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Distributed temperature sensing in optical fibers based on Raman scattering: demodulation algorithms

Abstract

Distributed temperature sensing systems (DTS) has improved over years thanks to the improvements in configurations, components and demodulation calculating algorithms. The demodulation algorithms have been improved depending on the application and the environment, in which the fiber is installed, in order to obtain accurate measurements of temperature and distance. This study discusses the conventional calculating methods and proposed algorithms for different configurations for DTS systems.

Keywords: Distributed Temperature Sensing (DTS), Optical Time Domain Reflectometry (OTDR), spontaneous Raman back-scattering, demodulation algorithms.

1. Introduction

The capability of the distributed temperature sensing (DTS) systems based on optical fibers has improved over the years. Systems' spatial resolution, temperature resolution and time resolution have been improved through apparatus optimization, system configuration and demodulation algorithms [1].

The self-calibration of the Raman distributed temperature sensing system enables detecting the location of the breakpoint if the fiber damages [2]. One must eliminate the effect of local attenuations at the time of deployment and afterward continuously in order to achieve an accurate temperature measurement. These local attenuations take place due to the inherent attenuation difference in Stokes and anti-Stokes signals. The difference in wavelengths between Stokes and anti-Stokes signals ranges from 100 to 200 nm depending on the light source [3].

Under static operating conditions, commercial DTS based on Raman scattering measure temperatures with an accuracy of ±0.2°C, while during periods of rapid heating or cooling may return temperatures with an accuracy of ±1–2°C. Errors of this magnitude affect the goals of the installation [4].

This article studies existing calibration and demodulation solutions that were proposed to enhance DTS systems' accuracy in different configurations and applications.

2. Conventional calculation methods

DTS systems use optical fibers as multi-point temperature sensors [5]. Multi-mode optical fibers are commonly used in DTS systems. Collected probes' results are analyzed in the optical time domain reflectometry (OTDR) [6], focusing on the Raman Stokes and anti-Stokes signals, which frequencies are [7]:

$$v_S = v_0 - \Delta v \tag{1}$$

$$v_{AS} = v_0 + \Delta v \tag{2}$$

where: v_0 – is the frequency of the light source, Δv – is the Raman frequency shift in Hz.

The number of scattered Stokes and anti-Stokes is given in equations [2]:

$$N_S = k_s S v_S^4 N_e exp[-(\alpha_0 + \alpha_s)L] R_S(T) , \tag{3}$$

$$N_{AS} = k_{As} S v_{As}^4 N_e exp[-(\alpha_0 + \alpha_s)L] R_{AS}(T) , \tag{4}$$

$$R_S(T) = \left[1 - exp\left(\frac{-h\Delta v}{kT}\right)\right] , \tag{5}$$

$$R_{AS}(T) = \left[exp\left(\frac{-h\Delta v}{kT}\right) - 1\right] , \tag{6}$$

where: k_S, k_{AS} – are the coefficient to the cross-sections of Stokes and anti-Stokes respectively, S – is the back-scattering coefficient of the fiber, v_S, v_{AS} – are the frequency of Stokes and anti-Stokes photons respectively, N_e – is the number of the photons at the injection point of the fiber α_0, α_S, α_{AS} – are the transmission loss coefficients of the incident, Stokes and anti-Stokes respectively, R_S, R_{AS} – are the coefficients relevant to the Boltzmann distribution describing population of the ground and excited vibrational levels of fiber molecules, L – is the length of the fiber, h – is Planck constant, k – is Boltzmann constant.

The intensity ratio between Stokes and anti-Stokes shifts is uniquely related to temperature, and can be calculated by [5]:

$$R = \left(\frac{\lambda_S}{\lambda_{AS}}\right)^4 exp\left(\frac{hc\Delta v}{kT}\right) , \tag{7}$$

where: λ_S, λ_{AS} – are Stokes and anti-Stokes wavelengths respectively, T – is the absolute temperature.

The intensity of Stokes signals is higher than the anti-Stokes signals intensity. The anti-Stokes transition probability is higher when molecule temperature is increased [8]. For a single-ended system, the ratio between Stokes and anti-Stokes intensities along the fiber can be obtained by [9]:

$$R(z,T) = \left(\frac{\lambda_S}{\lambda_{AS}}\right) exp\left(\frac{hc\Delta v}{kT} - \int_0^z [\alpha_{AS}(\xi) - \alpha_S(\xi)]\, d\xi\right) , \tag{8}$$

where: z – is the distance of the measured point from the source, $\alpha_S(\xi)$, $\alpha_{AS}(\xi)$ – are the respective fiber attenuation coefficients for Stokes and anti-Stokes. Thus temperature can be calculated using [10]:

$$T(z) = \frac{-h\Delta v}{k} \frac{1}{ln\left(R\left(\frac{v_0+\Delta v}{v_0-\Delta v}\right)^4\right)} , \tag{9}$$

The scattering point distance [5]:

$$z = \frac{ct}{2n} , \tag{10}$$

where: c – is the speed of light in the vacuum, t – is the measurement time, n – is the reflective index of the fiber. Raman anti-Stokes to Stokes Ratio for the loop configuration can be obtained by [4]:

$$R = \frac{\{[I_{AS}^1(T(x))][I_{AS}^2(T(X))]\}}{\{[I_S^1(T(x))][I_S^2(T(X))]\}} , \tag{11}$$

where: $I^{1,2}$ – are the detector signals for two measurements of the back-scattered Raman Stokes and anti-Stokes at the point x.

DTS systems based on Raman scattering and OTDR calculations suffer from the instability of the attenuation along the fiber, the heat and humidity around the fiber and the wavelength dependent losses (WDL) at the Stokes and anti-Stokes wavelengths [11]. In order to obtain more accurate temperature measurements, the effect of the above mentioned issues should be eliminated. Thus, many studies discussing possible solutions were published, presenting configurations and calculations for different applications and environments.

3. Demodulations for single-ended configurations

Liu and Zongjiu [2] present a demodulation method for temperature measurements in optical fibers using Rayleigh scattering to demodulate anti-Stokes power curve instead of Stokes scattering. The conventional demodulation, which method uses Stokes Raman scattering as a reference channel to demodulate Raman anti-Stokes power curve, relies on the measurements of Raman Stokes and anti-Stokes power curves at certain time t_0, and calculating their ratio at that time from:

$$\frac{N_{AS}(t_0)}{N_S(t_0)} = \frac{k_{AS}}{k_S}\left(\frac{v_{as}}{v_s}\right)^4 exp\left(\frac{-h\Delta v}{kt_0}\right) exp[-(\alpha_{AS}-\alpha_S)L] \quad (12)$$

Then the power curves of Raman Stokes and anti-Stokes is measured at a known time t, and the anti-Stokes to Stokes ratio at that time is calculated by:

$$\frac{N_{AS}(t)}{N_S(t)} = \frac{k_{AS}}{k_S}\left(\frac{v_{as}}{v_s}\right)^4 exp\left(\frac{-h\Delta v}{kt}\right) exp[-(\alpha_{AS}-\alpha_S)L] \quad (13)$$

Thus the temperature is calculated by:

$$\frac{N_{AS}(t)N_S(t_0)}{N_{AS}(t_0)N_S(t)} = \frac{exp(-h\Delta v/kt)}{exp(-h\Delta v/kt_0)}, \quad (14)$$

$$T = \frac{h\Delta v t_0}{h\Delta v - kt_0 ln\left[\frac{N_{AS}(t)N_S(t_0)}{N_{AS}(t_0)N_S(t)}\right]}, \quad (15)$$

This demodulation method is useful in eliminating the instability of pulse source and the effect of losses related to the coupling, fiber optic connectors, fiber bending and transmission. However, sometimes it is difficult to calibrate the temperature due to the inequality of scattering coefficient, responsiveness, and filter factor for both anti-Stokes Raman scattering and Stokes Raman scattering.

The demodulation method presented in [2] relies on the use of Rayleigh Raman power curve to demodulate anti-Stokes Raman power curve, basing on assumptions that the intensity of the Rayleigh scattered light is higher than the spontaneous Raman scattering light. This method measures Raman anti-Stokes and Rayleigh power curves at certain time t_0, their ratio is defined as a baseline. Then the power curves of Raman anti-Stokes and Rayleigh is measured at a known time t:

$$\frac{N_{AS}(t)}{N_R(t)} = \frac{k_{AS}}{k_R}\left(\frac{v_{as}}{v_R}\right)^4 exp\left(\frac{-h\Delta v}{kt}\right) exp[-(\alpha_{AS}-\alpha_R)L] \quad (16)$$

Basing on the fact that temperature effects of the Rayleigh scattering is insignificant, thus: $N_R(t_0)=N_R(t)$. The presented demodulation formula is:

$$S_s(t) = \frac{N_{AS}(t_{n+1},l)N_R(t_n,l)}{N_R(t_{n+1},l)N_{AS}(t_n,l)} = \frac{R_{AS}(t_{n+1})}{R_{AS}(t_n)} = \frac{\exp(h\Delta v/\mathrm{kt_n})-1}{exp(h\Delta v/kt_{n+1})-1}, \quad (17)$$

This is claimed to be a much accurate and more temperature sensitive method. The single-ended configuration of DTS systems is used in pipeline monitoring, oil and gas industries, fire detection, hydrology and other industrial applications [4].

4. Demodulations for double-ended configurations

In a single – ended system, temperature along the fiber is calculated by [4]:

$$T(z) = \frac{\gamma}{ln\left(\frac{P_S}{P_{AS}}\right)+C-\int_0^z \Delta\alpha(z')dz'}, \quad (18)$$

where: T – is the temperature in Kelvin, z – is the distance along the fiber, $P_S(z)/P_{AS}(z)$ – is the measured ratio between the power of Stokes and anti-Stokes signals, C – is the dimensionless calibration parameter that encompasses properties of incident laser and DTS instrument.

$$\gamma = \frac{h\Omega}{k}, \quad (19)$$

where: $\Omega = 16^{13}$ Hz, thus: γ = 490 K.

$$\Delta\alpha = \frac{ln\left(\frac{P_S(z_1)}{P_{AS}(z_1)}\right)-ln\left(\frac{P_S(z_2)}{P_{AS}(z_2)}\right)}{z_2-z_1}, \quad (20)$$

In a double-ended system, pulses are launched into the fiber from one end of the cable during a first measurement period (forward, starting at z = 0,), after which pulses are launched into the other end during the next measurement period (reverse, starting at $z = L$, L is the length of the cable) [12].

$$T(z) = \frac{\gamma}{ln\left(\frac{P_S(z)}{P_{AS}(z)}\right)_{\rightarrow}+C-\int_0^z \Delta\alpha(z')dz'}, \quad (21)$$

$$T(l-z) = \frac{\gamma}{ln\left(\frac{P_S(z)}{P_{AS}(z)}\right)_{\leftarrow}+C-\int_l^{l-z} \Delta\alpha(z')dz'}, \quad (22)$$

By setting $T(z) = T(l\text{-}z)$ over Δz:

$$\int_z^{z+\Delta z}\Delta\alpha(z')dz' = \frac{ln\left(\frac{P_S(z+\Delta z)}{P_{AS}(z+\Delta z)}\right)_{\rightarrow}-ln\left(\frac{P_S(z)}{P_{AS}(z)}\right)_{\rightarrow}}{2} + \frac{ln\left(\frac{P_S(z)}{P_{AS}(z)}\right)_{\leftarrow}-ln\left(\frac{P_S(z+\Delta z)}{P_{AS}(z+\Delta z)}\right)_{\leftarrow}}{2}, \quad (23)$$

Δz is set equal to the spatial measurements interval. The value of $\int_z^{z+\Delta z}\Delta\alpha(z')dz'$ is obtained by stepping along the complete cable with steps of Δz, and by summing these values, the $\int_0^z \Delta\alpha(z')dz'$ is estimated for every z. The differential attenuation is considered constant as these values are obtained from a time-average over the entire period. The noise is reduced by adapting a longer period of integration and by spatial averaging [12].

Double-ended configuration allows reducing the influence of multiple step losses on the measured temperatures by refining the collected data. This configuration is used in hydrologic applications [4].

5. Demodulations for loop configurations

The conventional demodulation algorithm for a DTS system in loop configuration is [1]:

$$\left(\frac{I_{As}(z)}{I_S(z)}\right) \times e^{-\alpha z} = c \times e^{\frac{-h\Delta v}{kT(z)}}, \quad (24)$$

where: I_{AS}, I_S – are the anti-Stokes and Stokes intensities along the z axis, in which direction the fiber is deployed, $\Delta\alpha$ – is the attenuation coefficient difference between Stokes and anti-Stokes wavelengths, c – is the characteristic coefficient of the optical fiber, $T(z)$ – is the temperature distribution along the fiber.

Xia, Guo, Li and Mao proposed a modification for the previous equation [1]:

$$\left(\frac{I_{As}(z)}{I_S(z)}\right) \times exp\left(-\int_0^z \Delta\alpha[T(z)]dz\right) = c \times e^{\frac{-h\Delta v}{kT(z)}}, \quad (25)$$

The attenuation coefficient difference dependency with temperature:

$$\Delta\alpha(T) = 2 \times 10^{6}T - 0.0028, \quad (26)$$

So, in the computer:

$$\left(\frac{I_{AS}^{n}}{I_{S}^{n}}\right) \times exp\left(-\sum_{n=0}^{i}(\alpha(T_n) \times \tau_i)\right) = c \times e^{\frac{-h\Delta v}{kT_n}}, \quad (27)$$

where: n – is the sampling point, τ_i – is the sampling step interval.

The loop configuration of DTS systems is commonly used in nuclear infrastructures due to lower differential losses [13].

6. Conclusions

DTS systems configurations allow obtaining accurate temperature readings in different environments and applications. This study presents the main reasons that may cause faulty temperature measurements. In order to improve these measurements, many demodulation algorithms were presented. This study discusses conventional calculation methods and existing demodulation algorithms, depending on the DTS system configuration and application.

One can notice that the environment around the fiber and temperature calculation method differs from application to another and from one configuration to another, which are essential issues to be taken into account during DTS systems designing.

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