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Experimental Detection of Sudden Stiffness Change in a Structural System Employing Laser Doppler Vibrometry

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ABSTRACT

Sudden changes in the stiffness of a structure are often indicators of structural damage. Detection of such sudden stiffness change from the vibrations of structures is important for Structural Health Monitoring (SHM) and damage detection. Non-contact measurement of these vibrations is a quick and efficient way for successful detection of sudden stiffness change of a structure. In this paper, we demonstrate the capability of Laser Doppler Vibrometry to detect sudden stiffness change in a Single Degree Of Freedom (SDOF) oscillator within a laboratory environment. The dynamic response of the SDOF system was measured using a Polytec RSV-150 Remote Sensing Vibrometer. This instrument employs Laser Doppler Vibrometry for measuring dynamic response. Additionally, the vibration response of the SDOF system was measured through a MicroStrain G-Link Wireless Accelerometer mounted on the SDOF system. The stiffness of the SDOF system was experimentally determined through calibrated linear springs. The sudden change of stiffness was simulated by introducing the failure of a spring at a certain instant in time during a given period of forced vibration. The forced vibration on the SDOF system was in the form of a white noise input. The sudden change in stiffness was successfully detected through the measurements using Laser Doppler Vibrometry. This detection from optically obtained data was compared with a detection using data obtained from the wireless accelerometer. The potential of this technique is deemed important for a wide range of applications. The method is observed to be particularly suitable for rapid damage detection and health monitoring of structures under a model-free condition or where information related to the structure is not sufficient.

Keywords: *Laser Doppler Vibrometry, Structural Health Monitoring, Damage Detection, Accelerometer.*

1 INTRODUCTION

Detecting structural damage is an essential part of Structural Health Monitoring (SHM). In that regard, reliable and cost effective methods are needed to detect damage in a structure. These methods include non-destructive techniques that can be applied to in-service structures, thereby reducing maintenance costs and improving safety and system performance [1-3].

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Amongst the many approaches in detecting damage in structures, the use of structural vibration data [4-7] is very popular. The successful detection of a sudden change in vibration data in the presence of noise is a critical component in damage detection. Important examples of these changes within a system are changes in stiffness of vibrating Single Degree of Freedom (SDOF) system and the local disruption of stress and strain fields due to the presence of damage [8-10].

In order to detect and describe such changes, new methods and analysis techniques are present in the area of SHM. Time-frequency analysis techniques, like wavelet analysis, have been very efficiently used in this regard for the detection of the presence, the location and the calibration of the extent of these changes [11-16].

This paper presents an application of non-contact measurements of vibration by Laser Doppler Vibrometry (LDV) and demonstrates the importance of wavelet analysis for the successful detection of damage in the presence of Gaussian white noise. The performance of a 3-D accelerometer and LDV with wavelet analysis on measured data is compared. The use of LDV combined with wavelet analysis is found to be advantageous over the use of 3-D accelerometer in the diagnostics of structural damage.

2 METHODOLOGY

The dynamic response of a bilinear Single Degree of Freedom (SDOF) system was measured using two wireless instruments, MicroStrain G-Link Wireless Accelerometer Sensor and Polytec RSV-150 Remote Sensing Vibrometer.

2.1 3D Accelerometer

MicroStrain G-Link Wireless Accelerometer Sensor was used to measure the acceleration of the vibrating SDOF system in Cartesian directions. The accelerometer represents a traditional and reliable way of monitoring structures adopted for laboratory and large scale in-situ measurements [17-19]. The disadvantage of using this type of sensors is that they have to be attached to the structure at all times during the monitoring, which is not always possible.

2.2 Laser Doppler Vibrometer

LDV has been successfully employed for a wide range of applications, including lifting of roof tiles in a wind tunnel test [20], vibration mode estimation [21, 22], estimation of acoustic parameters [23], non-destructive diagnostics of fresco paintings [24], estimation of natural frequencies of a rotating plate [25] and damage detection [26]. In this paper, a Polytec RSV-150 Remote Sensing Vibrometer is used for rapid, accurate, non-contact and long distance measurement of vibrating structures. The fundamental governing principle of LDV is the Doppler Effect. If a target moves away from a vibrometer of source frequency f in a straight line with velocity $\vec{v}$ then the target receives a frequency of

$$f' = (\frac{c - \vec{v}.\vec{e}_t}{c})f \tag{1}$$

where c is the velocity of light in vacuum and $\vec{e}_t$ represents the unit vector emanating from the vibrometer to the target and both the vibrometer and the target are considered to be points. The target, now a source of frequency f', reflects the light back and this light is received by the vibrometer with frequency

$$f'' = (\frac{c}{c - \vec{v}.\vec{e}_r})f' \tag{2}$$

where $\vec{e}_r$ is the unit vector corresponding to the reflecting situation. These two equations can be combined as

$$f'' = \left(\frac{c - \vec{v}.\vec{e}_t}{c - \vec{v}.\vec{e}_r}\right)f \tag{3}$$

and approximated to be

$$f'' = \left(1 + \frac{\vec{v}.(\vec{e}_t - \vec{e}_r)}{c}\right)f \tag{4}$$

under the assumption that the velocity of the target is insignificant as compared to the velocity of light. The change in frequency Δf can then be expressed as

$$\Delta f = f'' - f = \frac{2v}{\lambda} \tag{5}$$

where λ is the wavelength of source laser light emanating from the vibrometer (in this experiment an infra-red source was used) and v is the absolute value of $\vec{v}$ owing to the linearity of motion considered for equation 1.

If the direction of velocity of the target and the normal of wave front creates an angle θ.

$$\Delta f = \frac{2\vec{v}.\vec{e}}{\lambda} = \frac{2v}{\lambda}\mathrm{Cos}(\theta) \tag{6}$$

where $\vec{e}$ is the instantaneous direction vector between the vibrometer and the target at a given point of time. The measurements are quite precise for an angle θ up to 80^o, which is to say that in those circumstances equation 5 very successfully surrogates equation 6 without any loss of accuracy.

2.3 Experiment Setup

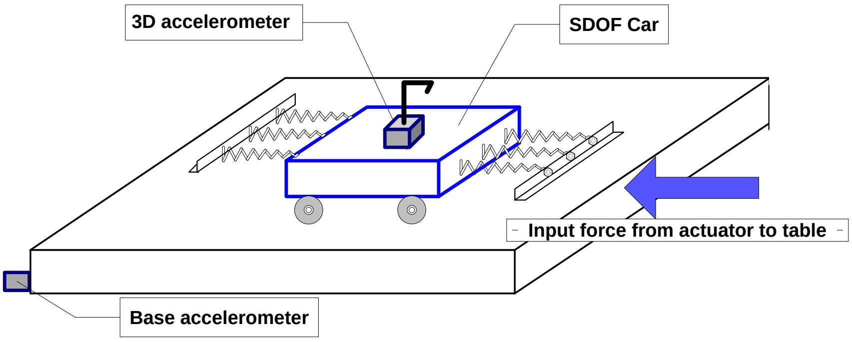

Figure 1 – Experiment Scheme.

A small scale bilinear SDOF model was tested. The model was made of a SDOF car connected to fixed supports on either side through calibrated springs (Figure 1). The SDOF car model was placed on a vibration bench and exposed to the external force in the form of white noise. The friction between the wheels of the SDOF car and the surface was low enough to be ignored. The experiment setup is shown in Figure 2. Prior to the experiment, the linear springs were calibrated and the results of this calibration are presented in Figure 3. Calculated equivalent stiffness of the combined springs at the beginning of the experiment was k = 0.378 N/mm. The sudden change of the stiffness was simulated by a sudden failure of the middle springs on either side during vibration measurements. The first spring got detached after 13 sec (k = 0.303 N/mm) and the second one after 38 sec (k = 0.249 N/mm) from the beginning of measurements. The sampling frequency of the accelerometer and the LDV were 128 Hz and 830 Hz respectively. The points on the time axis of responses for the instruments are representative of this sampling.

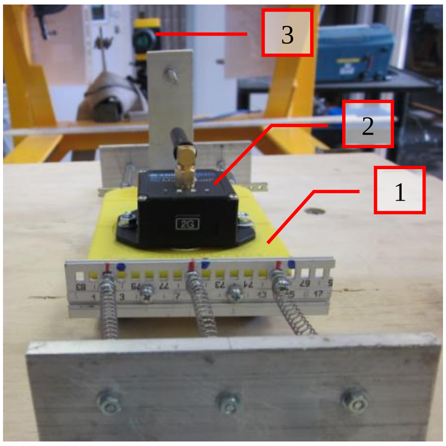

Figure 2 – Experiment Setup: 1) Single Degree of Freedom (SDOF) Car; 2) MicroStrain G-Link Wireless Accelerometer; 3) Polytec RSV -150 Remote Sensing Vibrometer.

The response of the system due to a white noise input was recorded and measurements obtained by both instruments were compared.

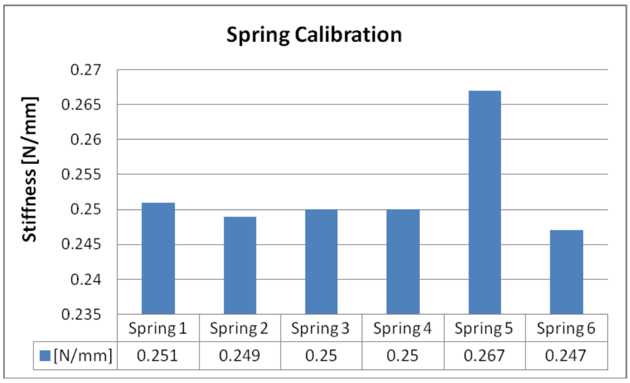

Figure 3 – Calibration of Spring Stiffness.

Acceleration responses to increasing 2Hz, 4Hz, 6Hz and 8Hz harmonic input respectively are shown in Figure 4 where the output of the 3D accelerometer are in the Cartesian directions (a-c) and the LDV measurement (d) is derived through simple numerical differentiation of measured velocity response. Channel 1 of the accelerometer corresponds to the principal direction of vibration. The comparable amplitude and the cleanness of data for numerically differentiated LDV acceleration response indicates the low presence of noise in the data and consequently, the velocity responses from LDV may be directly exploited to detect the sudden stiffness change in time.

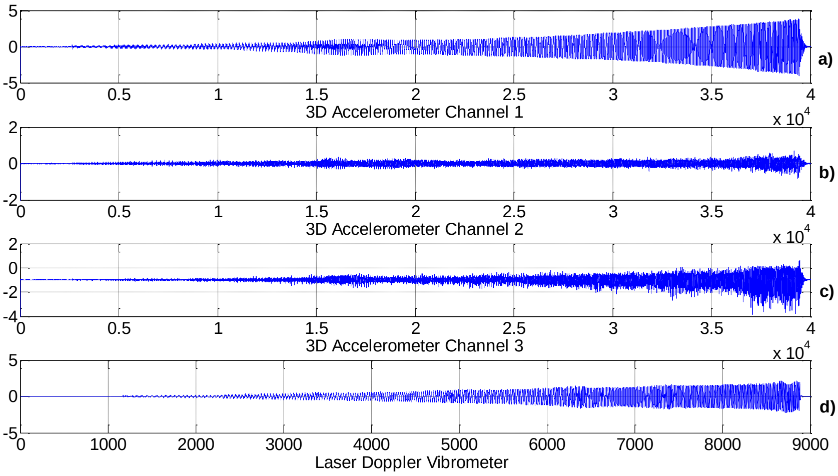

Figure 4 – Example Comparison between LDV and accelerometer results.

3 RESULTS

The time domain response of the SDOF system, including the failure of two (out of six) springs under white noise is shown in Figure 5 as recorded by the 3D accelerometer (a-c) and the LDV (d). The times of the failure of the springs are located at 13 sec and 38 sec from the beginning of experiment. It is difficult to identify any prominent peak related to the failures from Figure 5.

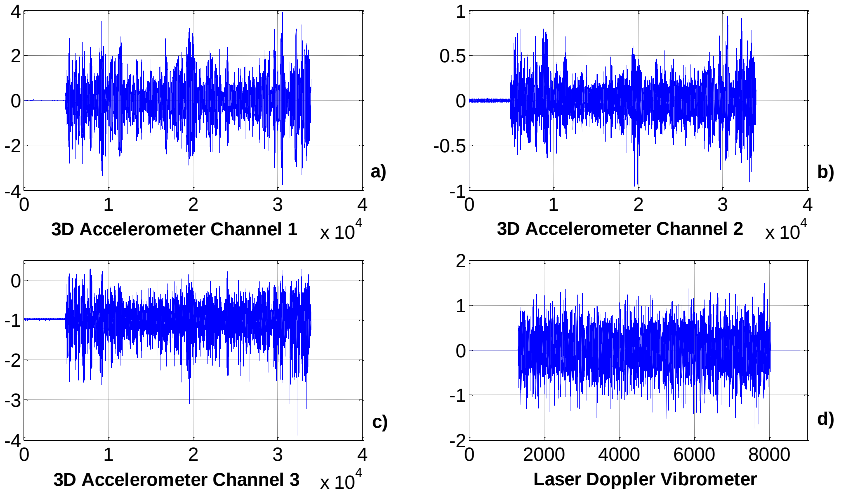

Figure 5 – Time Domain Response from 3D accelerometer: a) Channel 1; b) Channel 2; and 3) Channel 3 and d) Laser Doppler Vibrometer (LDV) for sudden change of stiffness.

The time domain responses are converted to the frequency domain through Fourier Transform (Figure 6). The frequency domain representation is unable to detect the sudden change in time due to the averaging effects of Fourier Transform.

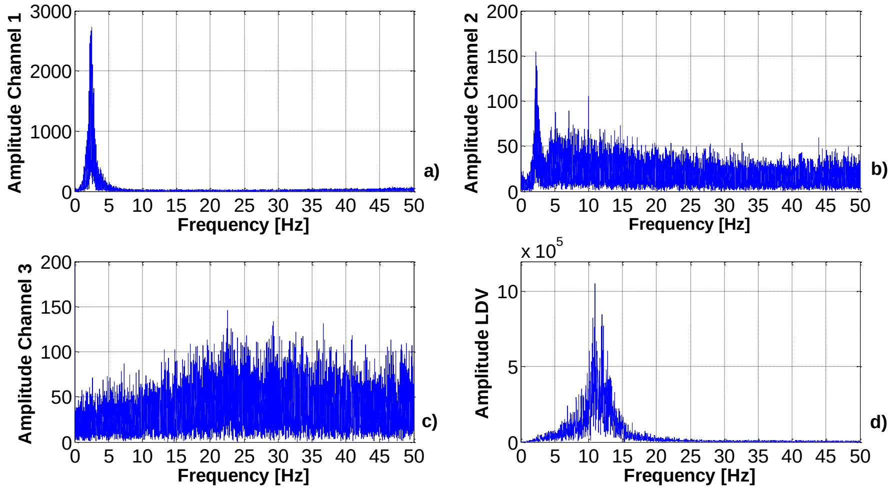

Figure 6 – Frequency Response from 3D accelerometer: a) Channel 1; b) Channel 2; and 3) Channel 3 and d) Laser Doppler Vibrometer (LDV) for sudden change of stiffness.

The peaks of the frequency domain response are different for the accelerometer and the LDV. This is dependent on the change of a relatively linear system to a strongly bilinear system with some lateral effects for a certain period of time and the return of the system to a relatively linear system, averaged over time. The velocity and the acceleration responses cannot necessarily be expected to be proportional under such circumstances. Independent of the difference in the peaks, the inability to detect sudden stiffness change in time through this method remains. A time-frequency domain analysis is attempted next for the detection of the sudden stiffness change.

Continuous Wavelet Transform (CWT), employing a Coif4 basis function and over scales up to 512 is carried out on the vibration responses detected by LDV and 3D accelerometer. The wavelet transformation of 3D accelerometer response could not clearly indicate the occurrence of the damages (Figure 7 and 8). The response of the dominant non-principal direction of vibration (Channel 2) was of little significance and consequently, noisier masked results of Channel 3 are not presented.

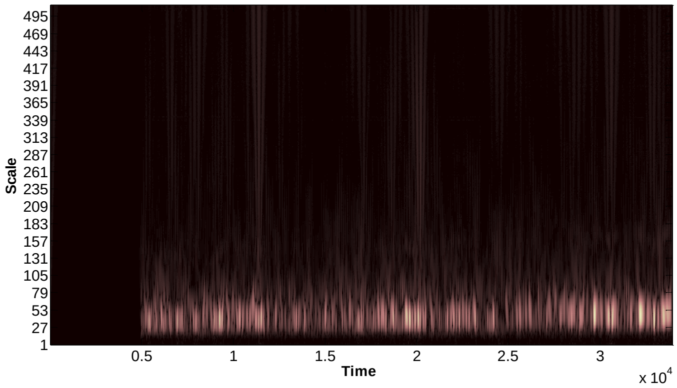

Figure 7 –Wavelet based analysis on 3D accelerometer data (Channel 1).

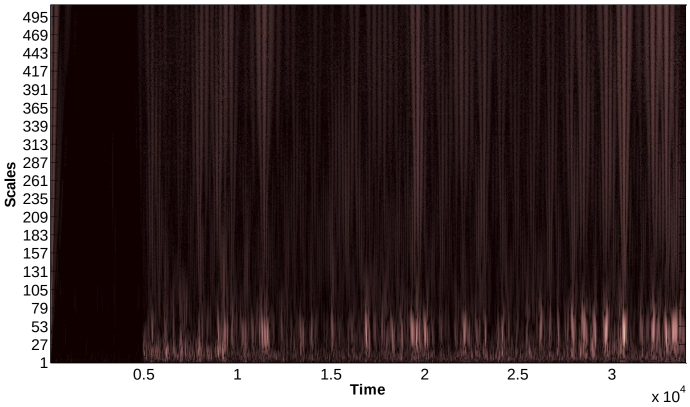

Figure 8 –Wavelet based analysis on 3D accelerometer data (Channel 2).

Figure 9 shows the CWT analysis on LDV output data. Occurrences of damage were clearly determined at the correct time instants as consistent maxima values were observed over all scales. Coif4 wavelet has eight vanishing moments and is efficient in detecting the singularity present in the signal itself.

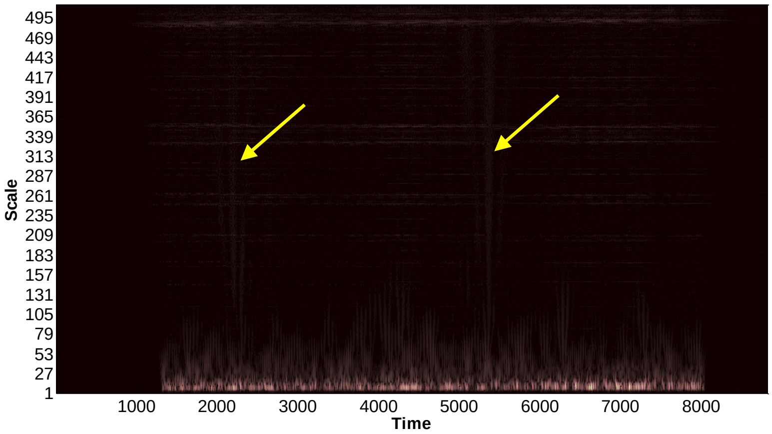

Figure 9 – Sudden change of stiffness detection using wavelet based analysis on Laser Doppler Vibrometer data.

4 CONCLUSION

The experiment demonstrates the effectiveness of LDV measurements to for damage detection and its superiority over a traditional accelerometer based approach. Where time or frequency domain detection of sudden stiffness change was not possible for a SDOF bilinear oscillator, the LDV based measurement, in conjunction with wavelet analysis, performed very efficiently in the detection of the presence the location of damage at each instance. The implementation of the LDV model is easy and the diagnostics damage is quick. This type of remote observation could be of the great importance when monitoring historical structures, strategically important structures, structures such as nuclear facilities and, rapid evaluation of large scale structures following disasters.

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