1st Conference on Sustainability in Civil Engineering, August 01, 2019,
Capital University of Science and Technology, Islamabad, Pakistan.

Estimation of Material Properties of SDoF Structures Using Visual Vibrometry

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Abstract

In order to evaluate the present status of aging structures, destructive and non-destructive testing (NDT) techniques are employed. Visual testing, as one of the oldest methods for NDT, plays a great role in the inspection of civil infrastructure. As NDT has evolved, more quantitative techniques have emerged, such as vibration analysis. New computer vision techniques for analyzing the small motions in the videos have been recently developed, allowing quantitative measurement of the vibration behavior of structures from videos. Video cameras offer the benefit of long-range measurement and can collect a large amount of data at once because each pixel is effectively a sensor. This work presents a video camera-based vibration measurement methodology for civil infrastructure. By projecting the vibrations of objects, we offer cameras as low-cost vibration sensors. The work includes the estimation of material properties for a variety of rods with known geometry by passively observing their motion in a regular frame rate video. Centering on the case where geometry is known or prepared, we indicate how information about an object's mode of oscillation can be excerpted from video and used to calculate the object's material properties.

Keywords: Visual Vibrometry, Material properties, Vibration analysis; Image processing

1. INTRODUCTION:

In the last century, there has been an unprecedented growth in infrastructure. With the passage of time, physical conditions and properties of structures change due to aging and environmental effects. Therefore, there is a need to assess the residual strength and stiffness of the existing infrastructure. Performance evaluation of the existing infrastructure is crucial to assess the strength/stiffness degradation of the structures to anticipate their performance under future extreme events. This identifies the structures under risk of major harm and even collapse in the aftermath of future extreme events which may result in loss of lives and damage to property. Structural health monitoring (SHM) field has therefore been developed in the past to come up with effective techniques to predict the performance of existing structures against extreme events. Different techniques developed for the SHM consist of both destructive and non-destructive testing (NDT) methods. NDT is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or deviations in characteristics without destroying the serviceability of the component or system. NDT includes rebound hammer test, ultrasonic pulse velocity test, half-cell Penetrometer test, carbonation test, etc. These tests usually predict the residual compressive strength, stiffness and durability properties of structures. However, the results usually provide an assessment of local properties of different members while an explicit assessment of the global behavior of structures is limited. Degradation of the stiffness of existing structures will result in an increase in the natural time periods and change of mode shapes which may result in an increase or decrease in the force and displacement demands against seismic and wind actions depending upon the seismic characteristics and soil conditions of the area, manifested by the design response spectra. Certain methods have been developed in the past which relies on the calculation of natural time periods and mode shapes of existing structures to relate it to the health of the structure (Carden et al. 2016 and Doebling et al. 1996). It is well recognized that structures vibrate at preferred frequencies and mode shapes. The frequencies and forms of these modes mainly depend on the type of structure, material properties, mass, and boundary conditions. Field testing with the help of sensors placed at predetermined locations to record the vibrations is required to estimate the properties of these dominant vibration modes through vibration analysis. Different sensors with different arrangements have been utilized in the past for this purpose (Lynch JP. 2006). However, these sensors are usually limited in number, giving limited data and their cost and availability, especially in developing countries, may limit their use. In the recent past, ambitious works have been performed in the area of image and video processing where the video of a vibrating object has been used to get the natural frequencies (Davis et al. 2015). Use of such techniques is mostly limited in structural engineering, but it has huge potential as an alternative to traditional structural health monitoring of existing structures using sensors. Image processing has been used in the past works to measure deflection and crack width in civil engineering structures. However, use of video processing to calculate modal properties of structures is quite limited. The current work aims to explore the possibilities of using visual vibrometry techniques in predicting the natural frequencies of vibrating structures and ultimately assessing their material properties, resulting in a cost-effective and more detailed health monitoring of existing infrastructure.

2. METHODOLOGY:

2.1 Scheme of the experimental setup:

The experimental setup is presented in . In this experiment, three rods of different materials were used with boundary condition at the base as fixed and free end at the top mounted with an accelerometer at the tip of the rod, which assist the two roles: firstly it works like a lumped mass in order to get the rod to vibrate in the first mode and second to record acceleration data. A small video camera of 60 frames per second (fps) was clamped with the aid of a stand such that the camera was perpendicular with respect to the rod. A black dot target was attached at the tip of the rod. The background was made clear in order to get our target more visible. Improper setup could compromise the accuracy of the results, therefore, the apparatus chosen and setup established was considered to avoid any error. The oscillations were induced in the rod by using a sound amplifier and by hand.

Figure 1: Experimental Setup

2.2 Material of the rod and dimension:

Three rods of different material, i.e. Steel, aluminium, and brass were used in the experiments. The length and diameter of all the rods were 533.4 mm and 6.35 mm, respectively.

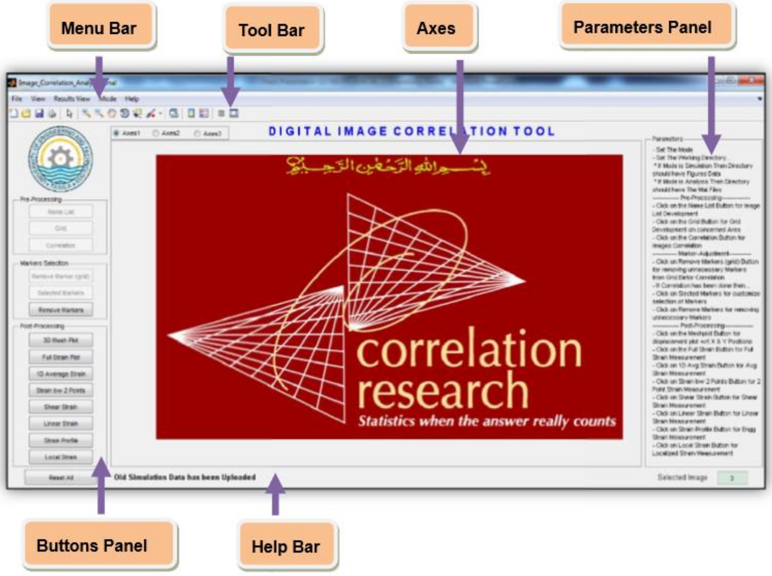
2.3 Experimental Procedure:

In the first experiment, vibrations were induced in the rod by giving it an initial deformation and then letting it go. At the same time, the accelerometer was switched on to record acceleration data. By using a stopwatch, the time span between on/off of the accelerometer was noticed. In the 2nd experiment, vibrations were induced by using the sound of frequency starting from 32 to 2000 Hz by using a sound amplifier. The accelerometer recorded the acceleration in rods due to these vibrations. Same experiments were done on all three types of rods.

2.4 Calculation of Natural frequency of rod:

Natural frequency or time period is an inherent property of a structure as it depends upon the stiffness of the structure which is a function of material and geometric properties of the structure. If the mass, geometry and boundary condition of a structure are known, its natural frequencies can be used to calculate its material properties/stiffness. For this purpose, three procedures were employed. In the first procedure, the video of the vibrating rod was analyzed manually to calculate the time required for a complete cycle of vibration. In the second approach, shaking in the rod was induced by using a sound amplifier and accelerometer data was used to find out the dominant frequencies by using Fast Fourier

Transform. In the 3rd approach, the video of the rod was analyzed by using a code in MATLAB developed by Kashif (2014). The Graphical Use Interface (GUI) of the MATLAB code is shown in Figure 2. The MATLAB code first divides a video into several images depending on the fps rate of the video. These images are then analyzed to find out the displacement of the target.



Old Simulation Data has been Uploaded

Figure 2: Digital Image Correlation Software Interface

2.5 Estimation of modulus of elasticity

After calculating the fundamental natural frequency and using fixed geometric parameters of the rods i.e. Length and diameter, the following formulas were used to calculate the modulus of elasticity of the rod.
Bending frequencies of beams, rods, and pipes (Irvine et al. 2012) is given by:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{3\text{EI}}{(0.2235\rho L + m)L^3}} \qquad (1)$$

Where f_1 is the fundamental frequency, E is the modulus of elasticity, I is the area moment of inertia, L is the unsupported length, ρ is the mass density (mass/length) and m is the mass of the attached objects.

Another formula for calculating natural frequencies introduced by (Shabana and Shabana. 1991) is as follows:

$$\omega_1 = 3.51563\sqrt{\frac{EI_Z}{ml^3}} \qquad (2)$$

Where, ω_1 is the angular frequency equal to 2πf, E is the modulus of elasticity, I_Z is the area moment of inertia, l is the length and m is the mass of the rod.

3. RESULTS AND DISCUSSION:

The results from both the Eq (1) and Eq (2) are quite close, but Eq (1) gives more accurate results due to the involvement of additional important parameters like it consider the mass of the object (rod) and the end mass which is attached at the end of the object (rod) while these parameters are not considered in Eq (2). Thus, these two main equations are applied to obtain the material properties of the targets.

Different materials have different strength properties. Rods made of steel, aluminium, and brass used in the present study have material properties shown in **Error! Reference source not found.**. After going through certain experiments and by adopting different methodologies as explained in the methodology section, results were obtained from the accelerometer and form processing the video of the vibrating object. Modulus of elasticity calculated by using accelerometer results is shown in Table 1, which shows a reasonable accuracy level with aluminium results showing minimum error while brass showing more than 20% error.

Table 1: Comparison between Results from Accelerometer and Actual values

Material	Experimental E (GPa)	Actual E (GPa)	% Error
Steel	164.5	193	14.77%
Brass	127.93	105	21.84%
Aluminium	72.13	69	4.54%

The MATLAB code used is not able to capture the video of vibration of the objects against sound vibrations generated by a sound amplifier. So, the vibrations of the bars were processed by using the video in which an initial displacement was given to the bar top by hand. The MATLAB code provided the displacement time history of the top end of the bars. Figure 3 shows the displacement time history of aluminium and steel bars. Once the displacement time history is known, it is easy to find out the fundamental time period/frequency of the bar, which is then used to calculate the modulus of elasticity using EQ 1 as shown in Table 2.

The results exhibit a reasonable accuracy with the percentage of error for modulus of elasticity ranging from 3% to 20% for different material types. The results can be further refined by minimizing the impact of different sources of errors. Like the use of a high-speed camera capable of recording largest possible frequencies along with a more sophisticated testing apparatus. Furthermore, future studies can be focused on simple multi degree of freedom structures to find out natural frequencies as well as the mode shapes.

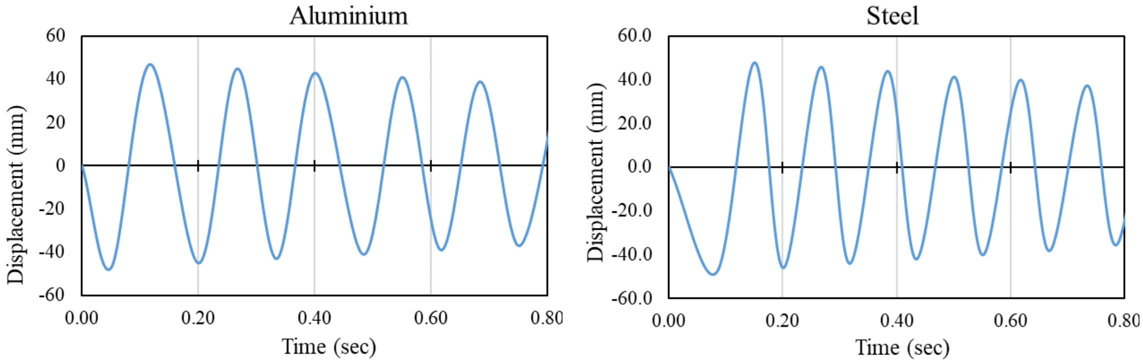


Figure 3: Displacement time history of a. Aluminium and b. Steel

Table 2: Comparison between Results from MATLAB and Actual values

Material	Experimental E (GPa)	Actual E (GPa)	% Error
Steel	163.247	193	15.42%
Brass	125.9	105	19.90%
Aluminium	71.23	69	3.23%

A comparison of % error in both the cases is shown in the form of a histogram as shown in Figure 3.

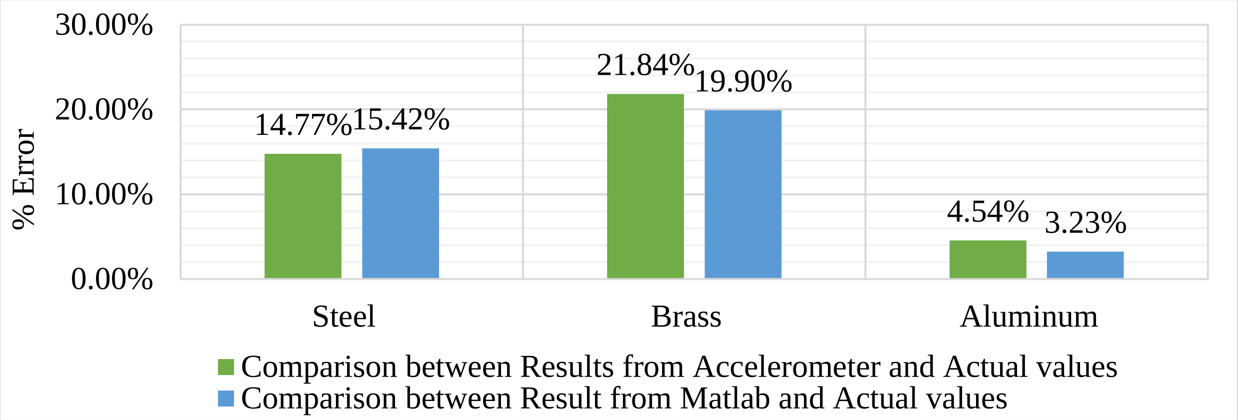


Figure 3: Comparison of error in two methods

Visual vibrometry has several applications for civil engineering works including the health monitoring of buildings, bridges, flexible structures, billboards etc. A lot of work has been done in the past to find out the deformation of structures using target or target-less approach with the algorithms being developed for target tracking. The current work aims to monitor and record this deflection in time domain, which may then be used to find out natural time period of structures. Also, such techniques can be extended to even calculate the strains in concrete using high speed video cameras. Currently, this work is underway in our research group for calculation of axial strain in concrete cylinders and the initial results are showing promising results.

4. CONCLUSIONS:

In the current study, the use of visual vibrometry to calculate the material properties of single degree of freedom structures is discussed. The results show that video-based evaluation of natural frequency gives comparable results to that of the accelerometer. The results for three different materials show a percentage error of 5% to 20%. However, the current code is able to analyze the vibrations where displacement is relatively high and visible through the naked eye. Future works should explore the efficiency of this technique for relatively smaller displacement values usually expected in building structures.

ACKNOWLEDGEMENTS:

The authors would like to thank Kashif Khan for providing MATLAB GUI code and for his valuable suggestions. The careful review and constructive suggestions by the anonymous reviewers are gratefully acknowledged.

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