The first uses the discretization technique (finite element method), where modal analaysis is done to determine the natural frequency and time period of bridge. The second uses experimental data to define the natural frequencies, and vibrational modes. A combination of theoretical and experimental modal analysis is employed to compare natural frequencies of the bridges. The response changes with degradation of the structural components stemming from the gradual or sudden variation in the distribution and intensity of the load. Changes in the physical properties (mass, rigidity, and damping) that adversely affect the modal parameters (natural frequencies and modal shapes) of the structure lead, in general, to structural damage. In other words, structural damage can result in changes to the dynamic characteristics of the structure. FFT applied to the samples of the behavior in each case study transforms the data to the frequency-time domain. As a result, the frequency graphs show peaks that indicate the natural frequencies of the structure and verify the existence of vibrational modes. The modern smartphones with several kinds of sensors. The most popular sensors which most smartphones have are accelerometer, gyroscope, magnetometer, microphone, and camera. VibSensor is a vibration meter geared to science and engineering applications where quantitative accelerometer and vibration data are needed. It turns the mobile device into a vibrometer or seismometer, with easy collection, data storage, and email of data.

In the recent years, with the development and popularization of Smartphone, the utilization of Smartphone in determining system identification has attracted increasing attention owing to its unique feature. Compared with a wireless sensor, Smartphone's CPU are stronger in the capacity of data collection, processing, and communication. More important, almost everyone has a Smartphone, and it is convenient to operate and needs less professional requirements, which makes SHM popular in the lives of people. Although the developed countries are using this method for determining the structural health, this concept is very new for Nepal. The structural health monitoring of bridge in Nepal is a very new practice but a very effective and efficient method for system identification of bridges. Therefore the result of this thesis work is hopefully be useful for diagnosis of health of bridges and other civil infrastructures.

There are many system identification method but in this research Frequency Domain Decomposition Method is employed which overcome the existing drawback of other method and is user friendly[3]. In this research for System Identification only the first three mode frequencies are computed and compared with SAP results. The new generation Smartphone is reasonably accurate for measuring vibration in the frequency range relevant to most of the civil engineering structures[4]. The first three natural frequencies of the tested bridges can be quite accurately extracted using the data collected from Smartphone sensor[5].

2. Objective

The overall objectives of the current research are:

- To measure the acceleration of truss bridges.
- To find the modal properties of truss bridges by measuring the real time vibration.
- To find the modal properties of truss bridges by using FEM.
- System identification of typical single span truss bridge

3. Material and Method

3.1 Material

The various material, tools and application that are employed while doing these research are listed below.

- Steel tape for measuring the dimensions of the truss bridges
- Distance meter laser for measuring the height and inaccessible part of truss.
- New generation Samsung S6 smartphone
- Vibsensor application for collection the vibration data of truss bridge.
- Mat lab for Fast Fourier Transform of the obtained data for determining the model parameter of the truss bridge.
- SAP2000 for FEM modeling of truss bridge.

3.2 Method

For this research process firstly the three motarable truss bridge of single span were identified. Then the feasibility of these truss bridges for collecting the data was studied and finally the two truss bridges were selected for conducting the research. The method for this study includes the following processes. The procedural steps in this research are outlined in the flow chart of methodology given below.

3.3 Vibration Data Collection Using Smartphone

Here built-in accelerometer of a Smartphone is used for collecting data. These Smartphone devices include an accelerometer sensor. Using Smartphone, the vibration data is collected and stored in the device. An IOS app (VIbSensor) which is available at the IOS App Store is used for data collection which enables quantitative accelerometer and vibration data measurements with easy collection, data storage and transfer of data. It gives the user following five tools:

- Live Display, which allow you to see vibration data in real time
- Acquisition, which is timed or vibration activated acquisition, with settable delay, duration, and trigger level. It can collect raw accelerometer data for up to 10 min (600 s) at sampling rates up to 100 Hz.
- Data Storage, where acquired collections are stored on the device with date and time stamp for later retrieval. Collections can be named for easy identification.
- Analysis, that is each collection can be viewed to see the raw accelerometer data, processed vibration and calculated power spectral densities, both in graphical and report format. Units can be selected to be either g or m2/s.
- Email Access, which allows users to transfer raw or processed data in text (csv or tab-delimited) or MATLAB format via e-mail.

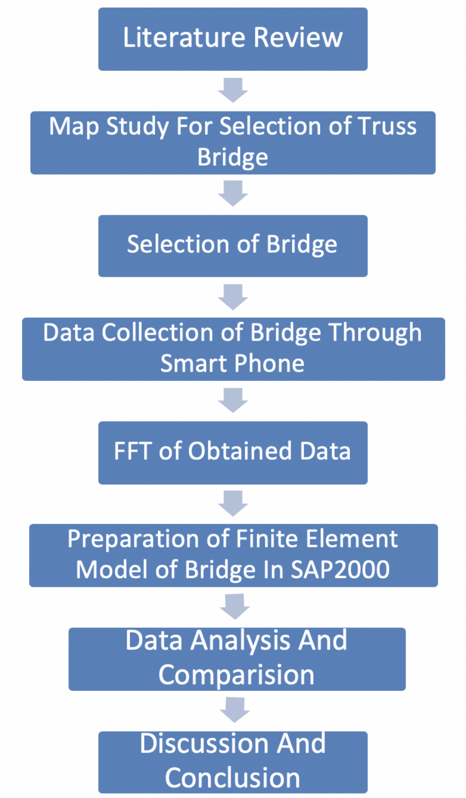

Figure 1: Flow Chart

3.4 Computation of modal properties of truss bridges

After the collection of the data by smartphone via VibSensor a transformation of the signal is required when the measurement data is recorded in time domain to obtain a representation of the signal in a frequency domain. Fourier transformations can be either performed by a Discrete Fourier Transformation or by the Fast Fourier Transformation. But the Fast Fourier Transformation reduces the computational time, which is advantageous for our analysis process. For the transformation of the data, the code Matlab is used, where the data first is imported and then by Fast Fourier Transformation the data is transformed into the frequency domain. After the transformation, the data has noise which makes it difficult to read the graphs. To reduce the noise and obtain a smoother curve in the frequency domain, a code named “pwelch” is used in Matlab, which returns a clearer and smoother curve that is easier to read by splitting the signal into segments which are multiplied by Hamming Windows. (Majala, 2017)

3.5 FEM modeling of truss bridge

Using SAP 2000 the FEM modeling of truss bridge is done and the model parameters are determined and these two model parameter are compared for determining the structural health of the bridge. Here the truss bridge component is modeled as line element. The connections between the trusses are assumed to be fixed. The transition between the rcc deck slab and truss bridge is not considered. The ends were considered embedded and the translation movement along the X, Y and Z axis were restricted along one end and translation movement along Z direction was restricted at other end for all the bridges considered.

4. Results

4.1 Data Acquisition

The VibSensor application was installed in the Smartphone and then recording interval of seven minute was set prior to data acquisition. Placement of sensor in middle of bridge span shows the most accurate data. But for the consistency seven different locations along a bridge span were selected. Then the deck surface was cleaned and Smartphone was attached at these points firmly to the deck with double tape. The main objective was to obtained undamped bridge vibration data. Here the sampling rate of 100 Hz was used for data acquisition. Then the collected data was stored in Gmail account and this raw data was extracted for further analysis. The collected raw accelerometer data in fourth position of the sensor in all bridges are presented below.

4.2 Raw Accelerometer Data

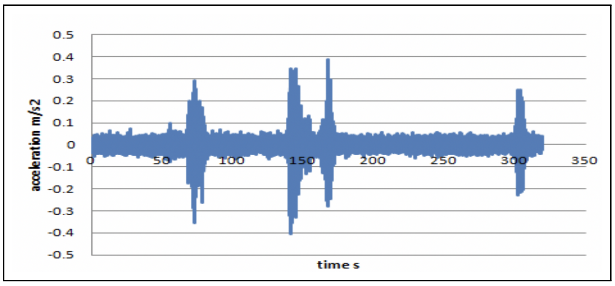

Figure 2: Raw Acclerometer data of Balefi bridge (sensor at 4th position)

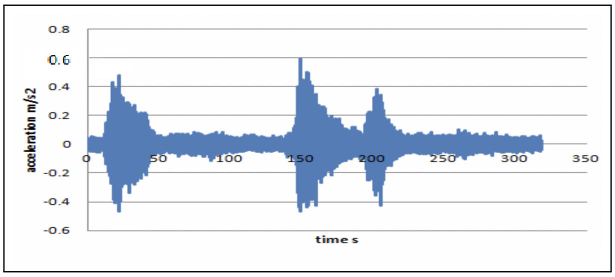

Figure 3: Raw Acclerometer data of Sunkoshi bridge (sensor at 4th position)

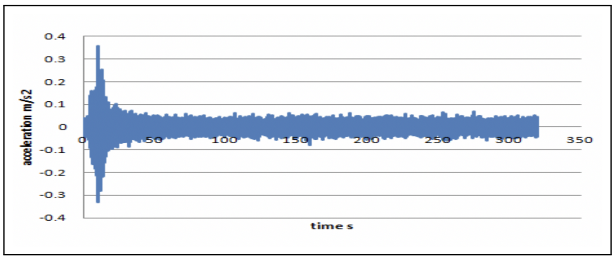

Figure 4: Raw Acclerometer data of Sukute bridge (sensor at 4th position)

4.3 Data Analysis

4.3.1 Spectral Amplitude vs Frequency of Balefi Bridge

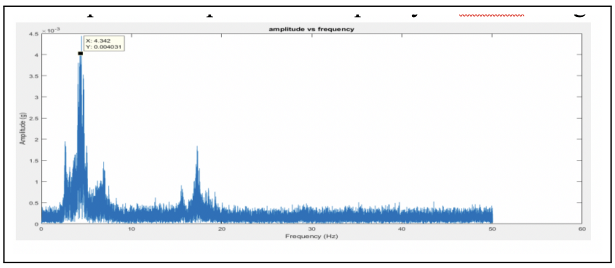

Figure 5: Spectral Amplitude Vs Frequency (Sensor at 4th position) without noise reduction

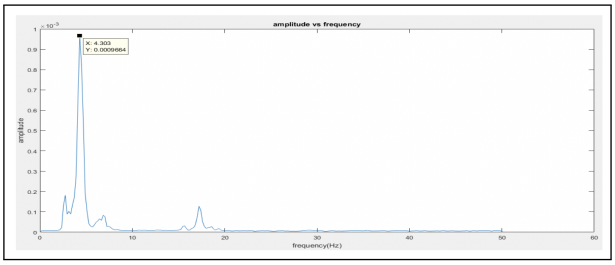

Figure 6: Spectral Amplitude Vs Frequency (Sensor at 4th position) with noise reduction

4.3.2 Spectral Amplitude vs Frequency of Sunkoshi Bridge

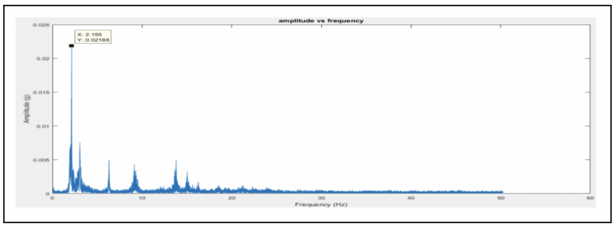

Figure 7: Spectral Amplitude Vs Frequency (Sensor at 4th position) without noise reduction

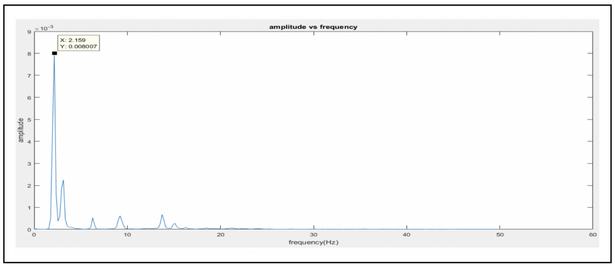

Figure 8: Spectral Amplitude Vs Frequency (Sensor at 4th position) with noise reduction

4.3.3 Spectral Amplitude vs Frequency of Sukute Bridge

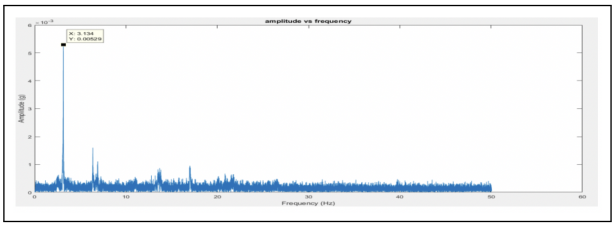

Figure 9: Spectral Amplitude Vs Frequency (Sensor at 4th position) without noise reduction

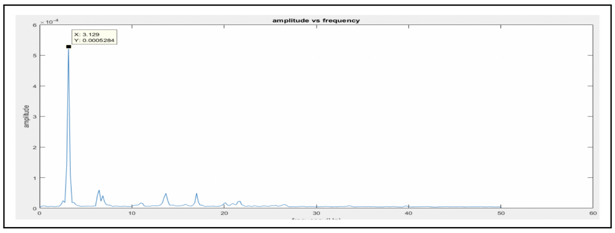

Figure 10: Spectral Amplitude Vs Frequency (Sensor at 4th position) with noise reduction

4.4 Numerical Modeling

All the data required for the modal analysis of the truss bridge were measured in the related field. For modelling Finite Element Analysis (FEA) was performed through the use of SAP 2000.

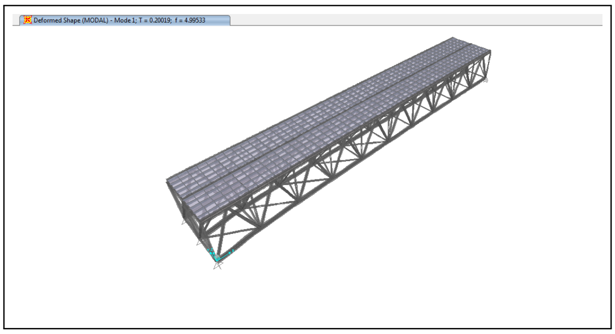

Figure 11: FEM of Balefi bridge

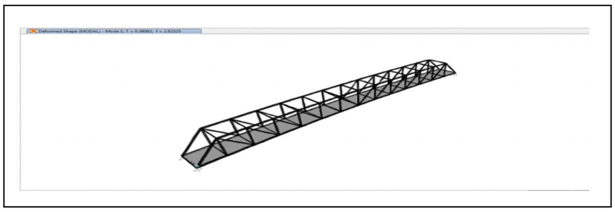

Figure 12: FEM of Sunkoshi bridge

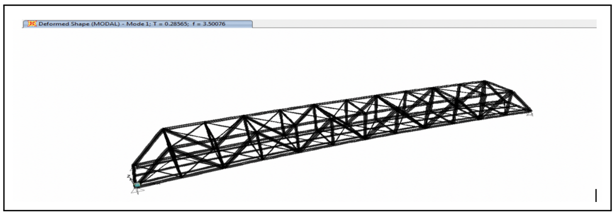

Figure 13: FEM of Sukute bridge

4.5 Numerical Modeling and Experimental Result Comparision

The summary of the result are shown in Tables 1 and 2.

Table 1: Modal properties Summary of Experimental Result From Smart Phone and FEM

S.N	Bridge	Experimental results of frequency (Hz) from Smartphone							Modal Frequencies (Hz) from FEM	Mode no.
		Setup of the Smartphone along the span								
		1st	2nd	3rd	4th	5th	6th	7th		
1	Balefi Bridge	4.305	4.108	4.303	4.303	4.503	4.514	4.502	4.995	1
		11.15	11.15	11.15	11.16	11.09	10.99	10.96	10.115	2
		12.22	12.91	12.91	12.91	12.72	12.76	12.72	13.517	3
2	Sunkoshi Bridge	2.234	2.152	2.157	2.159	2.17	2.157	2.155	2.625	1
		4.232	-	4.314	3.786	-	-	-	3.946	2
		5.889	5.674	5.686	5.731	5.72	5.667	5.682	5.23	3
3	Sukute Bridge	3.131	3.128	3.127	3.129	3.128	3.128	-	3.5007	1
		-	5.083	-	-	4.301	4.887	-	5.543	2
		6.85	6.842	6.45	6.453	6.342	6.842	-	7.007	3

Table 2: Percentage Difference of Experimental and Numerical modeling Frequencies

Bridge	*Percentage difference of closest corresponding values between experimental frequency and modeling frequency (%)*							Mode no.
	Setup of the Smartphone along the span							
	1st	2nd	3rd	4th	5th	6th	7th	
Balefi Bridge	*13.81*	*17.75*	*13.85*	*13.85*	*9.85*	*9.63*	*9.86*	1
	10.23	*10.23*	*10.23*	*10.33*	*9.64*	*8.65*	*8.35*	2
	9.53	*4.49*	*4.49*	*4.49*	*5.89*	*5.60*	*5.90*	3
Sunkoshi Bridge	*14.89*	*18.01*	*17.83*	*17.75*	*17.33*	*17.82*	*17.90*	1
	7.25	-	*9.33*	*4.05*	-	-	-	2
	12.60	*8.48*	*8.72*	*9.58*	*9.37*	*8.35*	*8.64*	3
Sukute Bridge	*10.56*	*10.64*	*10.67*	*10.62*	*10.64*	*10.64*	-	1
	-	*8.29*	-	-	*2.24*	*11.82*	-	2
	2.24	*2.35*	*7.95*	*7.91*	*9.49*	*2.35*	-	3

4.6 Discussion

In this research three major motorable single span truss bridges of Araniko highway were taken for the study purpose. With the help of smartphone and vib sensor application the data at seven different position along the span of the bridge (Balefi and Sunkoshi Bridge) and six different positions along the span in Sukute Bridge were collected. Ambient source is utilized for actuation of bridge. Then the obtained data is processed using FFT plots by using peak picking technique and the first three modal frequencies were determined in each bridge. Then modal analysis of bridge is done using SAP 2000 based on IS standard to obtain the modal frequency. Here the experimental data and numerical modeling data shows that the maximum percentage differences of different modal frequency of measured truss bridge is limited 18% .In some cases the second modal frequencies are missing in PSD plot as the second peak was relatively small so for determining such frequencies other process may have to be employed. Hence the first three modal frequencies are obtained using smartphone.

5. Conclusion

By exciting the bridges using ambient source the vibration response of the three major motorable truss bridges were collected using the Smartphone. The result shows that Operational modal analysis can be conducted in time domain for signal processing by using only output data in order to identify structural modal parameters for structures evaluation. The results can be considered acceptable and realistic. The estimation of damping is more difficult and these methods give only an approximation so we have not computed the damping. From the result obtained above we can conclude that the first three natural frequencies of the bridges can be accurately obtained using the data collected from Smartphone sensor. In some cases the modal frequencies may not seen in PSD plot due to relatively small peak so for determining such frequencies other process may have to be employed such as the Least Square Complex Exponential method (LSCE), the Autoregressive method (AR) and the Autoregressive Moving Average method (ARMA). The summaries are listed below:

- In context of Nepal, this method is very new but effective approach in system identification of not only bridges but also for various civil engineering infrastructures like buildings.
- Structural health monitoring of two major motarable truss bridges is being conducted using Smartphone technology and is interpreted using the actual FEM modeling of above bridges.
- It is found that the frequency of the truss bridge strongly depends upon the span of the truss bridge and types of the bridge construction.

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