Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 168 (2016) 721 – 724

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

Soft elastomeric capacitive sensor for structural health monitoring

Zoltán Rácz*, Eleanor M. Hackney and David Wood

School of Engineering & Computing Sciences, Durham University, Durham, DH1 3LE, United Kingdom

Abstract

Propagation of fractures due to high stress loads are a common cause of structural failure. This paper describes a thin soft elastomeric capacitor (SEC) sensor which can be adhered to structures to monitor strain fields and detect sub-millimeter deformations and fractures. Alterations in a mechanical structure change the geometry of the skin-like parallel plate capacitor sensor and the resulting capacitance change is measured as a change in the resonant frequency of a relaxation oscillator circuit. The sensor system comprising of the SEC sensor, the oscillator circuit and a microcontroller demonstrated its capability to detect millimeter scale stretches.

Keywords: capacitive sensor; soft elastomers; structural health monitoring; relaxation oscillator

1. Introduction

With growing demand for sustainable energy, wind is becoming a key alternative to fossil fuels, providing 15.6% of the European Union's power capacity in 2015 [1]. However, high incurred failure costs and long downtime periods mean that the industry require a robust and economically viable condition monitoring system [2]. Rotor blades are particularly susceptible to failure and their condition monitoring is challenging due to the large surface area and constant movement. Blades are estimated to take up 16-34% of the total turbine manufacturing cost and routine maintenance can rise to $15,000 annually for large 1500 kW turbines [3]. This highlights the need to monitor the conditions of wind turbines blades in order to better plan for maintenance [4]. Current commercial monitoring systems include the SCAIME and Moog RMS systems which rely on fiber optic sensors to monitor strain and temperature, and the BLADEcontrol system that uses accelerometers bonded to the rotor blades. The issues associated with these methods include monitoring large surface areas with high resolution, cost of implementation, and their adaptability to various blade sizes and shapes.

The work presented aims to develop a low-cost skin-like smart sensor array that allows the real-time structural health monitoring, analysis and data processing of wind turbine rotor blades and other mechanical structures. The

* Corresponding author. Tel.: +44 191 33 44300, Fax.: +44 191 33 42408.
E-mail address: zoltan.racz@durham.ac.uk

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.259

novelty of this method is its simplicity and adaptability. This novel technique has the promise to enable real-time monitoring of mechanical deformations and to detect high stresses and micron level surface cracks.

2. Materials and Methods

The soft elastomeric capacitive (SEC) sensor is a flexible flat parallel plate capacitor which consists of a high dielectric polystyrene-*co*-ethylene-*co*-butylene-*co*-styrene (SEBS Dryflex 500120) mixed with TiO_2 composite, enclosed between 64×64 mm^2 conductive electrodes composed of a mixture of SEBS and carbon black. Details of the synthesis method and materials used to create the SEC are provided by Laflamme [5]. The pure SEBS material has a dielectric constant of ϵ_R = 2.2 [6], and is mixed with TiO_2 with has a high static dielectric constant of ϵ_R = 128 [5]. The TiO_2 nanoparticles increase the overall dielectric constant of the capacitor dielectric to 6.5-7 [5]. The sensor is adhered flush against the monitored mechanical structure. As the capacitor is stretched due to a mechanical deformation, the changes in electrode area and dielectric thickness cause a capacitance change as given by Eq. 1.

$$C = C_o \frac{(1+\varepsilon_T)(1-\nu_{CB/SEBS})}{(1-\upsilon_{SEBS/TiO_2})} \tag{1}$$

where C is the stretched capacitance, ε_T is the transverse strain, $\nu_{CB/SEBS}$ is the Poisson ratio for the carbon black/SEBS mixture and υ_{SEBS/TiO_2} is for the TiO_2/SEBS mixture. Because both Poisson's ratios are equal to 0.3, Eq. 1. simplifies to $C = C_o(1+\varepsilon_T)$, and therefore, the capacitance change is $\Delta C = C - C_o = \varepsilon_T C_o$. The capacitance change is measured as a change in the resonant frequency of a relaxation oscillator circuit shown in Fig. 1.

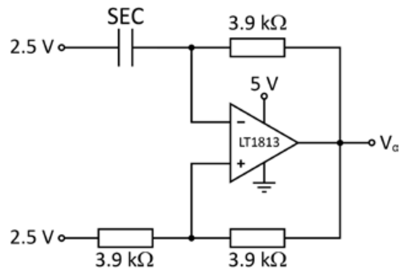

Figure 1. Schematic circuit diagram of the relaxation oscillator.

The resonant frequency of the oscillator is

$$f = \frac{1}{2\,ln(3)RC_{SEC}} \tag{2}$$

where R is the resistances in the circuit and C_{SEC} is the capacitance of the capacitive sensor. The circuit utilizes a Linear Technologies LT1813 operational amplifier and high precision resistors and is connected to an Arduino Mega 2560 microcontroller board for data recording and processing. The capacitive sensor is mounted on two acrylic plates that are separated manually to stretch the sensor. The complete system is shown in Fig. 2.

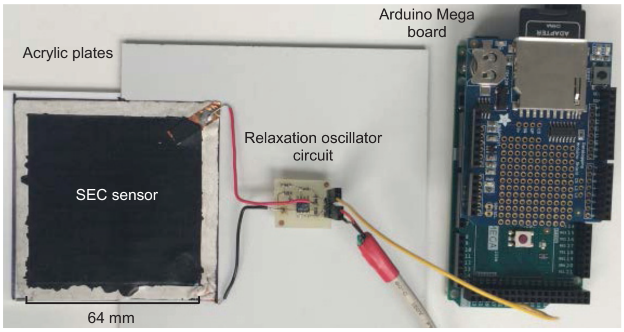

Figure 2. Photograph of the soft elastomeric capacitor based sensor system showing the sensor, the relaxation oscillator circuit and the Arduino microcontroller board.

The Arduino board is powered through its USB port which allows the output values to be processed in real time by a connected computer using the Processing software.

A finite element model, shown in Fig. 3., was developed in COMSOL Multiphysics to calculate the expected changes in capacitance. This will provide a basis to understand the mathematical and physical fundamentals of the SEC and to predict its response for more complex mechanical strains.

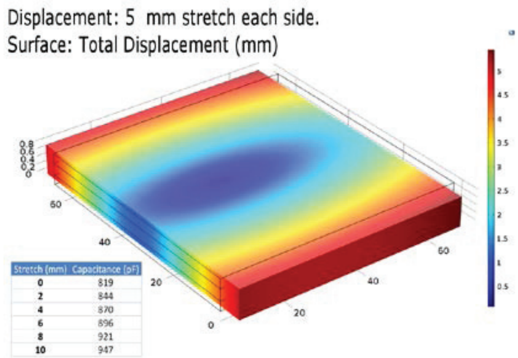

Figure 3. Three-dimensional finite element model of a stretched soft elastomeric capacitor showing changes in capacitance due to changes in the sensor geometry.

3. Results and Discussion

A typical frequency response of the sensor system to a random stretch pattern is shown in Fig. 4. The sensor was stretched in one direction by 0, 1, 2 and 3 mm in a random sequence.

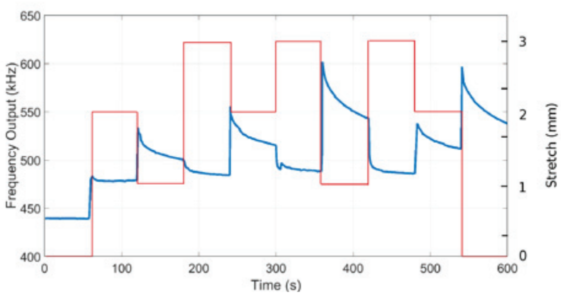

Figure 4: Frequency output of the relaxation oscillator (blue) in response to the SEC being subjected to a stretch pattern (red).

The average frequency shifts caused by each millimeter stretch are shown in Fig. 5. The plot shows a linear relationship between the stretch length and the frequency change which is consistent with the theory and the finite element model described above. The sensitivity of the sensor based on the slope of the function is approximately 16 kHz/mm.

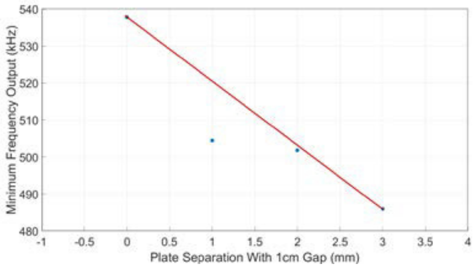

Figure 5: Frequency readout from the relaxation oscillator circuit when the SEC is stretched at millimeter intervals.

4. Conclusions

A system based on a soft elastomer capacitive sensor, a relaxation oscillator circuit and an Arduino microcontroller board has been introduced that has ~16 kHz/mm sensitivity to axial strain. The results have proven to be consistent with theory. Since frequency measurements on the order of a few hundred hertz are feasible with the used circuitry, the above described soft elastomer sensor has the potential to detect sub-100 micron cracks. A number of these sensors with the associated circuitry can be used in future to produce a smart sensing array which would allow the real-time structural health monitoring of mechanical structures.

Acknowledgements

The authors would like thank Simon Laflamme of Iowa State University for providing sample sensors.

References

[1] European Wind Energy Association, Wind in power, 2015 European Statistics, February 2016.
[2] C. Crabtree, D. Zappalá, P. Tavner, Survey of Commercially Available Condition Monitoring Systems for Wind Turbines, European Wind Energy Conference 2014. Barcelona, Spain, 10-13 March 2014.
[3] E. Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer 2nd edition, 2006.
[4] M. A. Rumsey, J. A. Paquette, Structural Health Monitoring of Wind Turbine Blades, in in Proc. SPIE, vol. 6933, Smart Sensor Phenomena, Technology, Networks, and Systems 2008, p. 69330E.
[5] S. Laflamme, M. Kollosche, J. Connor , G. Kofod, Robust Flexible Capacitive Surface Sensor for Structural Health Monitoring Applications, J. Eng. Mech., 139 (2013) 879–885.
[6] McCarthy, D.N., Risse, S., Katemol, P., and Kofod, G. (2009). The Effect of Dispersion On The Increased Relative Permittivity of TiO2/SEBS composites. Journal of Applied Physics. 42 (2009), p. 145406.