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Large-Scale Flexible Membrane for Automatic Strain Monitoring of Transportation Infrastructure

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Abstract: Structural Health Monitoring (SHM) of transportation infrastructures is a complex task, typically conducted by visual inspection due to the technical and economical constrains of existing health monitoring technologies. It results that health monitoring is highly dependent on scheduling and on the judgment of the inspectors, which can be costly and ineffective. Thus, it is fundamental to automate the SHM process to allow timely inspection, maintenance, and management of transportation infrastructure. The authors propose a flexible membrane that can be deployed over large surfaces, at low cost, for automatic and continuous monitoring of strains. The membrane, termed sensing skin, is constituted by several patches for surface discretization. Each patch is a soft capacitor, where a measured change in capacitance has a linear correspondence with changes in strain, which allows simple data processing. This paper discusses recent advances in the sensing skin, and demonstrates its promise at smart monitoring of transportation infrastructure. The novel sensor is currently installed on a highway bridge in Ames, Iowa. Preliminary results show the sensor is still functioning as designed. Direct benefits of the proposed technology to transportation infrastructure include 1) improved cost-effectiveness; 2) increased life-span; 3) enhanced resiliency; and 4) higher confidence of the public.

***Key words**: Bridge monitoring; Flexible membrane; Smart infrastructure; Soft sensor; Structural health monitoring.*

Introduction

Developing and integrating automatic damage assessment methods into civil structures is a solution to improving maintenance scheduling and inspection programs. Such improvement would directly benefit our transportation infrastructure by reducing risks associated with insufficient maintenance and increased utilization [1-3]. A solution is to develop a cost-effective monitoring method, with simple data processing, and ease of installation and maintenance. We have presented a novel SHM method in Ref. [4, 5] for large-scale applications. The method consists of a flexible membrane, termed *sensing skin*, easily deployable on large surfaces. This membrane is patterned into numerous individual soft capacitors, forming a matrix of capacitance-based strain gauges.

Advantages of the flexible membrane include 1) inexpensive materials; 2) full polymeric preparation; 3) ease of installation; 4) low voltage consumption of equipment (1-2.5 volts); 5) customizable; and 6) robust with respect to physical damages. The sensing method is similar to fiber-optic approaches for monitoring of large-scale surfaces [6-8], but different in being cost-effective, and capable of monitoring strains over large areas. Piezoceramic-based SHM methods have also been proposed in the literature [9-11] with primary applications to high-frequency measurements.

This paper discusses recent advances in the sensing skin, and demonstrates its promise at smart monitoring of transportation infrastructure. Section 2 summarizes the sensing principle. Section 3 describes a field application, and shows preliminary results. Section 4confirms the performance of the sensing skin in a laboratory setup. Section 5 concludes the paper.

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Sensing Principle

The proposed method is analogous to biological skin, in the sense that it is capable of global monitoring by deploying sensors over very large regions. The strain sensor, termed *sensing patch*, consists of an elastomer film (thermoplastic elastomer) sandwiched by soft compliant electrodes (carbon black) forming the soft capacitor. The external induced strains result in geometrical changes, and therefore in changes in the electronic signals. Fig. 1(a) schematizes the sensing principle. The sensor is adhered to the monitored surface by a bonding agent. A strain (bottom red arrows), for example bending or a crack, produces a change in the sensor geometry (top red arrows), which in turn results in a change in capacitance. Fig. 1(b) is a picture of a sensing patch.

The geometry and material properties of a sensing patch can be altered for customized applications. For instance, to increase a patch sensitivity with respect to a change in its area ΔA, the thickness of the patch can be reduced. Alternatively, it is also possible to increase the polymer permittivity by changing the nano-composition of the material. The sensing patch shown in Fig. 1(b) is composed of a thermoplastic elastomer with 15%vol titanium dioxide for enhanced sensitivity. The change in capacitance of a sensing patch under quasi-static strain is shown in Fig. 2. Here, the sensor shown in Fig. 1(b) is pre-strained at 10% and clamped into a tensile tester (Zwick/Roell Z005). Results show that the signal raises well above noise after 0.2 ppm, where 0.1 ppm corresponds to approximately 0.750 μm. Results from Fig. 2 exhibit a drift in the measurements, which could be a consequence of relaxation of the material. To minimize the drift (including drifts caused by a change in

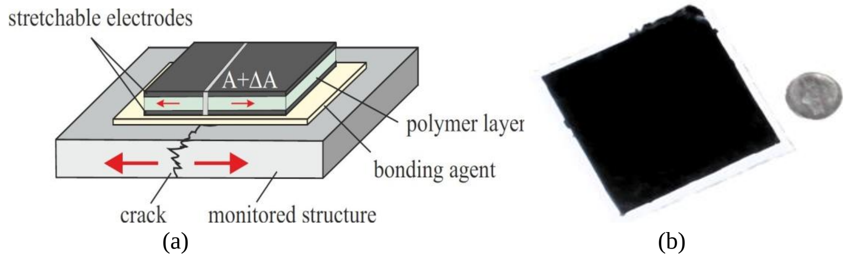


Fig. 1. (a) Schematic of Sensing Principle [14]; and (b) a Sensing Patch, 75 x75 mm (3 x 3 in).

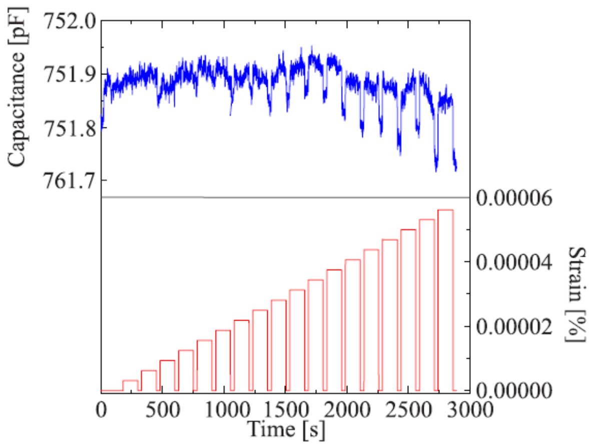


Fig. 2. Capacitance Time History (Above) Under a Quasi-static Strain (Below) [12].

Table 1. Comparison of Modal Properties.

Mode Number	1	2	3	4
Mode Type (Axis)	Weak	Polar	Strong	Weak
FEM (Hz)	12.3	26.5	42.9	55.5
Experimental (Hz)	12.0	23.8	47.2	71.1
Difference (%)	-2.44	-10.2	10.0	28.1

temperature and humidity), a differential measurement method is used, where the difference in capacitances between two nearly identical patches is measured, also enhancing the sensing precision.

The performance of the sensing solution has been demonstrated at detecting cracks [4, 5], quasi-static strain [13, 14], and dynamic strain [12].

Field Application

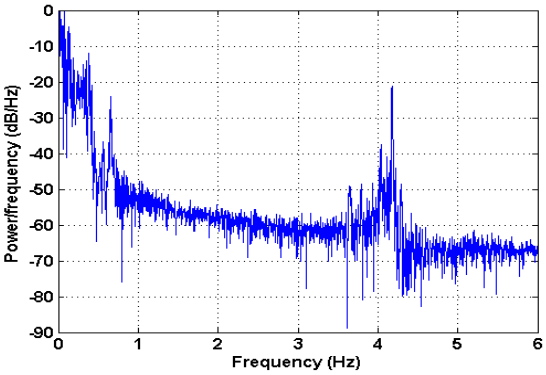
Two sensing patches are being tested on the South Skunk River Bridge, located in Ames, IA, to assess their performance when exposed to a harsh environment. The bridge is a three-span two-lane highway overpass, 98 m (320 ft) long by 9.1 m (30 ft) wide, spanning the South Skunk River on the US-30. The structure has been previously used for an SHM project by Lu et al. [15]. Fig. 3 is a picture of the bridge (eastbound view), and Fig. 4(b) shows two patches installed under the deck in the longitudinal direction above the first girder from the west side, on which the data acquisition system is located (shown in the bottom right corner of Fig. 4(b)). The installation methodology consisted of sanding the surface, cleaning it with acetone, and adhering the patches using an off-the-shelf epoxy for concrete (J-B KWIK^{TM}). The sensing patches were installed in early December 2011.

Preliminary Results

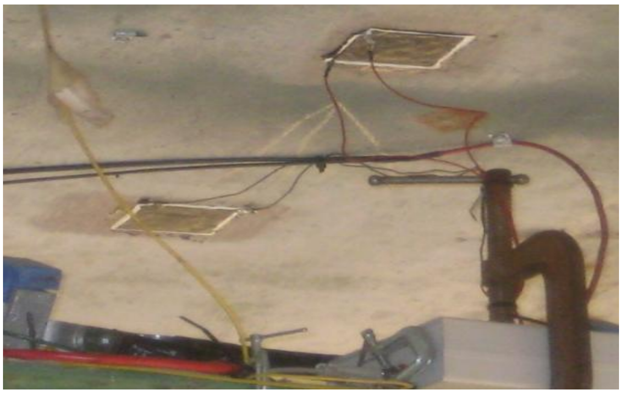
The sensing patches installed on the South Skunk River Bridge are still functioning as designed, but data collection has been considerably impeded by a malfunction of the wireless communication system. The router located under the bridge, the same one as used by Lu et al. [15], has been severely damaged by the Ames flood of Summer 2010. The router has been recently replaced and is now functioning.

Fig. 4(a) shows the frequency response from the patches obtained on March 18th, 2012. The power spectral density was plotted after minor data cleansing. A principal component analysis (PCA) was performed on the autocorrelation of the signal, and the power spectra density plot obtained from a fast Fourier transform on the reconstructed signal from 68% of the singular values. Results show resonant frequencies at 0.63 Hz and 4.2 Hz. Those results are consistent with a previous SHM campaign conducted in 2010 on the same bridge using fiber optic sensors [15], where the authors identified a quasi-static frequency around 0.5 Hz and a fundamental frequency around 4.2 Hz.

Fig. 3. Skunk River Bridge on the I-30, Ames, IA (Eastbound View) [12].

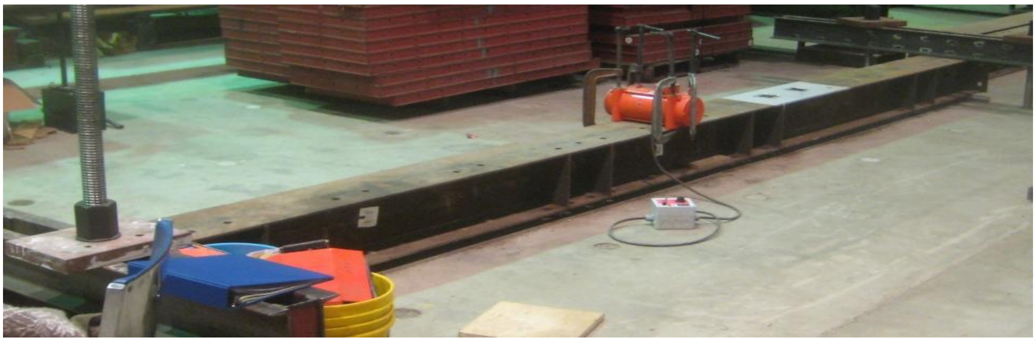


(a)

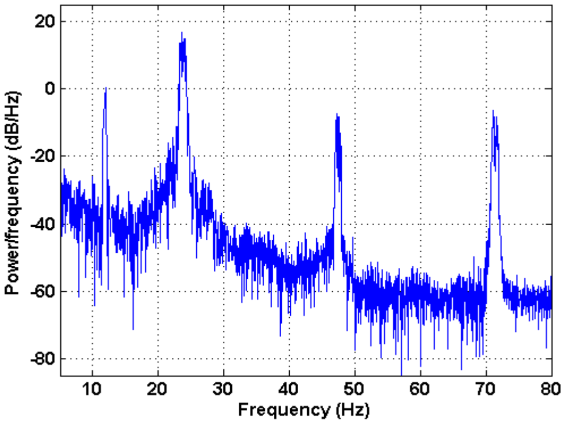


(b)

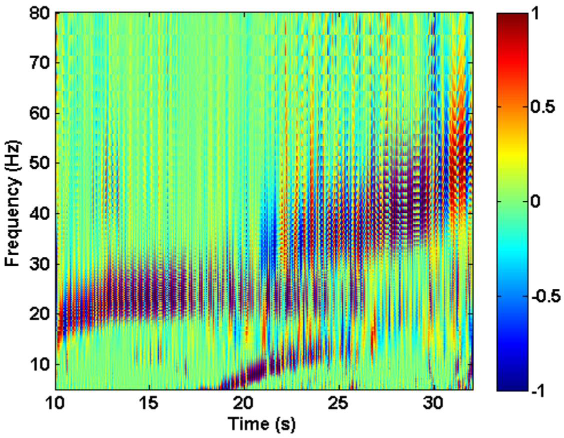
Fig. 4. (a) Power Spectra Density of the Capacitance Signal; and (b) Two Sensing Patches Deployed Under the Deck [12].



(a)



(b)



(c)

Fig. 5. (a) Picture of the Experimental Setup; (b) Pseudo Spectral Density Plot Showing the First Four Frequencies; and (c) Normalized Wavelet Transform of the Response [12].

Laboratory Verifications

Laboratory verifications were conducted to confirm the dynamic sensing capabilities of the patches. Patches were installed on a 5.5 m (18 ft) HP10x42 steel beam simply supported at its extremities, as shown in Fig. 5(a). The beam was excited using a 4000 rpm capacity shaker installed on the top flange, at 2.85 m (9.3 ft) from the right extremity of the beam. Both patches were installed at distance of 280 mm (11 in) from each other, 1.8 m (6 ft) from the right support. A chirp signal was generated manually and the patches responses were recorded over approximately 35 seconds sampled at 200 Hz. A plot of the filtered power spectral density is produced in Fig. 5(b). Table 1 compares modal properties obtained experimentally against a finite element model (FEM) of the beam. The model was built in SAP2000, using soft boundary conditions in the weak direction to match the first modal result. The first 4 modes were identified in the frequency response, but with a larger error for the 4^{th}mode, which can be explained by noise and/or modeling inaccuracies. The sensing patches showed to be capable of detecting the first four natural frequencies of the beam.

Fig. 5(c) shows a wavelet transform using Morlet wavelets on a section of the original signal extracted using a Tukey windowing function to reduce frequency leakage. The chirp signal is denoted by the increasing frequency response over time. The plateau at 23.8 Hz is the fundamental frequency of the torsional mode, which strongly resonates in its neighborhood. A second increasing frequency response can be observed at the bottom center of the plot. This is likely caused by the shaker producing different excitation frequencies along the weak axis of the beam. Results show that the sensor is capable of detecting frequency responses.

Conclusion

We have presented a novel bio-inspired sensor for SHM of transportation infrastructure. Constructed from an array of polymeric capacitors forming soft strain gauges, the membrane allows discretization of strain over large areas, analogous to biological skin.

Preliminary results from the field application on the Skunk River Bridge show the promise of the membrane as a cost-effective SHM solution, and indicate that the sensing material is robust with respect to harsh environmental conditions. Results from laboratory verifications confirmed the dynamic performance of the sensing skin. Impacts of the technology to transportation infrastructure include 1) improved cost-effectiveness; 2) increased life-span; 3) enhanced resiliency; and 4) higher confidence of the public in the installations.

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