Speckle velocity sensor for underground infrastructure thermal monitoring

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A low-cost interferometric temperature variation sensor technique has been developed in the scope of underground infrastructure thermal monitoring. Based on speckle velocity analysis, the method allows for temperature change detection. A speckle video processing chain including Horn-Schunck algorithm is exploited in order to link the temperature solicitation to the measured speckle velocity. In-situ field validation, hot-spot localization and related thermal modelling are under progress.

Introduction

A thermal sensor that meets underground electrical distribution monitoring requirements is presented. Low-cost objective is reached through the exploitation of an intermodal interferometric speckle technique. In this paper, thermal problem is first introduced. Sensing technique is then described and finally experimental results are presented.

Thermal problem

From the thermal point of view (see figure 1), there is a balance between dissipated power by an underground cable ($W_{gen.}$), transferred power through the surrounding materials ($W_{trans.}$) and internal energy change of the surrounding materials ($W_{int.}$).

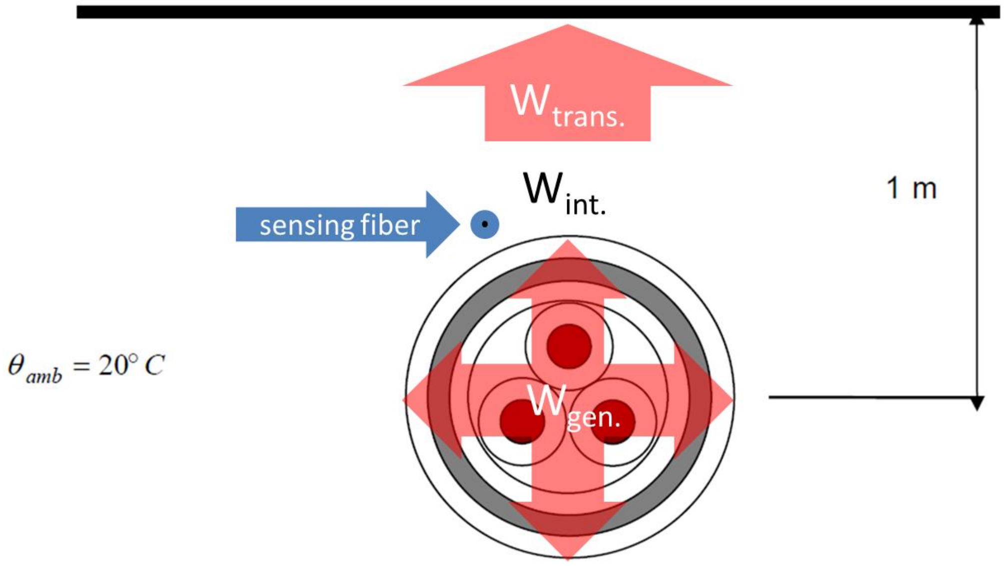

Figure 1 : thermal problem for an underground cable and its surroundings

This balance can be expressed by equation (1) and (2) with θ the temperature (K), *I* the current in the cable (A), *V* the volume of heated material (m³), ρ the thermal resistivity of the surrounding materials (K.m.W^{-1}) and c_v the volumetric specific heat of the material (J.m^{-3} K^{-1}).

$$W_{\text{gen.}} - W_{\text{trans.}} = W_{\text{int.}} \quad (1)$$

$$\frac{I^2.R}{V} + \frac{1}{\rho}\nabla^2\theta = c_v\frac{\partial\theta}{\partial t} \quad (2)$$

Global increase of cable charge can be tracked by current measurements and comparison with rating computations from thermal models. Unfortunately, even very sharp modelling cannot take into account complex soil and local variation like drying due to mislaying of surrounding materials or unknown obstacles. This is why, with cable over-exploitation or complex soil structure, absolute temperature fiber optic sensing is an answer. In the market context, only strategic cable can afford this sharp but expensive technique.

Instead of absolute temperature monitoring, it is proposed to monitor thermal power by conventional electrical method ($W_{gen.}$ term) and internal energy variation ($W_{int.}$ term) of the surrounding materials by an optical fiber laid down next to the cable (see figure 1). With these parameters, it is possible to compute transferred heat power ($W_{trans.}$ term) and compare it to an acceptance level that insures cable integrity. Compared to absolute temperature measurements, temperature variation measurements are cheaper as soon as relative interferometric techniques can be used.

Sensing technique

Historically treated as a drawback for fiber optic telecommunications, speckle has been extensively studied from the modal noise point of view ([1], [5], [2]). When coherent light is launched into a multimode fiber, power is distributed among different modes. If coherence conditions are satisfied, these latter interfere and create at the output of the fiber a pattern called speckle. Individual modal propagation constant and phase change with external physical conditions like temperature and vibration. As a consequence, the pattern changes also in shape and contrast (see figure 2).

This technique has been widely described and applied to vibration measurements ([3], [7], [8]). Temperature action on the fiber leads to two phenomena: modal propagation constant variation via refractive index (*n*) variation and path length (*L*) modulation via thermal expansion. According to [4], we have the following values for fused-silica:

$$\frac{1}{L}\frac{dL}{d\theta} = 5.10^{-7}K^{-1} \quad (4)$$

$$\frac{dn}{d\theta} = 10.10^{-6}K^{-1} \quad (5)$$

The main objective that has been identified is to measure temperature variation against time for a kind of material in order to assess its internal energy modification at volume kept constant. The proposed sensing technique is based on speckle contour velocity computation. The pattern is first thresholded at a level that allows individual spots discrimination. Thresholded speckle is then processed by the Horn-Schunck optical flow ([6]) computation algorithm. Speckle Rate of Change (SRoC) is then defined as the averaged velocity of all the pixels in the speckle image. Finally, we have the equation (5), with x and y respectively the row and column index of the image, R and C respectively the total number of rows and columns of the image and V the velocity. Figure 2 shows the sensing technique principle.

$$SRoC = \frac{\sum_{x=0}^{R-1}\sum_{y=0}^{C-1} | \overline{V(x,y)} |}{R.C} \quad (5)$$

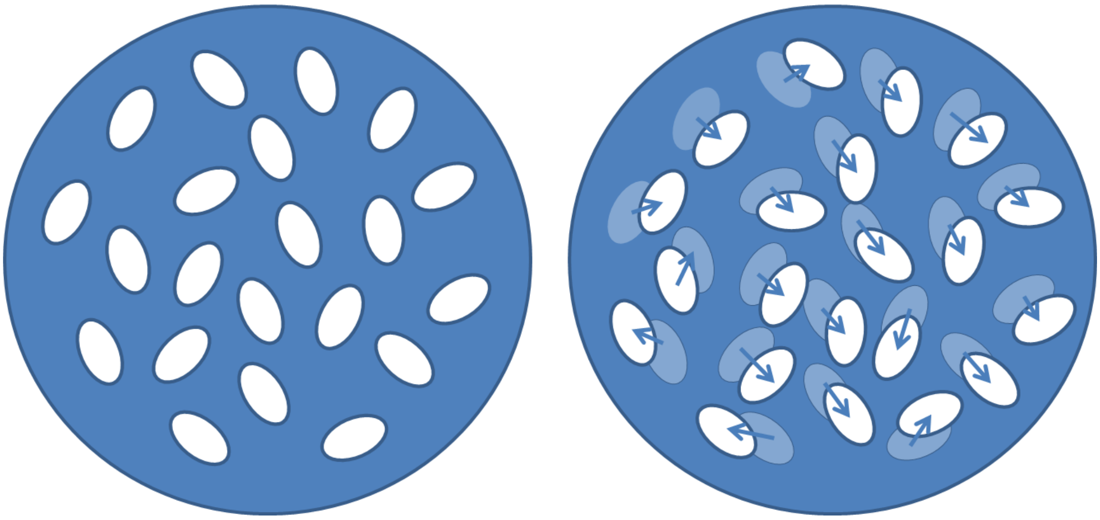

Figure 2 : speckle patterns and velocity vectors (left : initial state, right : after temperature increase)

Experimental approach

A 1 meter long section of a MOLEX PREMISE NETWORK OM1 patchcord fiber has been brought from 17°C to 35°C within 40 minutes. Figure 3 shows computed speckle and measured temperature variation on the same graph. A linear dependency between SRoC and temperature variation against time has been observed through the analysis of a 7000 samples set. Signal to noise ratio can be increased both by image filtering and environmental (vibration and temperature) parameters control. Further analysis needs to be conducted with constant temperature variation for calibration and reproducibility assessment purpose.

Conclusion

A speckle velocity based fiber optic sensor for temperature variation monitoring is presented. This system is intended to monitor internal energy of underground infrastructure surroundings. Low-cost setup is achieved through speckle image processing and Horn-Schunck optical flow computation. A linear dependency between computed speckle velocity index and temperature variation against time has been observed. Further developments are focused on in-situ validation, advanced thermal modelling and hot spot localization.

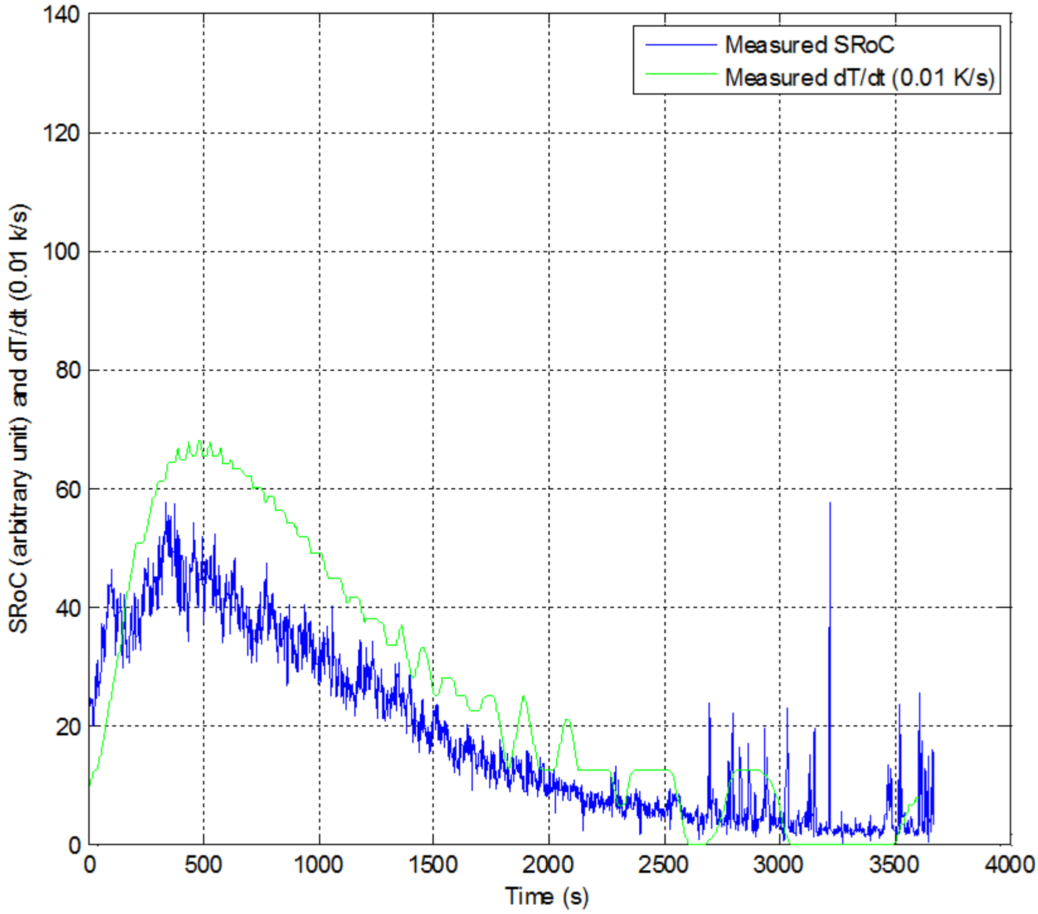

Figure 3 : experimental results - measured temperature variation and measured SRoC

References

[1] R. Epworth, “The phenomenon of modal noise in analogue and digital optical”, Fibre systems. 4th European Conference on Optical Communications, page 492, 1968.

[2] J. Goodman and E. Rawson, “Statistics of modal noise in fibers: a case of constrained speckle”, Optics letters, 6(7):324 6, July 1981.

[3] J. Bucaro, H. Dardy and E. Carome. “Optical fiber acoustic sensor”, Applied optics, 16(7):1761, January 1977.

[4] G B Hocker. “Fiber-optic sensing of pressure and temperature”, Applied Optics, 18(9):1445-1448, 1979.

[5] E. Rawson, J. Goodman, and R. Norton, “Analysis and measurement of the modal-noise probability distribution for a step-index optical fiber”, Optics letters, 5(8):357, August 1980.

[6] Berthold K.P. Horn and Brian G. Schunck, “Determining optical flow. Artificial Intelligence”, 17(1-3):185-203, August 1981.

[7] W. Spillman, B. Kline, L. Maurice, and P. Fuhr. “Statistical-mode sensor for fiber optic vibration sensing uses”, Applied optics, 28(15):3166 76, August 1989.

[8] Z. Zhang and F. Ansari, “Fiber-optic laser speckle-intensity crack sensor for embedment in concrete”, Sensors And Actuators, 126(May 2005):107-111, 2006.