Long-range, Power-efficient Distributed Flow Measurements Using Chirped-pulse Phase-sensitive Reflectometry

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Abstract: We demonstrate a technique allowing to perform distributed wind speed measurements over >17 km with <0.6 km/h uncertainty at only 60 mW/m of power dissipation. Applications in dynamic line rating and catenary monitoring are envisaged.
OCIS codes: (060.2370) Fiber optics sensors; (290.5870) Scattering, Rayleigh; (280.0280) Remote sensing and sensors; (120.4825) Optical time domain reflectometry; (280.7250) Velocimetry.

1. Introduction

Certain engineering applications are currently putting attention in obtaining distributed measurements of wind speed across large distances (tens of kilometers). One interesting potential application of large-scale spatially-resolved anemometry is the optimization of power transmission along overhead power lines [1]. The line ratings typically applied by electric grid operators are well under the maximum possible values, essentially because of reliability and safety concerns. Improved efficiency can be achieved through new power rating models named dynamic line rating (DLR) [2]. These models are intended to maximize the electric power delivered through the power cables by tracing the temperature distribution along their length and section, and ensuring that no point goes over the specified temperature rating. They depend on the conductor geometry, the local weather conditions, and the forecast confidence intervals to which they are subject. Real-time update of these models requires accurate and real-time weather information along the power line network, with particular emphasis on temperature and wind speed. While temperature distribution monitoring is currently becoming almost standard [3], wind speed distribution monitoring is still far from being solved. Another interesting example of this need is catenary monitoring in high speed railway, where lateral wind may cause disruption in the catenary-pantograph interaction (for moderately high wind loads), and even wagon derailment and overturn in more severe cases [4,5].

One of the most accepted techniques providing flow speed measurements relies on adapting *hot wire anemometry* concepts [6] to devise a reliable distributed anemometer. This technique considers the electrical power dissipated as heat by a thin, conductive wire as a way to monitor its convective cooling efficiency and, indirectly, the speed of the fluid that takes the produced heat away. Indirect flow measurements are thus performed simply by monitoring the fiber temperature distribution via conventional distributed sensing methods, like in Ref. [7]. There, to achieve wind speed resolutions of < 1 km/h, the temperature variation in the fiber under test was in the order of 100 K, leading to a large power dissipation per meter of fiber. Such power dissipation turns out to be unassumable for infrastructure operators. Moreover, while the spatial resolution proved in [7] was remarkable, the range covered by the interrogation system used was < 2 km, making the performance not suitable for applications like DLR, where long spans need to be monitored.

Recently, the authors demonstrated a technique (chirped-pulse Phase-sensitive Optical Time-Domain Reflectometry, ΦOTDR) allowing the distributed monitoring of temperature over tens of km with mK resolution and kHz update rate [8]. Here we show that this technique can be successfully adapted to measure the wind speed once a proper calibration of the sensor is done, potentially reaching sensing ranges two orders of magnitude longer than the exiting implementations [7].

2. Sensor fundamentals and setup

When a thin wire (like a metal-coated optical fiber) is heated by a current, the incoming power is completely dissipated to its surrounding medium allowing a steady temperature to be reached. According to the theory of heat transport [9], the main dissipative contribution for the considered system is convection, which can be forced by an imposed flow. The value of the final wire temperature is determined by the balance of the dissipated and input (P) powers, which depends on the speed of the fluid (u) through the convective efficiency $h(u)$. The mentioned balance can be described by *Newton's law of cooling*:

$$P = h(u)\, S\, \Delta T, \quad (1)$$

where the term ΔT represents the temperature difference between the wire surface and the fluid and S represents the surface of the wire exposed to the flow. According to Eq. 1, measuring the wire temperature at a constant input power allows to calibrate the system as an anemometer. Although these principles have previously been implemented on fiber optic setups [7], there is an important handicap if the injected power is to be kept within a reasonable range: the temperature sensitivity of the system. To solve this limitation, we propose applying a distributed temperature sensing method able to improve the sensitivity in two orders of magnitude: the chirped-pulse ΦOTDR sensor.

The traces outcoming from a chirped-pulse ΦOTDR qualitatively differ from the conventional ΦOTDR ones in the way they reflect a local perturbation on the fiber under test. While the usual local change in conventional ΦOTDR traces is a non-linear reshaping of the detected signal, the chirped pulse echo shows a time shift in the local trace shape proportional to the applied stimulus [8]. Thus, by analyzing the local delay $\delta t(z)$ (which maps the intensity of the applied temperature stimulus, $\delta T(z)$), temperature sensitivities of mK can be achieved, with an update rate limited solely by the time of flight of the fiber under test (typically kHz for tens of km long fibers). The relation of these variables with the chirp bandwidth ($\delta \nu$), its central frequency (ν_o) and the duration of the pulses (τ_p) is [8]:

$$\delta t(z) = 6.92 \cdot 10^{-6} \mathrm{K}^{-1} \frac{\nu_o}{\delta \nu}\, \tau_p\, \delta T(z). \quad (2)$$

The setup of the interrogator (Fig. 1) includes all the elements present in a conventional ΦOTDR system but adds the means to generate the chirp and perform the detection at the bandwidth it yields (~1 GHz). A stabilized continuous wave signal is generated by a laser diode (LD, ~1550 nm). The pulses and their linearly chirped frequency pattern are achieved by modulating its bias current and synchronously chopping the LD output. This is done through a common signal generator (SG) which drives both the LD and a semiconductor optical amplifier (SOA). At its output, a stage comprising an erbium-doped fiber amplifier (EDFA) and a tunable filter complete the generation of the required pulses. To detect the signal backscattered along the fiber under test (FUT), a circulator redirects the returning power to a second amplifying and filtering stage, producing the adequate signal for the fast p-i-n photodetector. Traces are acquired in a 40 GSa/s oscilloscope and processed in a computer. The isolators and attenuators included in the scheme provide control over undesired reflections and the power entering each component. Otherwise, an excess of power could cause non-linear effects in the amplifiers and FUT.

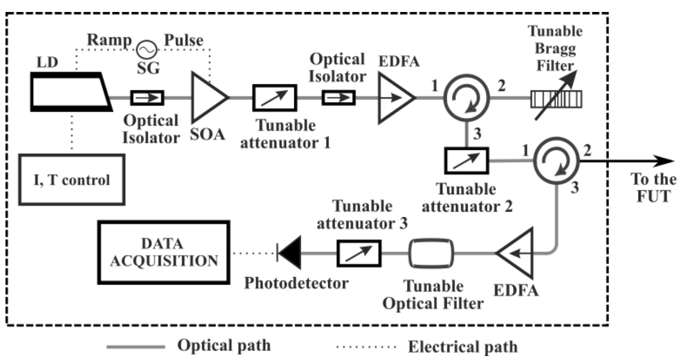

Figure 1: Sensor interrogator setup. Acronyms are explained in the main text.

The FUT (a 13 m long copper-coated single-mode fiber) was placed inside a wind tunnel where wind speed was controlled and monitored by a calibration anemometer. In our case, the temperature measurement tracked the heating and cooling cycles due to a switched current (60 mW/m at 100 mHz) over 4 minutes before the wind speed was modified, with 10 m spatial resolution (100 ns pulses). Owing to the current switching, a spectral analysis of the temperature evolution at the driving frequency easily quantifies the difference between the heated fiber (on state) and the room (off state) temperatures, while it naturally bypasses slow thermal drifts, laser phase noise effects, etc. Note that the measurements have been performed with and without a 17 km lead fiber in front, obtaining roughly the same results.

3. Results

The acquired temperature exponential curves were processed by a Fast Fourier Transform (FFT) algorithm. The spectra resulting from the measurements done at different values of the wind speed is shown in Fig. 2 (left). The plot demonstrates the dependence of the peak-to-peak amplitude of the temperature evolution (ΔT) with u, reflected on the magnitude of its peaks at the driving frequency and its harmonics. The FFT amplitude at the 100 mHz peak is considered together with the calibration anemometer data to obtain the quadratic fitting shown in Fig. 2 (right). The fitting statistics allows to set an uncertainty margin in the wind speed measurements performed with our system. We have chosen to define it as $\delta u/2$, where δu corresponds to de width between the shown fit 95 % confidence bounds. Although this uncertainty depends on the wind speed, it could be adaptatively optimized for a range of interest by tuning parameters like the temperature sensitivity (chirp bandwidth), the current switching frequency, or the total measurement time. In the settings given above, for speeds around 0.25 m/s, the achieved ~±0.15 m/s uncertainty is comparable to the one obtained in [7]. To characterize the fiber anemometer sensitivity, we have calculated and represented the inverse of the calibration curve slope in the same figure (red curve, right axis), obtaining a maximum absolute value of ~$1.8\,\frac{\mathrm{m}}{\mathrm{s}}\mathrm{K}^{-1}$. This result is roughly two orders of magnitude higher than the sensitivity reported in [7], and it shows the fact that the same wind speed accuracy than that reported in [7] (with a 100 K temperature change) can be obtained in our system using only ~1 K change. In other words, for a performance comparative to be fair, these parameters must be normalized by the power per fiber unit length invested in its heating process. As one may expect, the power injected in our system was reduced in a factor 90 when comparing with the one employed in [7], while achieving a similar value of uncertainty.

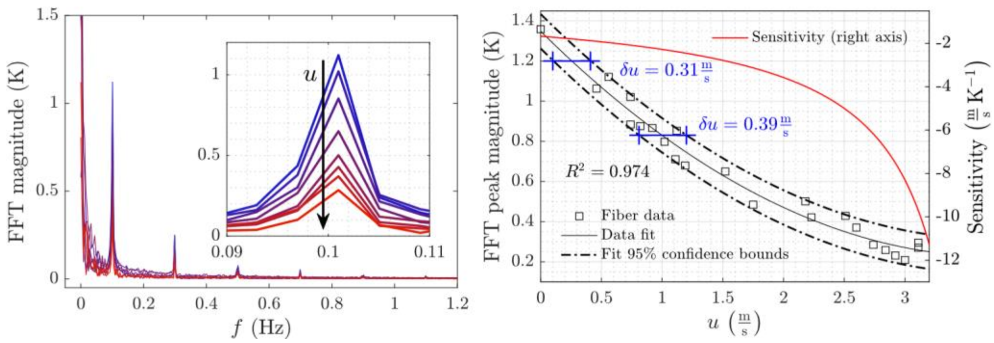

Figure 2: Left: Fiber thermal response to the switching current for different wind speeds in the frequency-domain. Right: driving-frequency peak values obtained from the FFT curves. The sensitivity is also plotted (right axis).

4. Conclusions

An anemometer based on chirped-pulse ΦOTDR and hot wire anemometry principles has been designed and tested. Thanks to the high sensitivity and single-shot temperature tracking capabilities of the chirped-pulse ΦOTDR, the presented method has been able to perform accurate wind speed measurements while dramatically reducing the power density required to reliably operate the sensor. The results have proven a power consumption reduction that could represent a sensing range increase of almost two orders of magnitude, when compared with the existing literature, while keeping similar values of measurement uncertainty. This solution to the range limitation could bring a useful tool to the field of distributed sensing, having a deep impact in many industry sectors where truly distributed weather monitoring is essential, like rail transport and power lines operation.

4. Funding

This work was supported by: the ERC through project U-FINE (gr. 307441) and a FP7 ITN ICONE program (gr. 608099); the EC H2020 and Spanish MINECO (project DOMINO, ERANET Cofund Water Works 2014 call); the FINESSE project MSCA-ITN-ETN-722509; the MINECO (projects TEC2013-45265-R, TEC2015-71127-C2-2-R, a FPI contract and a “Ramón y Cajal” contract); the regional program SINFOTON-CM: S2013/MIT-2790; and the University of Alcalá (FPI contract).

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