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TOWARDS BUILDING INFORMATION MODELING-BASED AUTOMATED STRUCTURAL HEALTH MONITORING TOOL

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Abstract: In the past few decades, long-term structural health monitoring (SHM) has garnered significant attention towards retrofitting and maintenance of large-scale structures. One of the issues with SHM is to analyze a large amount of raw and processed data that must be effectively managed using appropriate tools. Building Information Modelling (BIM) is a powerful data management and visualization tool that can provide a digital environment for obtaining, sorting, sharing and recalling the data. However the current BIM based software rarely go beyond the construction phase. BIM models are treated as static information sources that contain as-built data. The main objective of this research is to take a step forward from static towards dynamic BIM by managing and representing the data of SHM systems in real-time. The workflow developed in the study serves a three-fold advantage of online visualisation of data, real-time system identification and efficient decision making. First, a 3D model of a bridge is created in Autodesk Revit and raw vibration data is collected from the bridge using the instrumented sensors. Virtual sensors are created in the BIM model corresponding to the real sensor locations of the bridge and the associated measured (collected at different period of time) data are tagged to the virtual sensor to retrieve them in future whenever needed. Lastly, by integrating system identification within the BIM model, the resulting real-time modal parameters can be used for decision making. The proposed framework enables improved visualization of SHM results from different data sets and facilitates bridge owners in real-time tracking of the bridge conditions.

1 INTRODUCTION

Structural Health Monitoring (SHM) has been an invaluable tool for detecting anomalies in critical structures such as heritage buildings or highway bridges through the measured responses (Carden and Fanning 2004, Sadhu et al. 2017). Recently developed SHM techniques focus on collecting vibration data using inexpensive sensors without a significant interruption to traffic. Even though a structure may survive a natural disaster, its serviceability needs to be evaluated in a continuous basis within a network of sensors through long-term structural monitoring (Farrar and Worden 2003, Aktan and Grimmelsman 1999). Systematic interpretation of long-term monitored data can provide valuable information to diagnose and predict damages than visual inspection-based regular maintenance. This paper utilizes building information modeling (BIM) and leverages its visualization capability to develop an automated SHM tool for improved decision making of the infrastructure owners.

Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a structure (Ren et al. 2018). BIM is not only a computer aided design (CAD) tool but also a 3D modeling and information management framework with improved visualization capability. Traditional BIM focuses on design and life cycle analysis of a new building and its construction (Arayici and Aouad 2010). Data related to building models in design and construction phase is described using industry foundation classes (IFC). It constitutes a specification that provides descriptions to model data related to all phases of life cycle of a structure (Rio et al. 2013, Liebich et al. 2013). IFC model represents tangible building components such as walls, ceiling, door, windows and abstract entities such as activities, cost, time schedules, etc. On the other hand, sensors are essential parts of SHM systems and can be represented in 3D BIM models to store SHM data. Recently, there has been significant effort in developing BIM-based SHM strategies. For example, Zhang and Bai (Zhang and Bai 2015) created a low-cost structural condition assessment device that used BIM computing environment for automated health management of civil structures. (Chen et al. 2014) achieved a dynamic BIM framework by developing a prototype to insert real-time data into the BIM model. A geothermal bridge deck-based de-icing system monitored with embedded sensors was used as a case study.

(Delgado et al. 2017) formulated a standard data model to include and visualise performance-monitoring data directly to BIM models using a pre-stressed concrete bridge. The goal was to accurately represent the SHM sensory system including damage sensitive features within the object properties (Grosso et al. 2017). The authors demonstrated the linking of SHM data to sensor representations within the BIM model. In order to manage real-time sensor data and make the BIM model dynamic, Valinejadshoubi et al. (Valinejadshoubi et al. 2017) investigated how to link BIM with external data captured by the virtual sensors. Huston et al. (Huston et al. 2016) discussed about the integration of BIM and Repair Information Decision Making Systems with SHM that involves collection, storage, transmission and processing of information obtained from visual inspection reports, sensor data, design documents, etc.

(Delgado et al. 2018) enabled the automatic generation of parametric BIM models of SHM systems and effective integration with other data sets. This study generated IFC compliant models that facilitate data exchange and long-term management of data from a fibre-optic sensor-based monitoring system. The potential of BIM in modeling SHM sensors and their optimal placement in a building was highlighted by (Valinejadshoubi et al. 2018). The current IFC schema does not support the full description of modelling related information. Therefore, the study by (Theiler et al. 2017) extended the IFC schema referred to as IFC Monitor that can facilitate the documentation of SHM systems. The proposed framework was validated by modelling a prototype wireless SHM and control. The proposed extension can model information related to aggregation of sensor node components and grouping of sensor nodes into sensor networks.

Despite the broad spectrum of existing open standard data models, the available BIM models are inadequate to fully describe, manage and visualize condition assessment data. One of the major drawbacks is the lack of a standardized neutral exchange format for sharing information among the various data software. Problem arises when attempting to extract data from sensors in many different protocols and format that sensors in real-time. Most of the BIM-related research have focused on implementation related to strain sensors, however vibration-based sensors such as accelerometers have not been explored in the literature of BIM based SHM techniques. Moreover, systematic and real-time decision making of measured dynamic data is not yet implemented within the BIM software. In this paper, the authors integrated system identification within BIM platform to develop real-time decision-making tool for SHM.

2 PROPOSED FRAMEWORK

This section provides an overview of the proposed methodology implemented to visualize the SHM information within BIM. A web-based workflow is developed to automate SHM with the help of BIM for the maintenance of large-scale infrastructure. The approach uses Revit and MATLAB as base platforms to integrate the sensor information with the diagnostic results. The dynamic behavior of the structure is then analyzed using sensor data in MATLAB. The need for data exchange using different formats can be omitted as the process is web-based which features real-time integration of data from sensors. Unlimited amount of data can be extracted and processed without the need for high performance hardware using the cloud-based approach. The collected data and system identification information of SHM are systematically embedded with the BIM software so that long-term health monitoring information can be visualized and used for maintenance and decision-making purposes.

Accelerometers are used to collect the SHM data. In order to embed the sensor data in BIM environment, accelerometers are modelled as virtual sensors with the help of IFC properties. Furthermore, system identification of the collected data associated with any virtual sensor is performed using time-varying filter-based empirical mode decomposition (TVF-EMD) algorithm. The details of the TVF-EMD algorithm can be found in the literature (Lazhari and Sadhu, 2019) and are not repeated here. Owing to its capability of analyzing a single sensor data associated with a virtual sensor, the TVF-EMD is adopted here to undertake system identification from the single-channel data. This is an automated and real-time implementation of condition assessment data of structures within BIM platform.

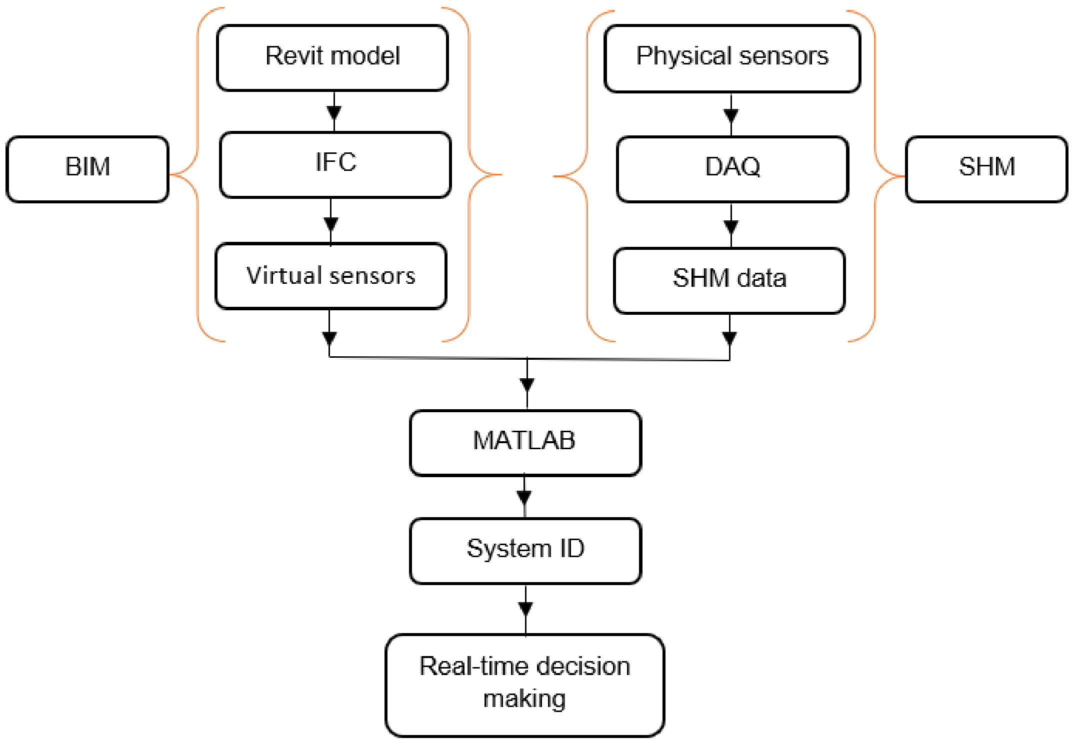

Figure 1: Proposed framework of the BIM-based SHM tool

Figure 1 shows the proposed framework that can automate the system identification and visualization of SHM data in the BIM environment. Firstly, a parametric 3D model of the structure is developed in Revit software. As the accelerometer sensors are not predefined in Revit, these are manually defined using the IFC property sets. On the other hand, the physical sensors which are connected to data acquisition system (DAQ), record the long-term monitored SHM data for structural condition assessment. The data file from each physical sensor is associated with the respective virtual sensor in Revit. System identification is performed using the TVF-EMD algorithm which is integrated in Revit model through MATLAB. The proposed framework has three-fold advantages of online visualization of data, real-time system identification and decision making by tracking identification results using data measured in different time periods. A case study is presented next to demonstrate the implementation of the developed framework.

3 CASE STUDY

The proposed framework is validated using a long-span bridge located in Thunder Bay, Ontario as shown in figure 2. This section demonstrates the application of proposed method developed in this study. The model developed in Revit is integrated with sensor information for SHM. System identification results of the SHM data are shown in a user-friendly format integrated with the visualization platform of Revit.

Figure 2: Large span bridge in Thunder Bay

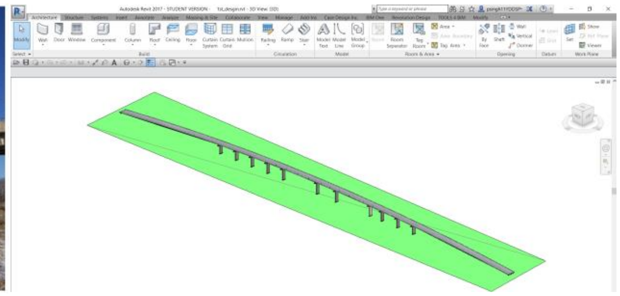

Figure 3: BIM model of the instrumented bridge

Autodesk Revit is used as a BIM tool to visualize the bridge model as shown in figure 3. Accelerometers used in this study are not predefined in Autodesk Revit. Therefore, these are manually created as a new Revit family and the corresponding sensor properties are defined within virtual sensors using IFC format as shown in figures 4 and 5.

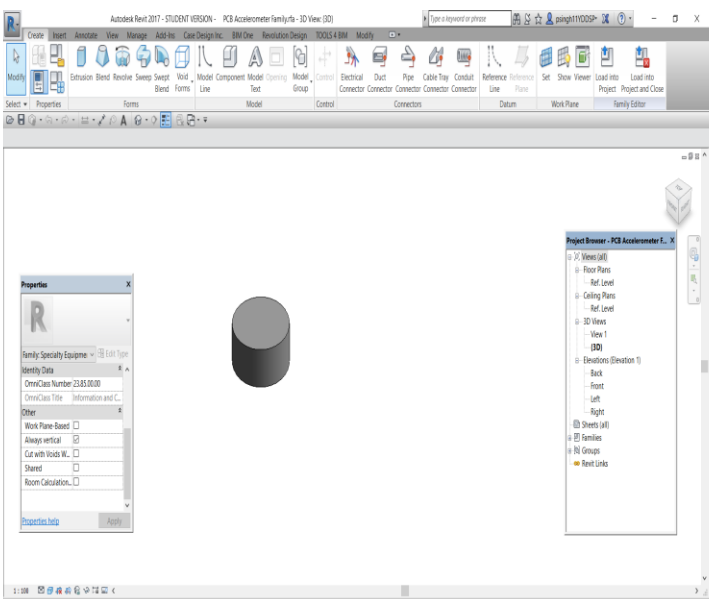

Figure 4: Virtual sensor

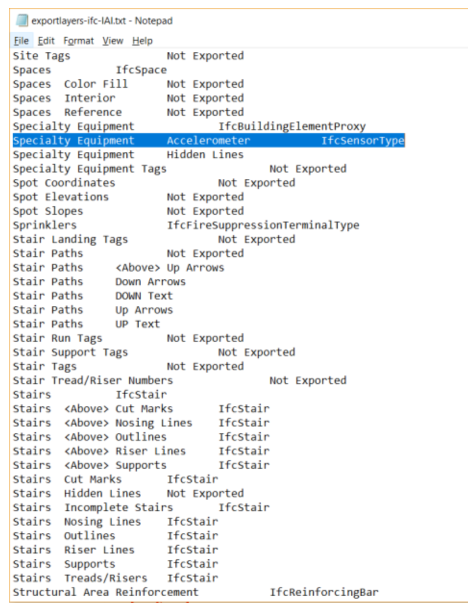

Figure 5: IFC sensor data

The bridge is instrumented with vibration sensors to collect long-term data for SHM (Barbosh et al. 2018). Ten sensors are placed along the walkway on the North side of the bridge and the sensors are set up to measure uniaxial vibration in the vertical direction. Data collection is performed through DAQ by connecting it with sensors using BNC cables and with a laptop using a USB cable. A number of vehicles travelled across the bridge at varying speeds during the tests. The duration of each test is between 30 seconds and 2 minutes and a sampling frequency of 500 Hz is used. As shown in figure 6, sensors are installed on the walkway, located close to one side of the bridge.

Figure 6: Sensors and DAQ placed on the sidewalk

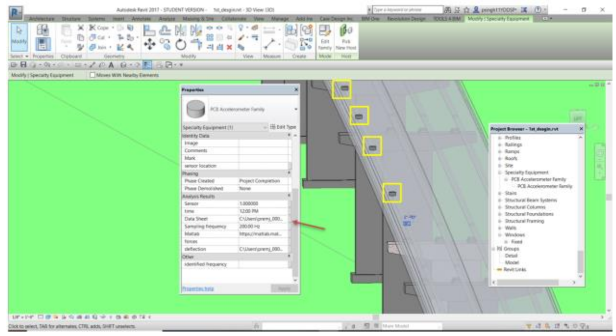

Figure 7: Virtual sensors in the BIM model

The SHM data collected by the sensors and MATLAB scripts (Mathworks, 2018) are linked with the virtual sensors modelled in Revit as shown in figure 7. By selecting a sensor, its related properties are shown in a property box which includes sensor serial number, time of data collection, SHM data sheet, sampling frequency of the DAQ, MATLAB link and measurements. Through MATLAB link, the user is taken to an online portal of MATLAB that performs system identification using the measured data assigned to a corresponding virtual sensor of the bridge at any given duration of data. In this way, the proposed framework enables automated visualization and long-term monitoring of the bridge.

4 RESULTS

The DAQ file, containing data collected by a single accelerometer, is a text file shown in figure 8. This file is linked with the virtual sensor of the BIM model for the bridge and can be accessed by clicking on the datasheet linked in the virtual sensor properties box as seen in figure 9. This text file is also uploaded in the MATLAB portal on the web along with the MATLAB scripts required for the TVF-EMD method (Lazhari and Sadhu, 2019). As the user clicks on a virtual sensor in the BIM model, its respective properties box gets highlighted which can be seen in figure 9. All the sensor information can be found in this box. By clicking on the datasheet link, the user is taken to the raw data file linked to the respective sensor in figure 8. Furthermore, upon clicking MATLAB link, the user is taken to the online MATLAB Portal that contains the necessary codes to analyse the data shown in figure 9.

QuickDAQ Data
4/23/2018 11:43:55 AM
Notes:
Sample Rate: 500 Hz
Measurement Type Time Waveform Time Waveform Time Waveform Time Waveform Time Waveform Time Waveform Time Waveform Time Waveform Time Waveform Time Waveform
Channel Name DT9857-16(00).Ain 1 DT9857-16(00).Ain 2 DT9857-16(00).Ain 3 DT9857-16(00).Ain 4 DT9857-16(00).Ain 5 DT9857-16(00).Ain 6 DT9857-16(00).Ain 7 DT9857-16(00).Ain 8 DT9857-16(00).Ain 9 DT9857-16(00).Ain 10
X Axis Units Sec Sec Sec Sec Sec Sec Sec Sec Sec Sec
Y Axis Units cm/s^2 cm/s^2 cm/s^2 cm/s^2 cm/s^2 cm/s^2 cm/s^2 cm/s^2 cm/s^2 cm/s^2

Time	Real	Real	Real	Real	Real	Real	Real	Real	Real	Real
0.00000E+000	8.45551E-004	-1.30057E-004	0.0017833710	7.10011E-004	-4.48227E-005	7.96318E-005	5.94616E-004	2.54154E-004	-8.15868E-004	8.46386E-005
0.0020000000	9.36389E-004	8.56519E-004	0.0024905205	0.0012851954	0.0012778044	-3.74198E-004	5.46455E-004	2.17915E-004	-6.75917E-004	1.32084E-004
0.0040000000	2.43187E-004	7.91550E-004	0.0041719675	0.0027663708	-0.0010470152	-8.24928E-005	3.54171E-004	-4.83990E-005	-6.62208E-004	1.08957E-004
0.0060000000	-2.00152E-004	-8.46028E-004	2.15530E-004	-3.88980E-004	-2.62976E-004	7.39813E-004	5.09858E-004	-2.98142E-004	-8.03232E-004	2.98023E-005
0.0080000000	1.90973E-004	-5.85198E-004	0.0010221004	3.98040E-004	0.0020052195	1.89543E-004	6.48022E-004	-1.18494E-004	-8.85487E-004	-1.94311E-005
0.0100000000	1.72734E-004	-2.89202E-004	-0.0012733936	0.0025326014	7.08461E-004	-4.99487E-005	4.28081E-004	1.00374E-004	-7.20382E-004	-6.33001E-005
0.0120000000	6.91295E-004	1.93596E-004	0.0031516552	0.0011467934	1.34587E-004	-2.90036E-004	5.10216E-004	6.84261E-005	-5.57065E-004	-1.18494E-004
0.0140000000	6.33836E-004	-4.24266E-004	-0.0022313595	-0.0017038584	3.01242E-004	2.56300E-004	6.60062E-004	-3.34978E-004	-4.58360E-004	-1.47462E-004
0.0160000000	3.01600E-005	-5.68151E-004	-7.71165E-004	0.0019199848	2.05278E-004	8.32081E-005	5.80311E-004	-3.98278E-004	-4.46916E-004	1.09911E-004
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0.0200000000	2.66552E-004	1.49012E-004	-0.0031000376	-9.40800E-004	-1.05023E-004	-2.11716E-004	-4.55379E-005	1.00136E-004	-9.77516E-005	1.30534E-004
0.0220000000	4.73499E-004	2.35677E-004	0.0015865564	0.0015057325	6.17504E-005	-3.03507E-004	2.34842E-005	-2.00629E-004	-1.21593E-005	-3.33786E-005
0.0240000000	0.0010833740	2.82049E-004	0.0011771917	6.87838E-004	0.0021800995	-1.96695E-004	2.84791E-004	-2.98738E-004	-8.61883E-005	-1.06215E-004
0.0260000000	2.61903E-004	5.50628E-004	-0.0023647547	-0.0014531612	0.0021746159	5.99742E-004	-1.62363E-004	-6.04391E-005	-2.12193E-004	-2.61068E-005
0.0280000000	1.41382E-004	8.38518E-004	-0.0010669231	0.0018531084	-4.45724E-004	2.74777E-004	-5.78880E-004	-9.40561E-005	2.33650E-005	3.69549E-006
0.0300000000	6.05583E-004	5.36442E-004	0.0017049313	4.89712E-004	3.68118E-004	-2.89679E-004	-4.03643E-004	-1.29104E-004	2.95758E-004	-4.72069E-005
0.0320000000	2.24829E-004	-2.83599E-004	8.41856E-004	0.0018889904	0.0011317730	-5.51820E-004	-4.50015E-004	-4.96984E-004	2.24829E-004	-4.41074E-005
0.0340000000	-4.44412E-004	-1.65939E-004	-0.0016826391	0.0020889044	-3.25918E-004	3.42846E-004	-3.97682E-004	-3.45826E-004	2.28405E-004	3.27826E-005
0.0360000000	-7.60913E-004	4.38333E-004	8.36372E-004	-0.0021369457	-1.75238E-004	3.99470E-004	-5.61714E-004	-2.15888E-004	3.44634E-004	1.94311E-005
0.0380000000	-6.47306E-004	-3.03030E-004	5.82814E-004	7.61032E-004	0.0011739731	2.61903E-004	-6.03914E-004	-2.98738E-004	4.79579E-004	-2.78950E-005
0.0400000000	-3.03388E-004	-9.66549E-004	0.0014702082	0.0031212568	-7.10726E-004	8.90017E-004	-4.25458E-004	-2.97070E-004	5.27859E-004	-8.82149E-005
0.0420000000	-3.16381E-004	-5.36203E-004	-0.0016140938	-0.0012080669	6.40035E-004	2.60234E-004	3.57628E-005	1.89900E-004	4.46796E-004	-6.33001E-005
0.0440000000	-4.36425E-004	3.49522E-004	8.98004E-004	-0.0030224323	0.0041060448	3.31640E-004	-3.11852E-004	-1.56164E-004	5.78523E-004	2.02656E-006
0.0460000000	-1.45912E-004	-1.16587E-004	3.76701E-004	0.0010272264	0.0021672249	4.45724E-004	-5.21541E-004	-3.77536E-004	6.89268E-004	-8.24928E-005
0.0480000000	1.69277E-004	-2.16246E-004	0.0036746264	-8.54731E-005	5.38945E-004	-5.87225E-004	-8.62122E-004	-4.38809E-004	7.80463E-004	-2.30074E-005

Figure 8: Visualization of the acquired data

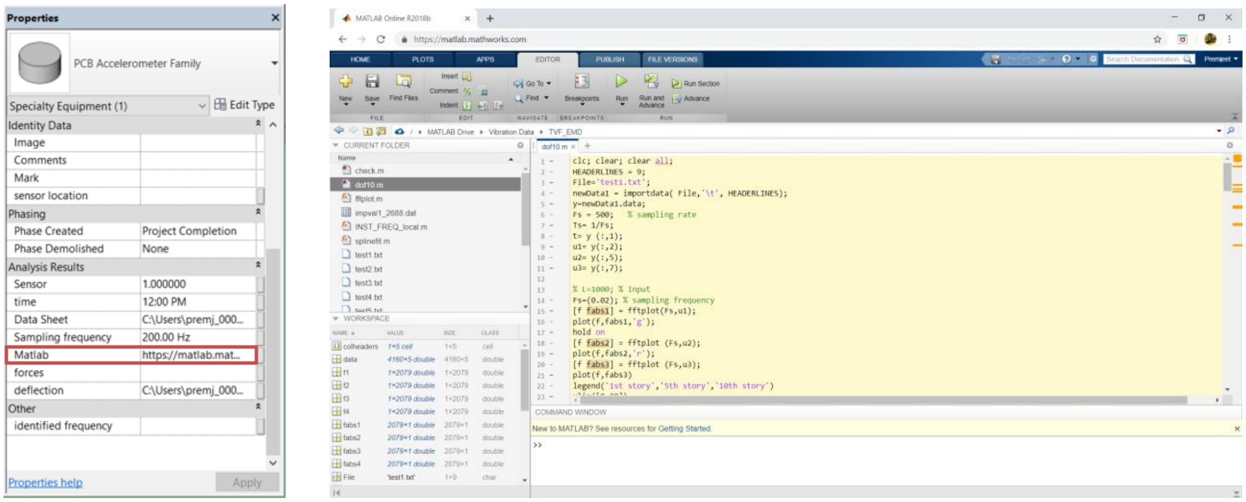

Figure 9: Execution of system identification within Revit using MATLAB's online portal

The framework presented in this study is used to perform the modal identification using a single sensor measurement. The proposed method successfully extracts the mono-component modal responses. The resulting intrinsic mode function (IMF) components (i.e. extracted modal responses) can be seen in figure 10 obtained from the TVF-EMD method. After finding the modal responses, auto-correlation function of the modal responses can be used to extract the damping ratio. The identified frequencies and damping ratio values obtained from a typical sensor using the TVF-EMD method are tabulated in table 1.

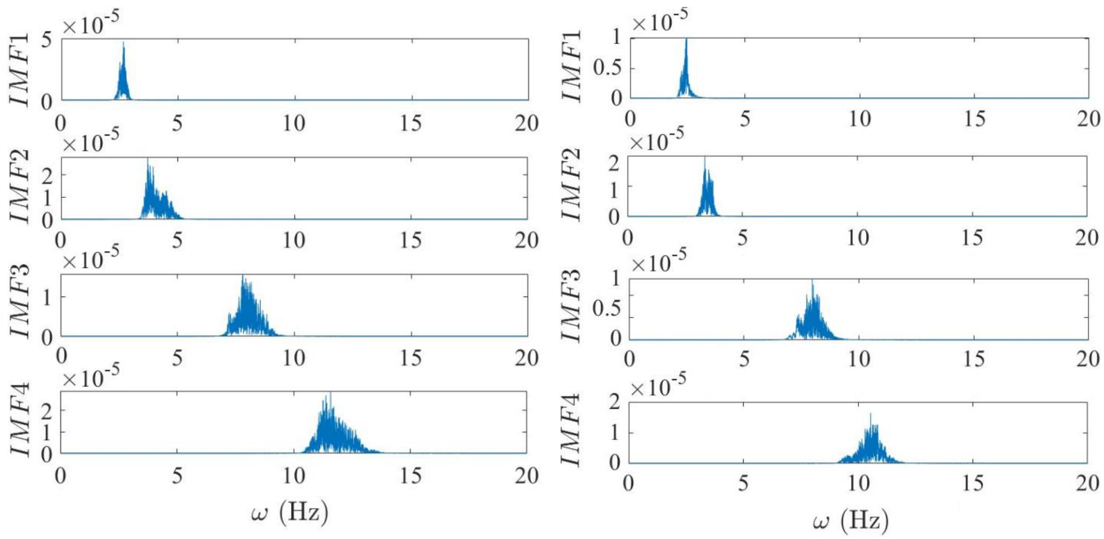

Figure 10: Fourier spectra of the IMFs from two virtual sensors

Table 1: Identification Results

Mode#	1	2	3	4
Frequency (Hz)	2.65	3.71	7.78	11.59
Damping ratio (%)	0.42	0.30	0.14	0.096

5 CONCLUSIONS

This study is intended to develop a fully adoptable work flow for the maintenance of infrastructure. A web-based work flow is developed to automate the long-term monitored SHM data with the help of BIM. The need for data exchange using different formats can be omitted as the process is web-based which features real-time integration of data from the sensors. Unlimited amount of data can be extracted and processed without the need for high performance hardware of any cloud-based approach. With the approach based on the internet that does not require a list of software to be installed in each computer, it improves the software interoperability and thus frequent communication which is required on transportation infrastructure. Accelerometers used for the vibration data and embedment of such data with BIM are attempted in this study. Furthermore, system identification of the collected data is integrated within the BIM model. Integration of BIM and SHM through a cloud-based service provides a user-friendly interface as well as better diagnosis of the structure. Real-time system identification, online visualization of data and efficient decision making are the main contributions of this case study. It is an effort to create a model that shows the sensor information and system identification results of data measured at different periods of time. Such model can be used to predict the behavior of the structure whether a rehabilitation is needed in the near future or not.

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