Optical monitoring of gas supply systems in metropolitan area

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Abstract—A novel fiber optic sensor system to monitor the gas pipeline network designed for PGNiG, Polish oil and gas exploration and production company is presented. The system is based on standard telecommunication fibers and devices, except for user-oriented and specially designed intensity-based optical sensors that utilize fiber macro- and microbending effects. Laboratory tests showed that the system is simple, easy to install, reliable, and fulfils the user requirements.

The elements of gas-supply systems, i.e. pipes, connectors, welding sectors etc., are often exposed to mechanical pressure and shocks mainly caused by human activity (traffic, construction works), but also evoked by natural rheological ground processes (soil replacements). This may result in various deformations as well as damages of a gas network. Losses caused by breakings in gas delivery are usually high; also repairs of the network are expensive. With this regard it is extremely important to prevent the damages of gas installations by continuous monitoring of its crucial elements and to detect early events (i.e. small deformations) which may signalize dangerous incidents. As the transported medium, in the considered system – gas, is highly explosive, then any sensing system mounted close to the monitored elements must not contain any electronics. In this respect the use of optical sensors is especially recommended.

The existing solutions and devices on the market are based either on fiber optic interferometric methods, FBGs - fiber Bragg gratings or more elaborated and reliable but also more expensive systems utilizing either BOTDR - Brillouin Optical Time Domain Reflectometry or BOTDA - Brillouin Optical Time Domain Analysis [1-2].

In this report we present a simple and relatively cheap fiber optic sensing system designed for bending and vibrations monitoring of gas-pipes. However, the designed system can be applied also in other fields like refineries, chemical industry and mines. The system is based on standard optical telecommunication elements (except for sensing heads), being specially constructed and operating in the telecom spectral windows 1310nm or 1550nm. It is simple and easy to install. This allows for a significant reduction in evaluated production, mounting and maintenance costs. The general concept of the system is shown in Fig.1.

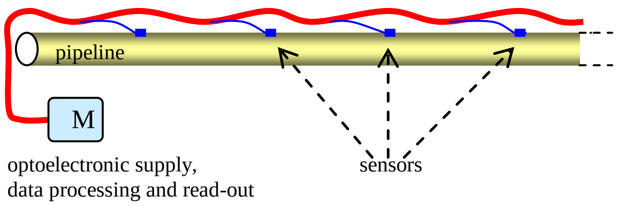

Fig. 1. The general view of the monitoring system of gas-pipeline bending and vibrations.

The system consists of an optical cable comprising a bundle of single-mode fibers, placed along the monitored pipeline. In the selected points of a pipeline, needed to be controlled, one of the fibers is separated from the cable without breaking its integrity and is coupled with an appropriate sensing head located there. Each fiber, together with the corresponding sensing head, forms a single, independent sensing channel. All fibers in the cable may be fed separately from a standard telecom transmitter, or by a common source. The output of each fiber is connected to a separate telecom receiver. The sensing head fixed at a point of the pipeline activates an optical intensity signal in the coupled fiber that controls this particular point. In this way, one cable installed enables controlling many points along the monitored pipeline.

The designed sensing head is a scrambler-type displacement sensor that operates on the micro- and/or macrobending effect. The macrobending is considered when the spatial period of fiber longitudinal deformation (e.g. bending) is greater than 1 mm, while microbending is attributed to high frequency perturbations, typically with the period between 0.2mm–1mm, and usually randomly distributed. Both cause transmission power loss in a fiber, although they present two different attenuation mechanisms. As a consequence, macro- and microbending exhibit different characteristics of attenuation, including its spectral dependence. In the case of microbending, a periodic perturbation results in spectrally selective response of the fiber. The attenuation sensitivity to some extend is limited to the wavelength λ related to the period of perturbation Λ according to [3]:

$$\lambda = \Lambda \cdot (n_{core} - n_{cladding}) \tag{1}$$

To obtain a measured signal in the scrambler-type sensor, the functional dependence of fiber attenuation γ on its bent radius is used, which for microbending is [4]:

$$\gamma = N \cdot h^2 \frac{D^4}{a^6 (n_r - n_p)^3} \left(\frac{E}{E_f} \right)^{3/2} \tag{2}$$

where N is the number of bumps of average height h per unit length, a, D are the core radius and the total fiber radius, E_f , E are the elastic moduli of the fiber and the coating correspondingly; the fiber bent radius is a function of the product ($1/N\,h$).

Relation (2) points out that the power transmitted by the sensor decreases exponentially as the bent radius decreases. This dependence is even stronger for the macrobending effect, since in this case the attenuation is:

$$\gamma = N \exp\left[C - \nu R \left(\frac{\lambda}{\lambda_{ce}(MFD)} \right) \right], \tag{3}$$

where MFD is the fiber mode field diameter, C, ν are the constant coefficients, and the fiber cut-off wavelength.

$$\lambda_{ce} = \frac{\pi D \left(n_{core}{}^2 - n_{cladding}{}^2 \right)^{1/2}}{2.4}. \tag{4}$$

The optical parameters in relations (2), (3), together with the fiber coating type, sensor head design, and operating wavelength selection, allow to adjust the sensor characteristics to the required values (i.e. sensitivity, spectral response, overall performance).

Practically, both effects appear simultaneously in any fiber deformation by some fractions, and the sensitivity of both can be modified by several fiber parameters, like the index profile, cut-off frequency, coating, etc.
The idea of using a scrambler for bending sensing is shown in Fig. 2.

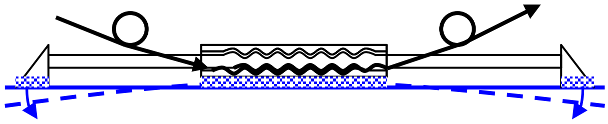

Fig.2. The use of a scrambler as a bending sensor.

Our sensor head is made in the form of the cylindrical rod, shown in Fig. 3.

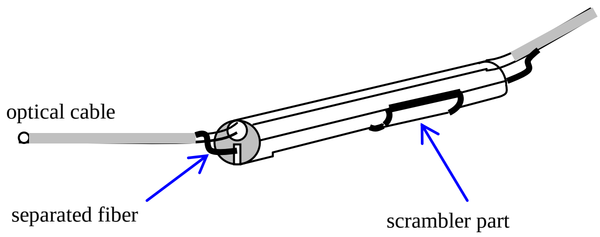

Fig.3 The schematic view of the designed sensing head.

The central fragment of the rod is cut out to build two semi-cylindrical pieces. On their plane surfaces formed by the cross-section a desired scrambler structure is fabricated and the operating fiber is placed in between. The length of the rod and the scrambler part size are determined by the desired sensor sensitivity. Two opposite rows are also cut along the rod – one for positioning the operating fiber, the other allowing passing the cable with remaining fibers. Such a construction enables easy mounting of the head at any point of the cable and the monitored pipeline. The rod head is closely inserted in a cylindrical protection cover and sealed. The cover cylinder is to be firmly fixed to the monitored pipeline. Thus, bending of pipeline results in similar bending of the cover cylinder and causes relative displacement (squeezing) of the two scrambler elements of the head rod. The sensing fiber inside is then compressed between the scrambling structures and experiences a deformation depending on the magnitude of the pipe bending radius. This influences fiber attenuation and changes transmitted power, to be detected next in an electronic controlling unit, which is located at a safe distance from the pipeline. The wavelength of the detected sensing signal has to be chosen within the sensitivity range of the scrambler (see Eq. (1)), whereas other wavelengths which are almost not attenuated may be utilized for a reference signal. This feature - selective attenuation - also allows for continuous checking of sensor performance and testing.
The sensor was built and examined. The operational characteristics obtained are shown in Fig. 4.

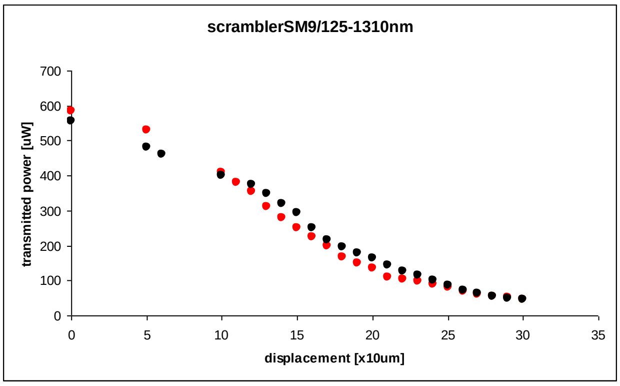

Fig. 4. Transmitted optical power by the tested sensor at wavelength 1310 nm versus scrambler displacement.

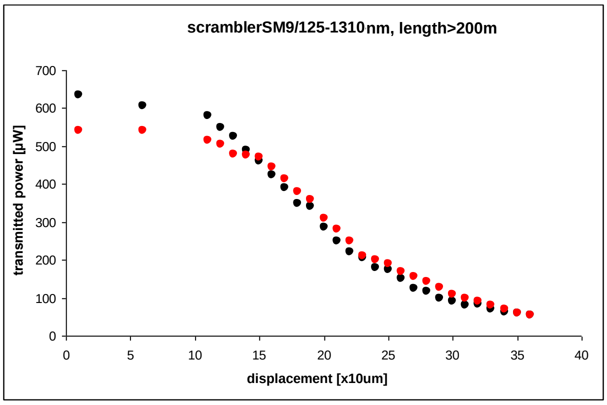

Fig. 5. Transmitted optical power by the tested sensor at a wavelength of 1310nm versus scrambler displacement for the length of an optical cable over 200m.

In order to check the measuring characteristics of the sensor in conditions close to reality we used a length optical cable over 200m for transmitting the signal from the sensor to the detector. As we can see in Fig. 5, the characteristic is almost the same as shown in Fig. 4, when the sensor is close to the detector.

Based on our previous research [5-7] we introduced multi-point optical fiber sensor particularly predicted for gas supply system monitoring in metropolitan area.

Significantly useful features of the designed monitoring system in this particular application are:

- continuous loop of optical channels – uninterrupted fiber connection (full-path fiber),
- possibility of channel multiplexing by wavelength separation according to (1),
- continuous operation controlling of each optical channel through spectrally selective sensor sensitivity

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