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Structural Health Monitoring of Buildings and Infrastructure

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Abstract**—**Structures such as buildings, bridges, dams, wind turbines etc. need to be maintained against various factors such as deterioration, excessive loads, environment, temperature, etc. Choosing an appropriate monitoring system is important for determining any critical damage to a structure and address that to avoid any adverse consequence. Structural Health Monitoring (SHM) has emerged as an effective technique to monitor the health of the structures. SHM refers to an ongoing structural performance assessment using different kinds of sensors attached to or embedded in the structures to evaluate their integrity and safety to help engineers decide on rehabilitation measures. Ability of SHM in identifying the location and severity of structural damages by considering any changes in characteristics of the structures such as their frequency, stiffness and mode shapes helps engineers to monitor the structures and take the most effective corrective actions to maintain their safety and extend their service life. The main objective of this study is to review the overall SHM process specifically determining the natural frequency of an instrumented simply-supported concrete beam using modal testing and finite element model updating.

Keywords**—**Structural Health Monitoring, Natural Frequency, FFT analysis, Finite element model updating.

I. INTRODUCTION

DUE to inadequate inspection and insufficient quality of visual monitoring in some critical infrastructures such as tall buildings and long-span bridges, prevalent structural issues such as corrosion of reinforcing bar and steel components, other internal defects may be overlooked. Therefore, using an effective monitoring system such as SHM can solve this issue.

According to ISIS Canada Research Network [1], SHM refers to the broad concept of assessing the ongoing, in-service performance of structures using a variety of measurement techniques.

All structures made by human beings have limited life spans and they begin to degrade as soon as they are built and put into service. Therefore, examining and monitoring of critical structural assets at periodic or continuous level to do the remedial action whenever it is needed is important for maintaining the structure in a good condition and extending its service life. SHM is applied in various civil engineering structures such as buildings, bridges and highways [2].

Although there are other assessment techniques for a structure such as None- Destructive Testing (NDT) and Non-Destructive Evaluation (NDE), they all refer to a one-time structural condition evaluation, while SHM is implemented as a real-time and ongoing structural assessment technique. While some owners of civil infrastructure may still be reluctant to use SHM due to the cost, but SHM system has proved that it can help in optimizing the life cycle cost of a structure by reducing the maintenance frequently when possible and continuous inspection costs, downtime cost etc. Recent and ongoing advancements of sensors and need for verifying the integrity of innovative designs and new materials have led to an increasing in the application of SHM in the construction industry.

Monitoring the significant factors such as load, deformation, strain, crack initiation etc. in key structural elements can guarantee the extension of the structures' service life by maintaining them in a good health condition. Therefore, making SHM intelligent using advanced sensors, appropriate data interpretation and analysis will be able to examine and evaluate structural damage-related factors, send alarms to engineers when required to make remedial actions and archive the analyzed data in database for future retrieval [3].

The other significant parameters of a structure are its mass and stiffness which need to be determined for calculating the natural frequency of the structure. Natural frequency is significant to be determined to prevent resonance. Resonance is a phenomenon which occurs when frequency of the seismic waves matches the natural frequency of a building which can lead to the failure of the structure. Finite element model updating is also another important step in SHM process used to establish stiffness reductions due to damage for health monitoring and condition assessing [4].

The main objective of this study is to investigate how to determine the mass, stiffness and natural frequency of an instrumented structural element, and perform the modal analysis and finite element model updating of a simply-supported concrete beam in service.

II. SHM ELEMENTS

Each system must have elements to become and maintain a system. An SHM system includes of hardware and software elements [5]. The hardware elements include the sensory system and their instrumentations (sensors, wiring, junction boxes, conduits, Data Acquisition System etc.) and the software elements consist of data acquisition, damage modeling and damage detection algorithms, and data

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interpretation and analyzes software. These algorithms should be chosen appropriately to be used effectively. For instance, well thought out data acquisition algorithms can capture an adequate amount of data.

There are two types of sensors in terms of receiving and transmitting data including passive and active sensors. Passive sensors are those which only receive signals such as conventional strain gauges while active sensors such as Poly Vinyle Dy Floride (PVDF) sensors, piezoceramic (PZT) sensors or Fiber Optic Sensors (FOS) not only sense and receive the signals but also have the ability of transmitting them [5].

There are various types of sensors used in SHM for different applications. Load cells installed within a structure are applied to determine whether the loads, concentrated or distributed, are as expected according to the design or not. Displacement transducers and tilt meter are used to measure excessive deformation although appropriate reference point for the transducer is still an issue [1]. Different kinds of strain gauges including standard electrical resistance strain gauges, vibrating strain gauges or developed FOS measure the magnitude of the strain which is the most common measurement used in SHM system. Some other sensors measure environmental effects such as temperature which can reduce the performance of the sensors by affecting on their outputs and produce thermally induced loads. These temperature sensors include thermocouples, thermistors and integrated temperature circuits. Recently, they have also been applied for energy efficiency purposes as well. Acceleration is a significant parameter mostly used for important structures or for those located in seismic regions and sometimes in non-seismic regions. Accelerometer sensors are typically used to measure the acceleration on the structures through determination of the modal response parameters. Wind sensors such as anemometers are used for tall buildings and long-span bridges.

With the development of wireless technologies, conventional wired sensors are gradually replaced by wireless sensors to avoid long lead wires which sometimes lead to errors resulting from electromagnetic interference (EMI), especially in the presence of high-voltage power lines or radio transmitters [1]. But, wiring method is still largely used where the structures are not so large. After capturing data by sensors, data will go transfer to the Data Acquisition System (DAS). As mentioned before this transferring can be in the form of wiring or wireless. The purpose of any data acquisition system is to collect valuable measurement data for classification, monitoring, or control [6] and digitize the information for entry into a digital computer. In data acquisition system first physical variables such as temperature, pressure, motion etc. are received from the sensors. Then transducer device converts these physical variables to the electrical signal. After that some operations such as filtering, excitation, signal sealing, implication, calibration etc. are performed to improve the quality of transducer generated signals [7]. Next, the analog signal must be converted to the digital data to enable the computers to store them (data digitization). At the end, digitized data are transferred to be stored for damage detection. After damage detection and localization using damage modeling and some kind of algorithm, the data are transferred for storage. After storing data, they should be handled and managed. Data management becomes more important when a single vibration measurement typically consists of hundreds of samples from each sensor. Therefore, in time domain approach, the amount of data becomes excessive and data management process becomes harder [8].

III. SHM SYSTEM DESIGN

Each system needs to be designed. Without any design, it does not work appropriately. Accurate and strong SHM design will guarantee to increase its performance and make them more efficient. But the successful design of SHM systems needs to consider different aspects such as physical constraints, sensing capabilities and installation constraints, economics, human interfaces etc. [9]. But, the important matter is that how to make interaction between these entities to reach the best result. In each successful SHM design, appropriate task definition is important. These tasks indicate what the engineers expect from the SHM system and what constraints may exist during the operations. List of some tasks which may have effect on the SHM system design are follows [9]:

- **Aesthetics**: Using weldable and bondable sensors may bring aesthetic concern. The sensors should be installed on the structure somehow they have minimal visual impact.
- **Calibration**: Calibration is defined as an act of determining or adjusting an instrument's readings. So, the matter that SHM system requires self-calibration or recalibration or pre-installation calibration can affect SHM system design.
- **Cost**: For each system, the cost of its whole life cycle such as installation, operational and maintenance costs. Regarding SHM system, sensors cost is not as much expensive as their installation.
- **Serviceability**: Factors such as test duration, environment and loading conditions will affect the choosing of sensors. For example, in long duration testing, being in harsh environment and in the conditions when the monitored building's components are subjected to severe loading, choosing the most appropriate sensors to sustain these conditions is critical.
- **Installation**: The situation whether sensors are installed in the new constructed structure or are used in rehabilitation process has different SHM system design. The differences can be using different kinds of sensors, place of installation or installation methods.
- **Maintenance and repair**: The systems need maintenance but based on their sensitivity and applications, the maintenance methods may be different that needs appropriate consideration on their design. For example, in harsh environment, the issues which accept different kinds of design is that whether it is worthwhile and

affordable to use repairable, more expensive and reliable sensors or not.

- **Measurand:** The situation that the SHM system measure one parameter or more will cause additional design complications due to using different kinds of sensor.
- **Purpose of the SHM system**: for which purpose, the SHM system is implemented will have effect on the SHM system design. For instance, if the SHM system just intends to detect the damage, localizes damage other than damage detection, or that estimates the remaining service life other than damage detection and localization, all of them have their own design type and it will be more complex respectively.
- **Security**: They way and method of protecting captured and analyzed data should be considered in the SHM system design.
- **Energy consumption**: Since the SHM system refers to ongoing or repeated assessment of the structure [1], an appropriate energy management technique should be considered during the design process to provide the energy required for each sensors. The most efficient way is to design a mechanism using renewable energy sources such as solar or wind energy to automatically provide the energy required for the sensory system.

IV. RESEARCH METHODOLOGY

A simply supported concrete beam of 7 m span was constructed by ISIS Canada Research Network in an outdoor location and instrumented for SHM purpose. Concrete has 35MPa compression strength at 28 days. Three kinds of sensor including eight strain gauges, two thermocouples, and one accelerometer were used in this case study. In terms of their placement, four strain gauges at the middle of the beam and two strain gauges at each corner were placed. One thermocouple was placed at each corner, and one accelerometer was placed at the middle of the beam. A number of regularly-spaced concrete blocks were placed on the beam as superimposed dead loads, and some dynamic tests were conducted before and after placing the blocks. Fig. 1 shows the beam with sensor details.

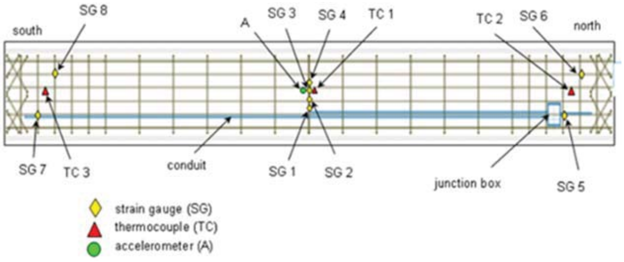


Fig. 1 Diagram of the beam with sensors details

This study has two sections. In section one, natural frequency of the beam before and after placing the concrete blocks are determined using FFT analysis to estimate the values of flexural rigidity of the beam and the equivalent distributed mass of the concrete blocks by using its natural frequency in each situation. In section two, modal analysis of the beam is carried out and the difference between the analytical and experimental frequencies is determined to do the finite element model updating process. For these purposes, MATLAB software called M-FEM, developed in [10] was used in this study.

V. PLACEMENT OF SENSORS

The moisture and oxygen could penetrate from the soil through concrete and cracks and then the corrosion could propagate in the concrete beam. We assume that the monitoring system include thermocouples, strain gauges and accelerometer.

One of the purpose of using thermocouples in SHM system may be monitoring the difference of interior and exterior concrete temperature, since the big difference in temperature will cause cracks. The number of thermocouple could be more than two for a beam, since they can be easily damaged during concrete placement. The other matter is that they should be placed near to the beam surface, because the temperature-change rate of the structural section is greatest near the surface but diminishes toward the center and thermal contraction on the concrete's surface will cause thermal differential and cracking. Regarding the placement of thermocouples, it should be noted that installing them symmetrically can be more effective, since it is the best way in the symmetrical section. And installing them near the joints is helpful as well, because joints are the most effective points to control cracking. One of the reason of installing thermocouples near other sensors is that changing temperature may affect the sensor readings or sensing equipment.

Strain gauges are generally used to determine the strains produced by various kinds of loads. The beam is subjected to different loads such as concrete blocks' load etc. As mentioned earlier, eight strain gauges were used for SHM implementation which half of them were installed in the middle of the beam where the deflection under the distributed load is the highest. Strain gauges should be positioned so that its long axis is parallel with the axis of loading. The strain gauges should be installed along the neutral axis of the beam to eliminate false readings.

Accelerometers are used to measure acceleration due to vibration of a structure. It can send the data in the form of signal to Data Acquisition system (DAQ) where then will be converted from time domain to frequency domain for better and easier analysis. As mentioned, there is just one accelerometer installed in the middle of the beam to record any vibration produced by some dynamic tests. It is used to avoid any negative dynamic effects such as resonance frequency which will lead to beam failure. The accelerometer can be easily damaged by impulsive forces.

VI. NATURAL FREQUENCY BEFORE PLACING THE CONCRETE BLOCKS

Data from two dynamic tests were used in this study to analyze the beam before and after placing the concrete blocks.

Acceleration data captured from the accelerometers in a dynamic test are time domain. For analysis, they have to be converted to frequency domain. Fast Fourier Transform (FFT) is used to do this conversion. FFT is an algorithm to compute Discrete Fourier Transform (DFT) and its inverse. It can spectrally decompose the signal from a vibration experiment. The results of the FFT will be used to calculate resonant frequencies in a structure which might cause the structural failures. For getting extremely accurate result, from the acceleration data, the most important periods of time and their data with higher changes should be selected in the Excel file, and FFT analysis for each of them should be implemented separately to determine their natural frequency and at the end, the calculated frequencies must be averaged.

The duration of the test was 5 minutes and 55 seconds and data sampling rate was 64. Sampling rate is defined as the number of data points per second. It means that in each second 64 numbers of data were recorded by accelerometer. After selecting the most important range of data FFT analysis was performed, and the average natural frequency was determined to be about 6.58 Hz. Fig. 2 shows the FFT analysis result plotted in MATLAB for one of the ranges of accelerometer data.

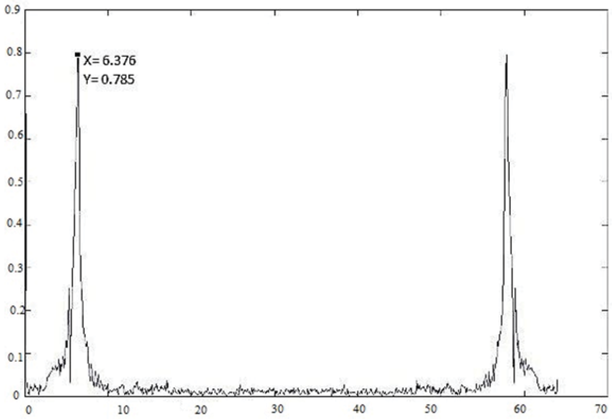


Fig. 2 Fourier spectrum of one of the selected ranges of accelerometer data

VII. Natural Frequency after Placing The Concrete Blocks

After doing some dynamic tests on the beam, several concrete blocks were installed on the beam as superimposed dead load, and with this added mass, dynamic tests were conducted on the beam its natural frequency was determined. It should be noted that the amount of data for FFT analysis must be in the form of "2^n", otherwise the amount of data in each analysis must be modified. For example, if the amount of data is 1031 records, it must be changed to 1024 numbers. Six ranges of data were captured from a SHM test and their frequency were determined 5.3, 6.5, 6.375, 6.25, 6.375 and 6.5 Hz respectively using FFT analysis in MATLAB. Therefore, the average frequency is about 6.22 Hz.

By comparing the beam's natural frequency before and after installing concrete blocks (case 1=6.58 Hz and case 2=6.22 Hz), it is obvious that natural frequency after installing concrete blocks is reduced by about 0.36 Hz due to increase in the mass. As the mass increases, the natural frequency of the system decreases as shown in (1):

$$fn = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

where: f_n = natural frequency in hertz (cycles/second); k = stiffness (Newton/meter or N/m) = $(48EI)/L^3$; m = mass (kg).

VIII. Estimating The Flexural Rigidity

A concentrated mass (68 kg) was applied on the beam while performing the dynamic test. The beam's cross section is irregular and the mass of beam with concrete blocks is to be estimated. For this purpose, first we have to estimate the dimensions of the beam's cross section using the test data before and after placing the concrete blocks. First, we assume that the dimensions of the cross section of the equivalent rectangular beam are (400mm wide) x (250 mm deep). By calculating E_c (Modulus of Elasticity of concrete) and I (Moment of inertia), flexural rigidity EI of the beam is calculated. Then, by using (2), the stiffness of the beam is calculated as 1940405 N/m.

$$\mathrm{K}=\frac{48\,EI}{\mathrm{L3}} \tag{2}$$

The total mass of the beam is calculated 840 kg, which is distributed over its length, and the concentrated mass at the mid-span of the beam (M_{con}) is 68 kg, therefore the total mass before installing concrete blocks is 908 kg. By using (1), and the mass and stiffness of the beam, its natural frequency was determined to be 7.36 Hz. But when we compare this value with the natural frequency of the beam before installing concrete blocks (6.58 Hz), we see that they are not equal. Hence, the dimensions of the beam must be modified. After examining different dimensions, finally the dimensions (370mm wide) x (225 mm deep) were selected for the beam's cross section to have a constant EI and K. As determined earlier, the natural frequency of the beam after concrete blocks installing was 6.217 Hz. Stiffness (K) for the modified dimensions was calculated about 1308463.7 N/m. Using the magnitude of the frequency of the beam after concrete blocks installing, concrete blocks' mass was determined 90.21kg using (1).

There may be different of factors causing this kind of frequency spectrum. One of them may be existing the precision error. It may be due to temperature effect (cold weather, freezing), environment (snow), electrical and magnetic noise due to wiring. These effects can be mitigated by protecting of measuring system, etc. If we ignore the sharp peaks in Fig. 3, we see that between 10 and 120 hertz, the signal includes a flat region. This is termed white noise because it consists of an equal amount of all frequencies.

It results from the noise on the time domain waveform being uncorrelated from sample-to-sample.

In signal processing, white noise is a random signal with a constant power spectral density. Frequency damage indicator can be used which one of its main advantages is its filtering nature. The situation can be happened due to the measurement error as well. One of the actions which should be implemented is structural model update. In structural model update some of the key parameters such as mass, stiffness, etc. are modified to achieve an agreement between the responses of the analytical model. It might be possible that the accelerometers had been affected by some external noise and parameters that recorded these abnormal data. In general, some preventive actions should be taken into account to mitigate the errors in data acquisition process from the sensors.

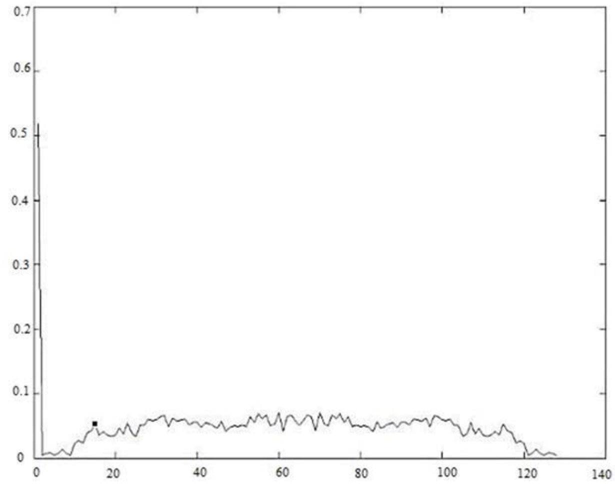


Fig. 3 Unusual frequency spectrum of acceleration data

IX. MODAL ANALYSIS AND MODEL UPDATING

In this part, a finite element model of the beam was constructed using M-FEM [10]. After analysis, output will be in txt format to indicate all the analysis results such as the difference between the analytical and experimental frequencies, etc. In this section, modal analysis of the beam is carried out using M-FEM program, and any changes between the analytical and experimental frequencies is reported and their difference is reduced by adjusting the beam dimensions. The model updating procedure implemented in M-FEM was developed in [4].

Several parameters such as number of beam elements, number of nodes to link the beam elements to each other and their coordinates, number of boundary conditions and their details, number of frequency, material properties, modulus of elasticity of concrete (assumed 24 GPa), shear modulus (assumed 10GPa), Possion's Ration (assumed 0.3), mass density of the beam, beam's cross sectional area and moment of inertia, the lower and upper limit of stiffness in terms of model updating, frequency limit, number of analysis must be used for creating the beam's M-FEM model. It should be noted that all above data must be used based on the specified sequence, otherwise the program is not run. To calculate the equivalent mass density, (3) was used:

$$P_{equiv} = P_{concrete} * (M_{beam} + M_{concrete\ blocks} + 2*M_{conc})/M_{beam} \quad (3)$$

By using the values determined in previous sections, the equivalent mass density of the case-study beam was obtained 3176 kg. By considering the identified cross section dimensions of the beam, the cross sectional area and moment of inertia (I_z) of the beam were calculated 0.083 m^2 and 0.00035 m^4 respectively. For model updating limits, the lower and upper limits of stiffness were chosen 0.6 and 1.4 respectively. Frequency limit was chosen 0.5 which means if the difference of frequencies (analytical and experimental frequencies) reaches to 0.5%, then the analysis will be stopped. For the number of analysis, 200 steps was considered. In terms of measured frequencies, two values of 6 and 23 Hz were assumed.

After analyzing the beam by M-FEM program [10], the beam was modeled and its two mode shapes (based on two assumed experimental frequencies) were plotted as shown in Fig. 4.

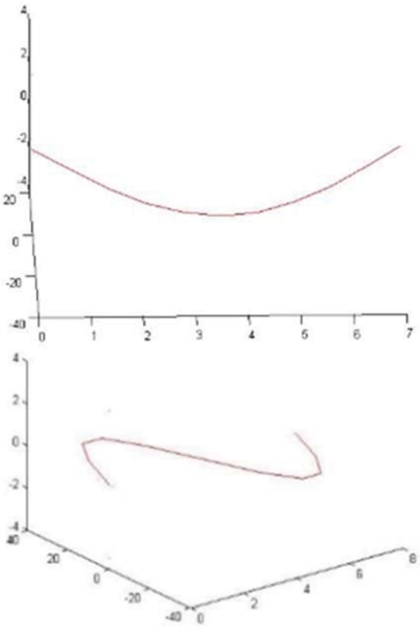


Fig. 4 Mode shapes of the beam

After modal analysis of the beam, model updating was done based on the input values. After it is completed, the program reports the difference between analytical and experimental frequencies. For the first model updating, program reported 0.4222 HZ that was the maximum difference in frequencies. At this step, although MATLAB shows the results, but the analysis results will be saved in text format as well that is more accurate where the difference between the analytical and experimental frequencies can be investigated separately. Furthermore, the program also plots the stiffness adjustment factors for all elements showing that the properties of which elements must be modified (increase or decrease) to make their stiffness closer to one. Figs. 5 and 6 indicate the stiffness adjustment factors, β and text file created by the program, respectively.

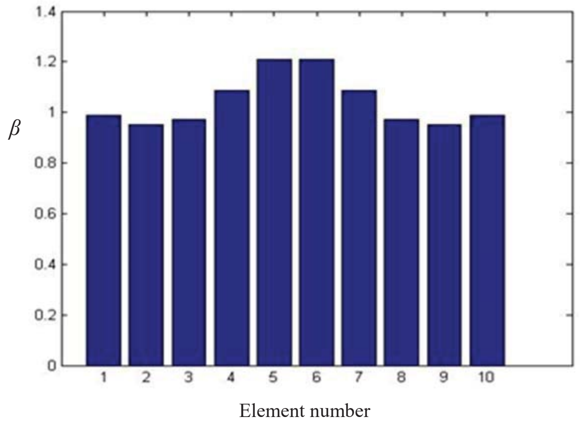
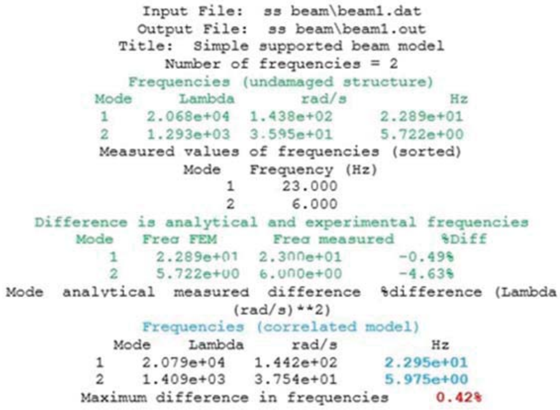


Fig. 5 Stiffness adjustment factors of all defined elements for the first analysis

As shown in Fig. 5, sectional properties such as the values of moment of inertia in some elements, specifically elements 4, 5, 6 and 7, must be changed to obtain an agreement with experimental response. In Fig. 6, green lines show the FEM (Finite Element Model) and experimental frequencies and their difference. As shown, FEM frequencies are 22.89 and 5.722 Hz while the measured (experimental) frequencies as mentioned earlier are 23 and 6 Hz. Blue text shows the frequencies (22.95 and 5.975 Hz) calculated using the FE model after the model updating process. As can be seen, the program carried out the model updating and tried to match the FEM and experimental frequencies together. As shown, the analytical and experimental frequencies 1 and 2 have 0.49% and 4.63% difference. But the red number indicates the maximum difference in analytical and experimental frequencies. Although the difference of analytical and experimental frequency values of mode 1 is not considerable (0.49%), but for mode 2 the difference is considerable (4.63%) and must be reduced. In next step, we will try to reduce the differences by dividing the beam into three segments and changing their moment of inertia values for each of them.

X. MODEL UPDATING

In this section, the beam was divided into three segments (segment 1: Element 1 to 3, Segment 2: Element 4 to 7 and segment 3: Element 8 to 10). Their material properties must be the same but the moment of inertia (I_z) values for each segment must be different. But since segment 1 and 3 should be symmetric, the moment of inertia of segment 1 and 3 must be the same.



```
              Input File:  ss beam\beam1.dat
             Output File:  ss beam\beam1.out
           Title:  Simple supported beam model
               Number of frequencies = 2
          Frequencies (undamaged structure)
       Mode      Lambda        rad/s              Hz
       1     2.068e+04  1.438e+02       2.289e+01
       2     1.293e+03  3.595e+01       5.722e+00
           Measured values of frequencies (sorted)
                   Mode    Frequency (Hz)
                      1        23.000
                      2         6.000
   Difference is analytical and experimental frequencies
         Mode     Freq FEM       Freq measured      %Diff
           1      2.289e+01  2.300e+01        -0.49%
           2      5.722e+00  6.000e+00        -4.63%
Mode  analytical  measured  difference  %difference (Lambda
                         (rad/s)**2)
              Frequencies (correlated model)
         Mode      Lambda       rad/s             Hz
       1      2.079e+04    1.442e+02      2.295e+01
       2      1.409e+03    3.754e+01      5.975e+00
        Maximum difference in frequencies       0.42%
```

Fig. 6 M-FEM program output in text format for the first analysis

By using the stiffness adjustment factor for all element shown in Fig. 5, the difference between frequencies can be reduced. As frequency has a direct relationship with stiffness (K) and stiffness has direct relationship with the moment of inertia, therefore, by changing the moment of inertia, stiffness and then frequency will be changed. It is obviously shown in Fig. 5 that the level of stiffness of all elements should be about one. But what is the most effective way for doing it? One of the easiest way is multiplying the average of stiffness level of two sections of the beam (elements 1 to 3 and 8 to 10 for section 1 and elements 4 to 7 for section 2) to the current moment of inertia. Therefore, the current moment of inertia in the program must be replaced by modified one. Then, if we see any considerable difference between the frequencies, we must do this process again and again till the smallest difference is achieved.

By checking stiffness factors of each element in Fig. 5, following averages were achieved:

- Average of stiffness factors of elements 1, 2, 3, 8, 9, 10 = 0.965
- Average of stiffness factors of elements 4, 5, 6, 7 = 1.15

And then this amount must be multiplied to 0.00035 to modify the amount of moment of inertia for each sections.

- I_z (section 1) = 0.965 * 0.00035 =0.00034
- I_z (section 2) = 1.15 * 0.00035 =0.00040

After multiplying above numbers to the moment of inertia of section 1 and 2 respectively and making some small changes the program was run again to determine the frequencies difference. Figs. 7 and 8 show the stiffness adjustment factors and text file after the second analysis.

As shown in Fig. 7, the stiffness adjustment factors of all element became closer to one, meaning that the difference between the analytical and experimental frequencies was reduced. It can be clearly seen in Fig. 8 that the difference between analytical and experimental frequencies of mode 1 and 2 became 0.40% and 0.62% and the maximum difference in analytical and experimental frequencies after first modification has been considerably reduced to 0.03%. According to these new values, it can be stated that the difference of analytical and experimental frequency of mode 2 has been reduced substantially compared to the first model updating. Now, we can claim that the difference between analytical and experimental frequencies are acceptable and model updating process was carried out successfully.

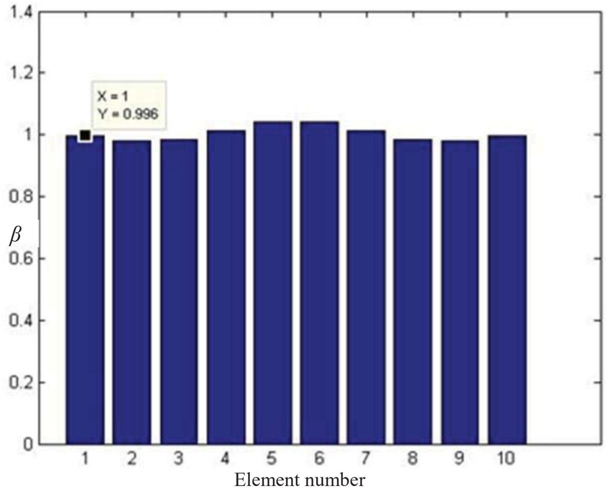
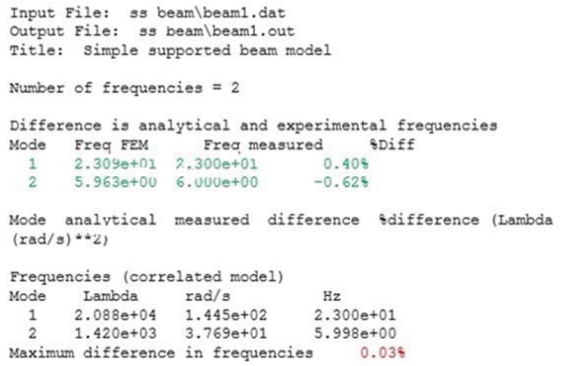


Fig. 7 Stiffness adjustment factors of all defined elements in the second analysis



```
Input File:  ss beam\beam1.dat
Output File:  ss beam\beam1.out
Title:  Simple supported beam model

Number of frequencies = 2

Difference is analytical and experimental frequencies
Mode   Freq FEM      Freq measured     %Diff
  1    2.309e+01  2.300e+01        0.40%
  2    5.963e+00  6.000e+00       -0.62%

Mode  analytical  measured  difference  %difference (Lambda
(rad/s)**2)

Frequencies (correlated model)
Mode    Lambda     rad/s         Hz
  1    2.088e+04  1.445e+02     2.300e+01
  2    1.420e+03  3.769e+01     5.998e+00
Maximum difference in frequencies     0.03%
```

Fig. 8 M-FEM program output in text format for the second analysis

XI. CONCLUSIONS

The study investigated some aspects of SHM process such as determining the natural frequency of the instrumented element, modal analysis and finite element model updating using a case study. The research has highlighted the applicability of the M-FEM software in performing model updating using the iterative method given in [4]. In order to achieve the objectives of the study, a concrete beam was considered. By using acceleration data, the natural frequency of the beam in two cases (before and after concrete blocks installing) was determined through FFT analysis. Furthermore, modal analysis was performed and finite element model updating processes was carried out to investigate how damages on a structural element can be detected. The study is useful for overall understanding of SHM process especially for university students to capture a helpful background on some aspects of SHM process of a structural system.

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