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Utilizing the Knudsen Effect in the Quest for Super Insulation Materials

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Abstract:
Initiatives to incorporate energy efficiency measures and strategies in the building sector have gained attention for several decades, and with increased focus on zero energy and zero emission buildings, such initiatives will probably still continue to emerge for several more decades to come. Development of new high-performance thermal insulation materials and super insulation materials (SIM) for the advanced building envelopes of tomorrow may play an essential role in this regard. Very thick building envelopes are not desirable due to several reasons, e.g. considering space issues with respect to both economy, floor area, transport volumes, architectural restrictions and other limitations, material usage and existing building techniques. Hence, the stage is set for the development of new thermal insulation materials with a very low thermal conductivity, thus allowing the usage of relatively thin building envelopes with a very high thermal resistance and thereby substantially reduced heat loss. In porous materials, when the mean free path of the gas molecules becomes larger than the pore diameter, there will be a decrease in the gas thermal conductivity including the gas and pore wall interaction, which is referred to as the Knudsen effect. This study will present our on-going efforts utilizing the Knudsen effect attempting to make SIMs with a nanoporous air-filled structure at atmospheric pressure, i.e. nano insulation materials (NIM). Some possible pathways to NIMs and SIMs like e.g. the template foaming method and the internal gas release method are promising with respect to their high potential, however, so far large experimental challenges have made us abandon these methods for the moment. That is, currently we are pursuing to make NIMs by the sacrificial template method, more specifically by the synthesis of hollow silica nanospheres (HSNS), where both the inner sphere diameter and shell thickness may be tailor-made and thereby determining the thermal conductivity.

Keywords:
Knudsen effect, super insulation material, nano insulation material, hollow silica nanosphere, thermal conductivity.

1. Introduction

The society of today is demanding an ever increasing focus on energy producing and energy saving strategies in several fields, where one of these is the building sector. In that respect, the development of high-performance thermal insulation materials may play a crucial role, where these are often denoted as super insulation materials (SIM). It has also been pointed out that energy efficiency measures are the most cost-effective ones, whereas measures like e.g. solar photovoltaics and wind energy are far less cost-effective than thermal insulation retrofitting of buildings regarding the global greenhouse gas (GHG) abatement costs [1]. Hence, there is a growing drive to develop SIMs for building applications also incorporating environmental aspects. The objective of the study presented herein is to investigate the opportunities for utilizing the Knudsen effect in the quest for developing SIMs. That is, nanoporous materials with low thermal conductivity values are being attempted made, i.e. nano insulation materials (NIM), where one of the possible pathways is through the development of hollow silica nanospheres (HSNS) by a sacrificial template method. Variations and optimizations of synthesis parameters are pursued in order to tailor-make HSNS with specific inner sphere diameters and shell thicknesses, with a final aim to reach as low thermal conductivities as possible.

2. The Knudsen effect

In short, the Knudsen effect may be described as an effect which occurs when the thermal conductivity is decreased in nanoporous materials due to the mean free free path of the gas molecules becoming larger than the pore diameter, i.e. pore diameters typically in the nanorange.

Taking into account the Knudsen effect, the thermal conductivity $\lambda_{gas,gas\text{-}solid}$, which in addition to the gas conductivity also includes the gas and pore wall interaction, may be written in a simplified way as [2-7]:

$$\lambda_{gas,gas-solid} = \frac{\lambda_{gas,0}}{1+2\beta Kn} = \frac{\lambda_{gas,0}}{1+\frac{\sqrt{2}\beta k_B T}{\pi d^2 p\delta}} \tag{1}$$

where

$$Kn = \frac{\sigma_{mean}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p\delta} \tag{2}$$

where $\lambda_{gas,gas\text{-}solid}$ = thermal conductivity including the gas thermal conductivity and the gas and pore wall interaction (W/(mK)), $\lambda_{gas,0}$ = gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK)), β = coefficient characterizing the molecule-wall collision energy transfer (in)efficiency (between 1.5 - 2.0), k_B = Boltzmann's constant $\approx 1.38 \cdot 10^{-23}$ J/K, T = temperature (K), d = gas molecule collision diameter (m), p = gas pressure in pores (Pa), δ = characteristic pore diameter (m), and σ_{mean} = mean free path of gas molecules (m).

When attempting to develop SIMs the thermal transport by solid state conductance and radiation must also be minimized. Noteworthy, in a nanoporous material, the thermal transport by convection will normally be negligible.

3. Experimental

There may be several pathways to develop SIMs through NIMs, including membrane foaming and gas release methods [8-9], probably also hitherto unknown methods, but currently we are investigating the sacrificial template method by making hollow silica nanospheres (HSNS) [8-9].

In short, spherical templates are first made, e.g. polystyrene (PS) spheres, which thereafter are coated with a silica layer using e.g. tetraethyl orthosilicate (TEOS) or water glass (Na_2SiO_3) as the silica precursor. Finally, the sacrificial PS templates are removed by a heating process where the PS template material is evaporated and diffused through the silica shell, thus leaving the final result as silica shells around spherical voids, i.e. HSNS. An illustration of the HSNS synthesis is depicted in Fig.1.

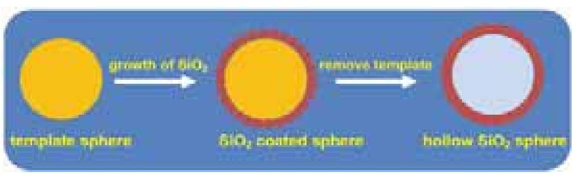

Fig.1. HSNS synthesis illustrated.

4. Results and discussion

The various parameters for the HSNS synthesis have been investigated, although far from fully, and have resulted in different HSNS formations where some have been more successful than others. For further information on the miscellaneous HSNS syntheses and their resulting properties it is referred to our earlier studies [10-14] and forthcoming ones.

Two key parameters are to control the sphere inner diameter and the sphere shell thickness. The sphere inner diameter is a key parameter in the Knudsen equation as given in Eq.1, thus part of determining the thermal conductivity including the gas thermal conductivity and the gas and pore wall interaction. That is, in principle, the smaller the inner sphere pore diameter the lower thermal conductivity (when not taking into account other varying parameters). The sphere shell thickness will also influence the thermal conductivity, i.e. in this case more specifically the solid state conductivity, and also the mechanical strength properties.

The sphere composition and surface roughness will also have an effect on the thermal conductivity and mechanical strength properties. The produced HSNS may have shells composed of silica nanoparticles with different diameters depending on the actual synthesis method and parameters. The surface roughness of the HSNS may also vary greatly with the chosen synthesis, i.e. a rough surface from a shell made of silica nanoparticles (TEOS as silica precursor) or a large, wrinkled silica sheet (water glass as silica precursor), the latter surface appearing much smoother than the former one [15].

Yet another key parameter is the packing of the HSNS, which will directly influence the voids formed between the HSNS and the solid state connections between the HSNS, i.e. the former one having an impact on the thermal conductivity including the gas thermal conductivity and the gas and pore wall interaction and the latter one having an effect on the solid state conductivity. These aspects are influenced by the size of the HSNS, i.e. the inner pore diameter and the shell thickness, and the outer morphology of the HSNS, i.e. the exterior surface roughness.

Typically, so far the thermal conductivity of the HSNS powder samples has varied between 20 to 90 mW/(mK), though there are some uncertainties with the Hot Disk apparatus method which have to be further clarified. However, there is an expressed goal to lower the thermal conductivity below 20 mW/(mK).

The sacrificial template synthesis is a crucial step in the making of HSNS. It is a rather hard challenge to make monodisperse PS template spheres with diameters below 100 nm. In Fig.2 there are given scanning electron microscope (SEM) images of PS spheres with diameters 80 nm and 195 nm, where the former ones represent a hard-gained effort in itself.

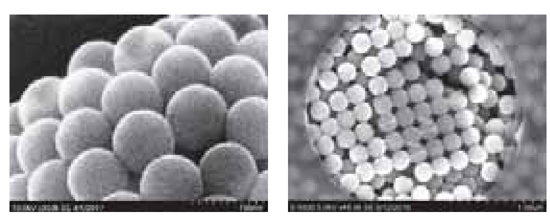

Fig.2. PS sphere SEM images with diameters 80 nm (left) and 195 nm (right). Magnification 350 000x (left) and 45 000x (right), scale-bar 100 nm (left) and 1 μm (right).

Examples of HSNS with two different inner diameters are depicted in the SEM images given in Fig.3 and Fig.4. These examples display rather rough HSNS surfaces due to the relatively large silica nanoparticles (compared to the HSNS diameters) which the HSNS shells are composed of. Hence, modification and optimization of the HSNS shells may enable us to tailor-make NIMs and SIMs with the desired thermal and mechanical properties. These aspects will be investigated in forthcoming studies within the project High-Performance Nano Insulation Materials [16].

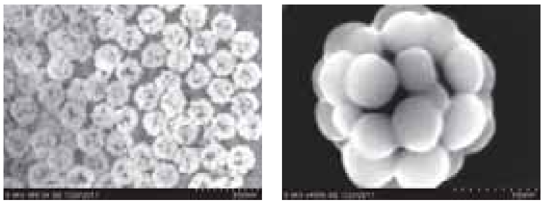

Fig.3. SEM images of HSNS with inner diameters 85 nm, several spheres (left) and a single sphere (right). Magnification 60 000x (left) and 400 000x (right), scale-bar 500 nm (left) and 100 nm (right).

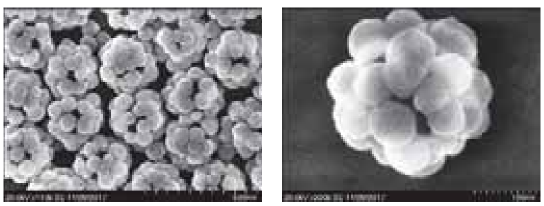

Fig.4. SEM images of HSNS with inner diameters 135 nm, several spheres (left) and a single sphere (right). Magnification 110 000x (left) and 300 000x (right), scale-bar 500 nm (left) and 100 nm (right).

5. Conclusions and outlook

In the quest for super insulation materials (SIM), nano insulation materials (NIM) have been made by various syntheses of hollow silica nanospheres (HSNS), where the resulting HSNS and their properties are very dependent on several parameters during the syntheses. Optimization and fine-tuning of these synthesis parameters will be important in the forthcoming experimental investigations.

Acknowledgements
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Condition Assessment of Bridges using Non-Contact Vibration Measurement: A Pilot Study

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Abstract:
Damage detection using measurement of change in the vibration signature of bridges is a well known fundamental technique which requires acquisition of vibration data of the bridge from mounted sensors such as accelerometers. Mounting multiple accelerometers and building a wireless network to monitor the vibration response can sometime become troublesome and very expensive to maintain. Also, the mounted accelerometers are very difficult to synchronize with each other to obtain the modal parameters of the bridge. This paper illustrates the use of a Laser Scanning Vibrometer (LSV) as a non contact damage detection technique for bridges. The LSV available at University of Victoria's Facility for Innovative Materials and Infrastructure Monitoring (FIMIM) can obtain the vibration response of a bridge from 100'. The LSV was used to compare the data obtained by the mounted sensors on the Portage Creek Bridge, Victoria, British Columbia, Canada during ambient vibration condition. Multiple points on the East Span of the bridge were selected to compare the data. The paper also described the various challenges faced by the authors during the measurement.

Keywords:
Non-Contact Vibration Measurement, Laser Scanning Vibrometer, Structural Health Monitoring, Bridges, and Non-Destructive Evaluation

1. Introduction

Study of the vibration signature of a structure periodically and estimating the performance of the structure is not a new concept. This is a very fundamental concept which is being used for detecting damage for a number of years [1-4]. The presence of damage or deterioration in a structure causes changes in the mass and or stiffness and hence changes in natural frequencies of the structure. Monitoring the natural frequency over the period and studying the changes can give information about the behavior of the structure. The most useful damage location methods (based on dynamic testing) are probably those using changes in resonant frequencies because frequency measurements can be quickly conducted and are often reliable [5]. Abnormal loss of stiffness is identified when measured natural frequencies are significantly lower than expected. A study led by Morgan et al. stated that frequencies higher than expected are indicative of supports stiffer than expected [6]. It would be necessary for a natural frequency to change by about 5% for damage to be detected with confidence [7]. However, it has been found that the significant frequency changes alone do not automatically imply the existence of damage since frequency shifts (exceeding 5%) due to changes in ambient conditions have been measured [8] for both concrete and steel bridges within a single day. It was found that the long-term changes of natural frequencies correlate well with the long-term changes of temperature [9].

Results from some experimental and numerical studies have suggested that the lower vibration modes would probably be best suited for damage detection [10]. However, Begg et al. [11] stated that modes higher than the first should be used in damage detection to improve the identification. The increased sensitivity of the higher modes to local damage has also been mentioned by others [12, 13].

For an effective utilization of dynamic testing as a diagnostic tool, it is necessary to understand the effects of deterioration and defects on the dynamic characteristics of structural systems. For example, long span bridges are not likely to show measurable changes in dynamic properties if local damage is sustained [14]. In addition, dynamic characteristics are sensitive to changes in support conditions that may have little structural consequence. Responses measured at boundaries (abutment, piers and other support types) could also yield erroneous results [15]. It is also important that the effects of environmental factors, such as temperature and humidity, on changes in dynamic characteristics be either small or predictable [16]. Identification of a 'sufficient' number of frequency variations may be necessary before defects can be adequately located. For safety inspection of long span suspension bridges, detection of natural frequency changes in the order of 0.01 Hz may be required [17].

Commercially available high resolution wired accelerometer system when compared with the Laser Vibrometer [18] shows that using LSV at frequency below 1 Hz, an uncertainty component due to threshold and resolution better of at least 1000 times can be obtained. This is due to the fact that the lowest displacements can be measured at higher frequencies, for example at 1 Hz, using the best transducers available, the measured displacement drops to about 2.5 μm [18]. It should be noted that the proposed research uses the PSV 500 from Polytec having better specifications compared to the one from Polytec OFV-303 used in the literature [18].

LSV uses the Laser Doppler Technique to measure the velocity of the object directly. Due to the Doppler effect, the light back-scattered from the moving target carries information about the motion quantities velocity and displacement at the point of incidence: Displacement of the surface modulates the phase of the light wave while instantaneous velocity shifts its optical frequency by a small amount. Because the optical frequency of the laser is far too high to demodulate directly ($5x10^{14}$ Hz), interferometric techniques are employed to reveal the measurement effects. With the help of an interferometer the received light wave is mixed with a reference beam so that the two heterodyne on to the surface of a photodetector [19].

Another research [20] on the comparison of contact sensors with non-contact laser vibrometer shows that the use of the laser Doppler vibrometer (LDV) system as a non-contact, non-destructive means of measuring bridge vibration and deflection can provide accurate results. It has also been reported that the LDV can be used to map the bridge response at various locations while the contact sensors only offer information about a particular location [20].

Laser Vibrometer was employed to develop a structural damage model by Siringoringo et al. [21]. In this study [21], authors used modal updating technique. The essential feature of this method was the non-iterative solving technique of inverse problem, which allows damage to be located and quantified by employing the modal parameters obtained before and after damage. Numerical simulation and laboratory-scaled experiments using bolted lap joint plate demonstrated that this technique can detect locations and magnitude of damage with incomplete modal information [21].

2. Experimental Work

<u>Lab Experiment:</u>

Before conducting an experiment at the Portage Creek Bridge, authors performed a small experiment in the Facility for Innovative Materials and Infrastructure Monitoring (FIMIM) to sense the displacement values obtained using LSV. For this, LSV was used to obtain displacement histories of a 12” long aluminum ruler as seen in Figure 1.

The vertical displacement of the ruler was measured using a highly sensitive displacement gauge and compared with LSV. Two different sampling rates 2.5 kHz (High) and 250 Hz (Low) were selected to see the performance. Displacement histories at both the sampling frequencies are presented here in Figures 2 and 3. It should be noted that the LSV system (PSV-500) available at FIMIM measures the velocity directly and since it is a digital system without any analog signal, the software performs the integration and display to displacement with less than 1% error on the measurement.

Fig. 1: Test Setup- Side View

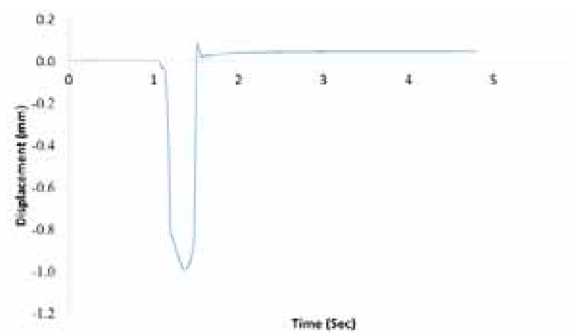

Fig. 2: Displacement using LSV at 2.5 kHz Sampling rate

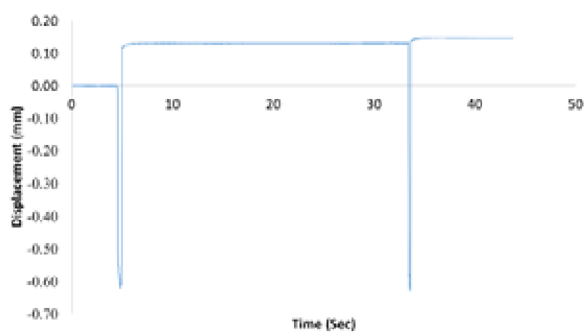

Fig. 3: Displacement using LSV at 250 Hz Sampling rate

Table 1 shows the maximum displacement values recorded using both LSV and a displacement gauge. It can be seen that the values obtained using LSV is very close to the value obtained using a displacement gauge.

Table 1: Vertical displacement values obtained using LSV and a displacement gauge

Test #	Stroke	Instrument/Sensor	Max Displacement
1 (2.5 kHz)	1	LSV	1 mm
		Deflection Gauge	Gauge reading-37 → 0.925 mm
2 (250 Hz)	1	LSV	625 μm → 0.625 mm
		Deflection Gauge	Gauge Reading-21 → 0.525 mm
	2	LSV	725 μm → 0.725 mm
		Deflection Gauge	Gauge Reading-27 → 0.675 mm

It should be noted that this experiment was conducted just to have a sense of the displacement values obtained using the LSV and hence for this, a highly sophisticated experimental setup was not required.

Field work:

Portage Creek Bridge was constructed in 1983 with three spans over the interurban road, Victoria BC, Canada. It is a concrete-steel composite structure with concrete deck and steel girders. Detailed information on the superstructure is given in [22]. This particular bridge has caught a lot of attention as the bridge was designed long before the introduction of current seismic design standards. The bridge has also undergone a seismic retrofit in 2003 by SIMTREC (Structural Innovation and Monitoring Technologies Resource Centre (Formerly known as ISIS Canada). This bridge is currently being monitored by BC Ministry of Transportation and Infrastructure (BC MOTI) as a part of the BCSIMS (Strong Motion Network and Seismic Structural Health Monitoring Network of British Columbia) project.

As a part of the seismic assessment, Portage Creek Bridge was selected for a dynamic analysis using modal updating technique in 2014. The study was carried out by Yu Feng et al. [22] and during the study they have found out the dynamic characteristics like modal frequency, damping ratio and mode shape using multiple mounted accelerometers and modal updating technique. As a first exercise, authors of this paper have tried using non-contact LSV to obtain the vibration response of the structure and compare it with the mounted accelerometer data.

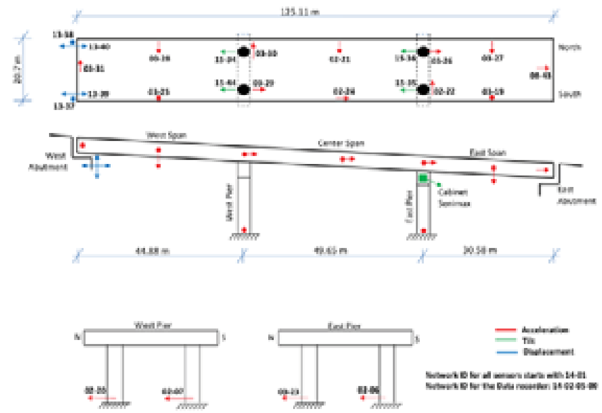

Fig. 4: Sensor Map of Portage Creek Bridge, Victoria BC

The bridge structure is equipped with a total of 20 sensors out of which 4 are for tilt measurement, 2 are for displacement, and the rest 14 are for acceleration measurement. Figure 4 shows the location of different sensors with their network ids.

Fig. 5: Experimental Setup: Portage Creek Bridge Site

For this pilot study, out of the three spans, only one span (east span) was selected as it was easily accessible. Figure 5 shows the measurement location at the Portage Creek Bridge Site. All three girders of the east span were chosen for the measurement. For simplicity, one point (mid point) on each girder was selected as seen in Figure 6. Figure 6 also shows the traffic direction (Shown with the arrows) on the McKenzie Ave. It should be noted that only 2-axle trucks were considered as an ambient traffic in this study.

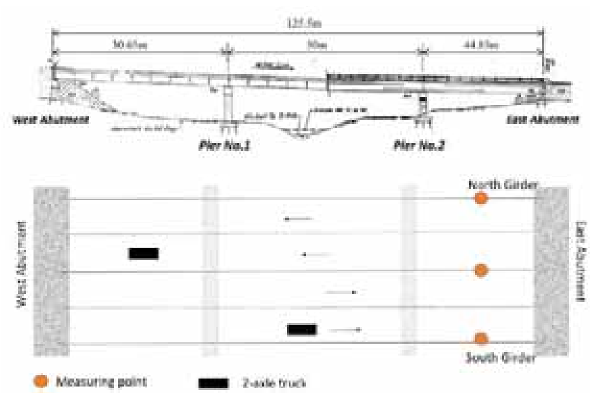

Fig. 6: Vibration Monitoring during Ambient Traffic

Following Table 2 shows the different traffic events that were considered.

Table 2 Different Traffic Events

Girder	Event	Measurement
South Girder	No traffic event	Acceleration and Displacement
	Truck above event	Acceleration and Displacement
North Girder	Truck away event	Acceleration and Displacement
Middle Girder	Truck away event	Displacement

Figures 7 and 8 below show the graphical representation of the "truck above" event and "truck away" event.

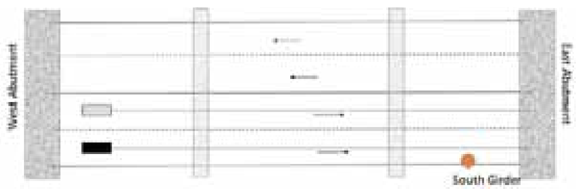

Fig. 7: Truck above Event - South Girder

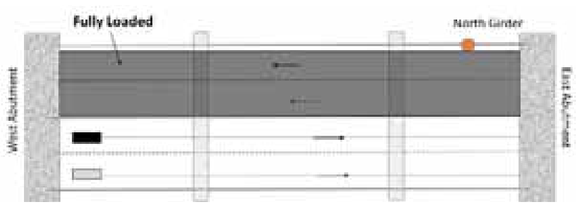

Fig. 8: Truck away Event - North Girder

It should be noted that the truck above event for north girder was not captured due to the heavy traffic on that lane. In Figure 8, fully loaded shows the high volume of static traffic on that particular lane.

3. Results and Discussion

To obtain the vibration response of the structure and compare the data with the mounted sensors, the LSV was set up right under the girder. This study was carried out on 2nd August 2017. The challenge was to shoot the laser beam perpendicular to the vibrating surface. As shown in Figure 9, the laser beam was focused next to the mounted accelerometer for both North and South girders.

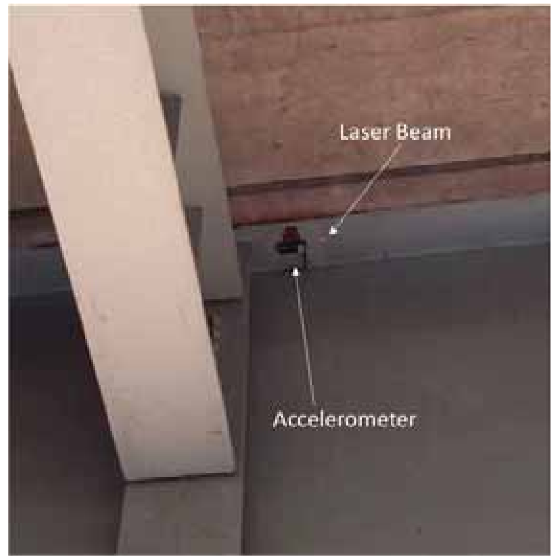

Fig. 9: Laser beam location

The sampling frequency of the LSV used was 250 Hz and maximum acquisition time was 225 seconds for every event of displacement and acceleration measurement.

South Girder:

As can be seen in Figures 10 and 11, the maximum magnitude of the acceleration without traffic and with a truck passing above were 0.14 and 4.1 m/s^2 respectively for the south girder.

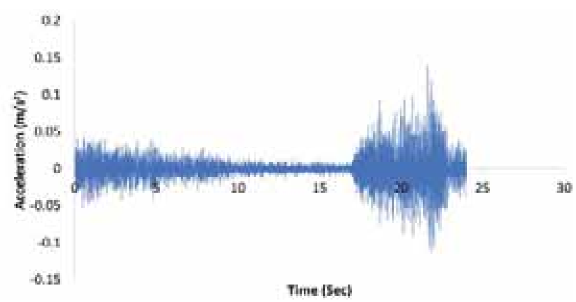

Fig. 10: Acceleration history of South Girder - No traffic event

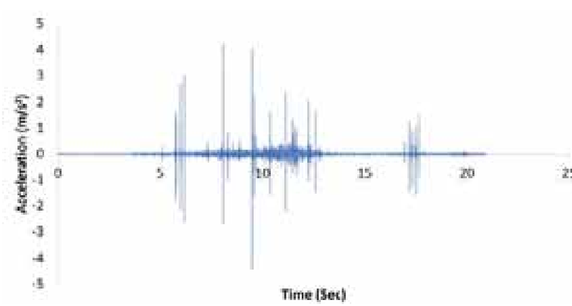

Fig. 11: Acceleration history of South Girder- Truck above event

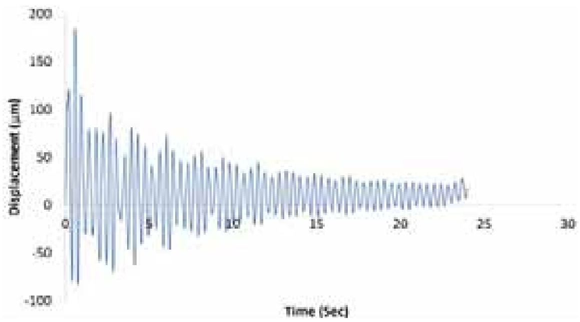

Fig. 12: Displacement history of South Girder- No traffic event

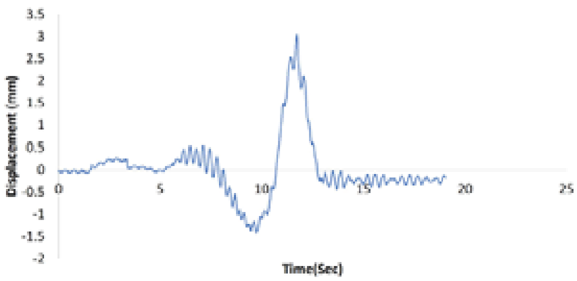

Fig. 13: Displacement history of South Girder- Truck Above event

The total maximum vertical displacement values during no traffic event and the truck above event were found to be 275 µm and 4.5 mm respectively (Figures 12 and 13). In addition to this, the displacement history captured shows the harmonic response of the structure.

Middle Girder:

It should be noted that there was no mounted accelerometer on the middle girder. Only displacement history was recorded using the LSV as shown in Figure 14. Due to high volume of static traffic on the lane above at the time of testing, only the truck away event was captured. The maximum total vertical displacement was found to be 1 mm.

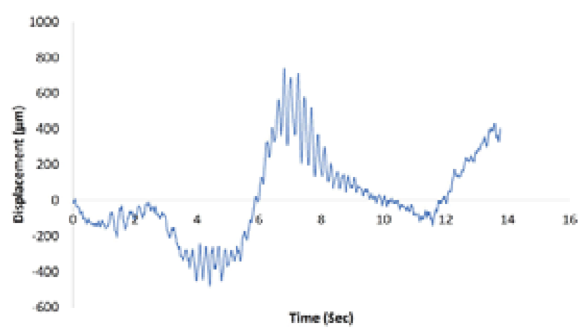

Fig. 14: Displacement history of Middle Girder- Truck away event

North Girder:

Figures 15 and 16 show acceleration and displacement histories of north girder during the "Truck away" event respectively. "No traffic" event was not captured at that time due to heavy traffic on that particular lane. It could be seen that the maximum acceleration was found to be 2.8 m/s^2 & -3 m/s^2 and displacement was found to be -100 µm & 200 µm.

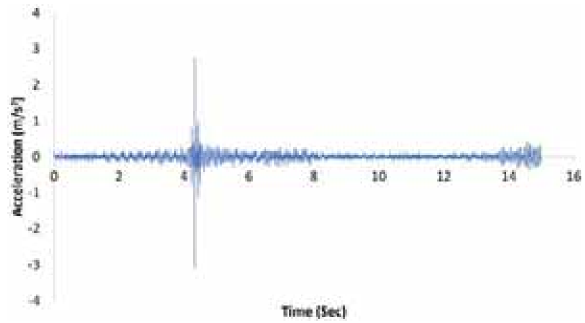

Fig. 15: Acceleration history of North Girder- Truck away event

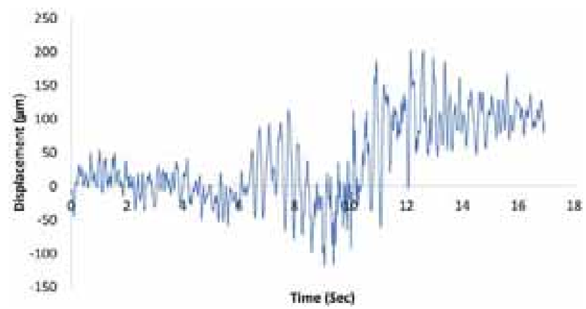

Fig. 16: Displacement history of North Girder- Truck away event

Mounted Sensors:

The time interval set between two measurements of the mounted sensors was 6 min for each sensor at certain threshold value to efficiently use the battery power. The authors found that the threshold values set by the sensor manufacturers were too high for the accelerometers and hence no data were recorded during the time LSV readings were gathered.

Following Figures 17-20 show the tilt measurements of both the cap beams. Direct comparison of the tilt measurements and the LSV data can not be made as the LSV data is in the form of either vertical acceleration or vertical displacements.

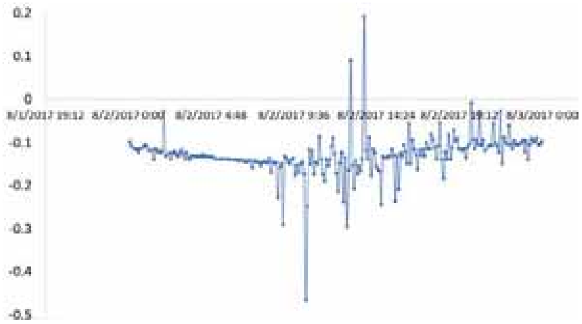

Fig. 17: Tilt (measured in degree) history - Sensor ID-15-44

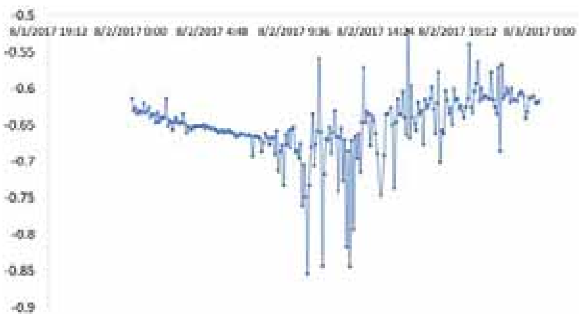

Fig. 18: Tilt (measured in degree) history - Sensor ID-15-34

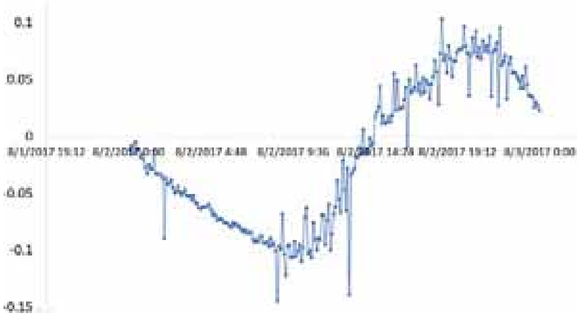

Fig. 19: Tilt (measured in degree) history - Sensor ID-15-35

Maximum tilts were recorded to be -0.45, -0.85, -0.14 and +0.91 degree for sensor 44, 34, 35 and 36 respectively. Negative sign presents the opposite direction of tilt.

Displacement sensor mounted on the abutment recorded the total displacement of 11 mm (Figure 21) in horizontal direction over the entire day.

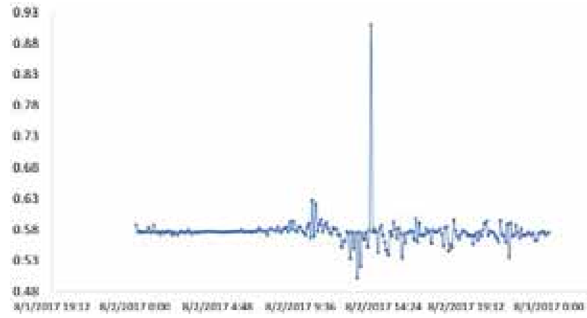

Fig. 20: Tilt (measured in degree) history - Sensor ID-15-36

Fig. 21: Displacement (measured in mm) history - Sensor ID-13-39

4. Conclusions and outlook

The paper demonstrates the use of LSV out on the field to measure the vibration response of the structure by means of true displacement values during the ambient traffic. The data recorded using LSV were very accurate and matched with the response of the structure. Unfortunately, due to lower threshold values of the mounted accelerometers, LSV data could not be compared with the mounted accelerometers' data. However, the future work includes the change of threshold value and conduct the experiment at full scale considering the entire bridge.

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