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Distributed fiber-optic pressure sensor based on Bourdon tubes metered by optical frequency-domain reflectometry

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Abstract. We report a distributed fiber-optic pressure sensor based on Bourdon tubes using Rayleigh backscattering metered by optical frequency-domain reflectometry (OFDR). In the proposed sensor, a piece of single-mode fiber (SMF) is attached to the concave surfaces of Bourdon tubes using a thin layer of epoxy. The strain profiles along the concave surface of the Bourdon tube vary with applied pressure, and the strain variations are transferred to the attached SMF through the epoxy layer, resulting in spectral shifts in the local Rayleigh backscattering signals. By monitoring the local spectral shifts of the OFDR system, the pressure applied to the Bourdon tube can be determined. By cascading multiple Bourdon tubes and correspondingly attaching SMF sections (i.e., a series of SMF-modified Bourdon tubes), distributed pressure measurements can be realized. Three Bourdon tubes are employed to demonstrate the proposed spatially distributed sensing scheme. The experimental results showed that linear relationships between spectral shift and pressure were obtained in all three SMF-Bourdon tubes (i.e., at three spatial locations). It is expected that the proposed sensing device, the SMF-Bourdon tube, can be used in applications where distributed/multipoint pressure measurements are needed. *© 2019 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.58.7.072010]

Keywords: distributed pressure sensor; Bourdon tube; optical frequency-domain reflectometry; single-mode fiber; Rayleigh scattering.

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1 Introduction

High-performance, static pressure measurements are extremely important in many applications, such as downhole monitoring, fluid engineering, and production of pharmaceuticals.[1,2] In recent years, fiber-optic sensors have been widely demonstrated for static/dynamic pressure monitoring in harsh environments. Compared with traditional mechanical and electrical methods, fiber-optic pressure sensors hold several unique advantages, such as being lightweight, chemical and thermal resistant, immune to electromagnetic interference, multiplexing, and capable of remote operation.[3,4]

The majority of reported fiber-optic pressure sensors are based on the diaphragm extrinsic Fabry–Perot interferometer (DEFPI) structure.[5] The pressure-sensing element in a DEFPI-based pressure sensor is a thin diaphragm, which is typically bonded to the tip of a micromachined optical fiber.[6–9] A Fabry–Perot cavity is formed between the optical fiber endface and the inner surface of the diaphragm. The thin diaphragm deflects in proportion to the external pressure, which leads to a change in the cavity length of the EFPI. By analyzing the shift of the interference spectrum induced by a cavity length change, the change in external pressure can be precisely and accurately determined. The sensitivity and dynamic range of the DEFPI-based pressure sensors can be flexibly designed using diaphragms with different properties (e.g., thickness, diameter, and Young's modulus) to meet different application requirements. However, the microfabrication process of a DEFPI-based pressure sensor is complicated and sometimes costly. Meanwhile, the stability and durability of the diaphragm (e.g., with a thickness on the micrometer/nanometer scale) fixed to a fiber tip are always a concern in real-world applications.[10] Additionally, the interferometry-based pressure-sensing technique, which takes advantage of the wavelength dependence over a broad range, is difficult to multiplex in a series arrangement.[11]

Another widely used pressure transducer, the Bourdon tube, operates using a different principle.[12] For example, a C-shaped Bourdon tube expands out slightly when subjected to an external pressure. Typically, a needle is permanently welded to the end of the Bourdon tube to quantify the movement of the free end caused by a pressure change. Recently, researchers have developed a new device with better pressure measurement performances (i.e., higher sensitivity and higher resolution) based on Bourdon tube and optical fiber Bragg grating (FBG).[13,14] For instance, FBGs were bonded to the outside and inside surfaces of a C-shaped Bourdon tube to measure the strain change during the pressure-induced mechanical movement. The FBG-based pressure sensor was potentially capable of achieving quasidistributed measurements by cascading a series of FBGs along an optical fiber.[15]

As an important distributed optical fiber sensor (DOFS) technique, Rayleigh backscattering-based optical frequency-domain reflectometry (OFDR) has been widely explored for sensing various physical and chemical parameters, such as temperature,[4] vibration,[16] strain,[17,18] and refractive index.[19,20] Compared to the multiplexed FBGs-based quasidistributed sensor, the OFDR-based DOFS achieves fully distributed sensing with high spatial resolution (millimeter scale or better) using an intact single-mode fiber (SMF). Combing the Bourdon tube as a rough mechanical pressure transducer with the Rayleigh backscattering-based OFDR system as an extremely sensitive signal interrogation unit for very small pressure changes, distributed and highly precise pressure sensing based on an SMF could be developed.

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In this paper, a Rayleigh backscattering-based SMF sensor combined with multiple Bourdon tubes (SMF-Bourdon tubes) is proposed and demonstrated for distributed pressure measurements. The sensor was interrogated with an OFDR system for achieving distributed and real-time monitoring of pressures with high dynamic range and precision. In the proposed sensor, a continuous length of SMF was attached to the inside surfaces of three cascaded C-shaped Bourdon tubes using thin layers of epoxy. As a result, the strain variations along the inside surfaces of the Bourdon tubes caused by pressure changes were coupled to the SMF. The strain variations along the SMF resulted in local Rayleigh backscattering spectral shifts in the OFDR system. Consequently, the pressure applied to the Bourdon tubes was correlated to the local spectral shifts along the SMF. In the demonstration experiment, three Bourdon tubes were placed at the positions 2.00, 3.65, and 5.25 m from the incident end of the SMF, functioning as three multiplexed pressure transducers. Pressures in the range of 0 to 0.5 MPa were simultaneously applied to the three Bourdon tubes to verify the capability for distributed pressure sensing by the proposed SMF-Bourdon tubes device.

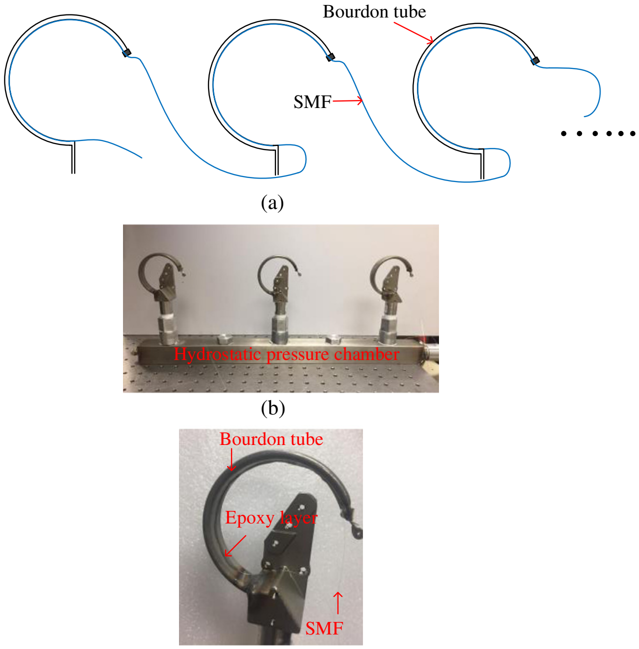
2 Sensor Design and Measurement Principle

2.1 *Sensor Design*

A schematic drawing of the proposed distributed pressure sensor based on SMF-Bourdon tubes is illustrated in Fig. 1(a). Figure 1(b) shows a photograph of a prototype sensor mounted on a homemade hydrostatic pressure chamber. Figure 1(c) shows an expanded view of one SMF-Bourdon tube. The prototype sensor principally consists of three C-shaped Bourdon tubes and one SMF. Each C-shaped Bourdon tube has a flat oval cross section with the free end sealed. When a pressure is applied to the tube, it tends to deflect and straighten out slightly, resulting in a change in the strain profile along the inside surface. The maximum strain (ε) along the inside circumferential surface occurs at the center point and can be calculated by[13]

$$\varepsilon = \frac{1-\mu^2}{E}\frac{R^2}{a^2}\left(1-\frac{b^2}{a^2}\right)\frac{3}{\beta+K^2}\frac{2\Phi}{K}P, \tag{1}$$

where μ and E are the Poisson's ratio and Young's modulus of the material, respectively; R is the radius of curvature of the Bourdon tube; a and b are the semimajor and semiminor axes of the flat oval cross section, respectively; h is the wall thickness of the tube; Φ is a position function for the relationship between a/b and h/b; P is the applied pressure; $K = Rh/a^2$. For a defined Bourdon tube (i.e., all the physical parameters are determined), the maximum strain is linearly proportional to the applied pressure. As shown in Fig. 1(c), in the design of the SMF-Bourdon tube, the SMF was bonded on the inside surfaces of the Bourdon tube. As the Bourdon tube deflects, a tensile strain is generated along the inside surface, and it is metered by the attached SMF. The variations in the tensile strain in the SMF result in local spectral shifts in the Rayleigh backscattering signals. By monitoring the spectral shifts along the SMF, the applied pressure can be determined. Thus, the Bourdon tube with a section of SMF attached can act as a pressure sensor after proper calibration. By cascading multiple Bourdon tubes (e.g., three) and correspondingly attaching a single SMF on the inside surfaces, distributed pressure sensing can be realized using the proposed SMF-Bourdon tubes.



(a)

(b)

(c)

Fig. 1 (a) A schematic diagram of the proposed distributed pressure sensor based on SMF-Bourdon tubes. (b) A photograph of a prototype sensor mounted on a homemade hydrostatic chamber. (c) An expanded view of the sensor showing that a section of SMF is attached on the inside surface of the C-shaped Bourdon tube using a thin layer of epoxy.

2.2 *Measurement Principle*

As discussed above, the pressure applied to each Bourdon tube induces a change in the local strain profile along the attached SMF, which is then correlated to the spectral shift of the Rayleigh backscattering signals along the SMF. A Rayleigh backscattering OFDR system is used to interrogate the SMF-based distributed pressure sensor. The Rayleigh backscattering along an optical fiber originates from the random fluctuations in the refractive index profile caused during the fiber heating/drawing process. The tensile strain that results from a force applied to an SMF elongates the optical fiber, causing a shift in the local Rayleigh backscattering signal. The shift in the Rayleigh backscattering signal can be determined by comparing the spectra to the original spectrum using the cross-correlation algorithm. The signal processing procedures are described in detail below. First, the reference signal and measurement signals under different pressure settings are collected separately. Fast Fourier transforms are performed to transfer the collected signals from the optical frequency domain to the spatial domain. Second, a sliding window is applied to the spatial-domain signals to spatially select the local Rayleigh backscattering. The spatially selected local Rayleigh backscattering signal is zero-padded to increase the frequency resolution for later processing. Third, inverse fast Fourier transforms are performed to convert these spatially selected local Rayleigh backscattering signals from the spatial domain back to the optical frequency domain. Last, cross-correlation analysis

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is performed between the local reference and measured Rayleigh backscattering spectra to extract the spectral shifts. The spectral shifts essentially reflect the pressure variations applied to the Bourdon tubes. Thus, distributed pressure sensing can be realized based on the proposed SMF-Bourdon tubes device.

3 Experimental Results and Discussions

The experimental setup for the distributed pressure measurements is shown in Fig. 2: (a) presents a diagram of the home-built OFDR system and (b) schematically shows a multipoint hydrostatic pressure setup. A tunable laser source (TLS, Agilent 81680A) is employed as the light source with tuning speed, tuning range, and starting wavelength of 5 THz/s (40 nm/s), 2.5 THz (20 nm), and 1530 nm, respectively. The light output from the TLS is split into two paths by a 2:98 coupler. The 2% light beam is coupled to an auxiliary interferometer (a Mach–Zehnder interferometer). The auxiliary interferometer provides an external clock to trigger the data acquisition card that samples the interference signals with an equal optical frequency spacing, thus reducing the nonlinearity of the frequency tuning of the TLS. The 98% light beam is coupled to the main interferometer. The fiber under test (FUT) in the main interferometer is a 6-m-long SMF.

The Bourdon tubes (YE-100-1MPa) used in constructing the prototype sensor with a dynamic range of 1 MPa were purchased from SYCIF (Shanghai, China). Three Bourdon tubes were mounted on a homemade hydrostatic pressure chamber in parallel, and three sections of the FUT, at positions 2.00, 3.65, and 5.25 m, were attached to the inside surfaces of the three Bourdon tubes. The pressure in the hydrostatic pressure chamber could be manually increased by a hydrostatic test pump which was calibrated using a commercial pressure meter (0.1% measurement accuracy). The inner diameters of the C-shaped Bourdon tubes used in the sensor construction are ~64 mm. From the spatial-domain signal of the FUT, no loss was introduced after attaching the SMF sections to the Bourdon tubes, theoretically indicating that thousands of Bourdon tubes could be cascaded in series along the SMF to achieve large-scale distributed pressure sensing.

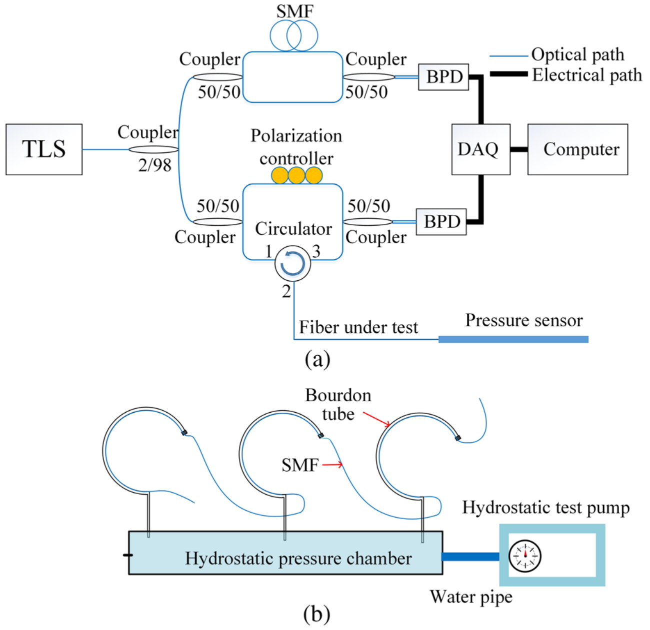

Fig. 2 Experimental setup for demonstrating the proposed distributed pressure sensor: (a) a diagram of the OFDR system and (b) a schematic drawing of the hydrostatic pressure setup.

A series of hydrostatic pressures ranging from 0 to 0.5 MPa was applied to the homemade hydrostatic pressure chamber to demonstrate the distributed pressure-sensing capability of the proposed sensor. Based on the parallel design, all three Bourdon tubes experienced the same pressure. Figure 3(a) shows the measured spectral shift as a function of the spatial position from the incident end of the optical fiber at a pressure setting of 0.5071 MPa. Noticeable spectral shifts were detected at the three locations, where the SMF was attached to the Bourdon tubes. Very small spectral shifts were measured at other locations along the SMF, indicating that there was little cross talk from the other sections of the FUT that were not attached to the Bourdon tubes. The spectral shifts as a function of spatial position from the sensing end of the optical fiber at various pressure settings at the three different positions (i.e., 2.00, 3.65, and 5.25 m) are shown in Figs. 3(b)–3(d), respectively. For the signal processing, the size of the sliding window and the number of points after zero-padding were set to 250 and 20,000, respectively. Thus, the spatial sampling interval was calculated to be 1 cm. As can be observed, the spectral shifts at all three positions increased monotonically with the increase in the applied pressure. An interesting observation is that the spectral shifts at the three pressure measurement locations are not identical under the same pressure settings; this is because of the variations in the stiffness of the Bourdon tubes during the manufacturing process. Meanwhile, the strain transfers between the attached SMF sections and the inside surfaces of the Bourdon tubes were not identical due to the different thicknesses of the epoxy layers.[21] Noticeable negative spectral shifts were obtained at the positions of 3.71 and 3.72 m. We checked the attached SMF at these two positions and found out that this section of SMF was compressed during the pressure increments due to the mounting fashion of the SMF, which matched well with the negative spectral shift measurement results. It should be noted that temperature cross talk can be compensated by employing the SMF that is not attached to the Bourdon tubes. Specifically, the sections of the SMF that are attached to the Bourdon tubes are sensitive to both pressure and temperature variations, while the remaining sections of the SMF are only sensitive to temperature variations, due to the thermal-optic effect and the thermal expansion effect. Therefore, the SMF that is not bonded to the Bourdon tubes can be used to monitor the changes in the surrounding temperature.

The spectral shift at spatial positions 2.00, 3.65, and 5.25 m as a function of applied pressure is shown in Fig. 4 in blue, yellow, and green dots, respectively. Linear curve fittings were applied to the experimental datasets. Good linear relationships were obtained in all three datasets with R^2 values of 0.9975, 0.9969, and 0.9981, respectively. The pressure measurement sensitivities of the attached SMF at the three positions, 2.00, 3.65, and 5.25 m, were determined to be 16.38, 28.32, and 35.42 GHz/MPa, respectively. The pressure measurement sensitivities of the proposed SMF-Bourdon tubes are tens of times higher than the intrinsic

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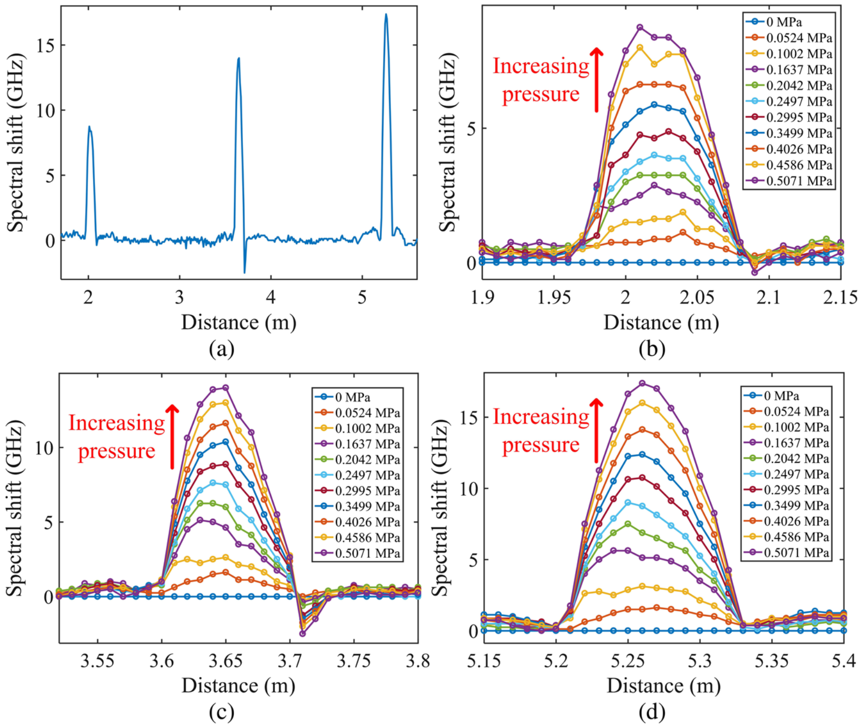

Fig. 3 Experimental demonstration of the spatially distributed pressure sensor. (a) Measured spectral shift as a function of spatial distance from the sensing end of the optical fiber at a pressure setting of 0.5071 MPa. (b)–(d) Measured spectral shift as a function of distance from the incident end of the optical fiber at various pressure settings at the three positions 2.00, 3.65, and 5.25 m, where SMF sections were attached to the Bourdon tubes.

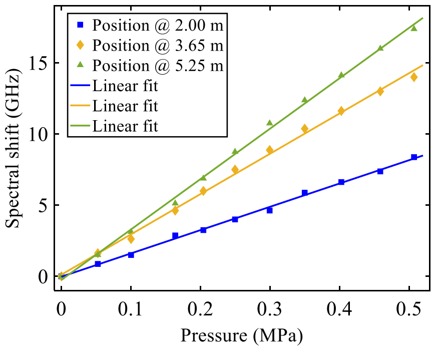

Fig. 4 Spectral shift at positions 2.00, 3.65, and 5.25 m as a function of pressure. Curve fitting was applied to the three datasets, and satisfactory linear relationships were obtained.

pressure sensitivity of a bare FBG.[22] There are differences between the three measured sensitivities, which are due to the variations in the stiffness of the Bourdon tubes (i.e., they were not manufactured identically) and different strain transfers between the SMF sections and the Bourdon tubes due to the epoxy adhesive layer, as discussed above. The different measurement sensitivities reveal that each of the SMF-Bourdon tubes has to be properly calibrated before applications. The sensitivity of the proposed SMF-Bourdon tubes pressure sensor can be improved using a thinner layer of epoxy, thus increasing the strain transfer coefficient between the SMF and the inside surface of the Bourdon tubes. On the other hand, different Bourdon tubes with different dynamic ranges can be employed for different sensing applications.

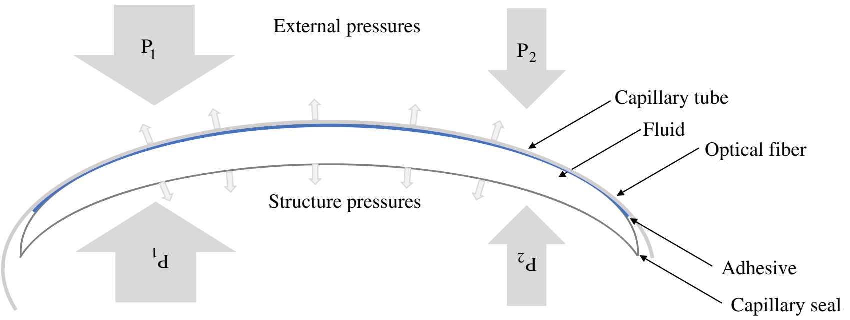

Fig. 5 Schematic diagram showing the general features of an optical fiber attached to a flexible mechanical structure (e.g., a capillary tube) that can function as a distributed pressure sensor device tailored for metering a wide range of external pressures.

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Based on the proposed SMF-Bourdon tubes, thousands of Bourdon tubes can be cascaded along an SMF to achieve extensive distributed pressure sensing. Here, inspired by the SMF-Bourdon tubes, we propose a general strategy for fully distributed pressure measurements. Figure 5 illustrates the external attachment of an SMF to a capillary tube that has material (e.g., glass and plastic) and design properties (e.g., stiffness) that allow mechanical flexing. Taking advantage of the distributed strain measurement capability of the OFDR system, the strain profile of the SMF attached to the capillary tube can be monitored in real time. The capillary tube, configured as a high-pressure chamber, can be made to have variable stiffness by pressurizing a fluid (gas or liquid) contained in the chamber. Variable fluid pressure (and fluid type) will provide adjustable stiffness in addition to the mechanical stiffness provided by the capillary tube. A condensed phase fluid (liquid) with low compressibility will afford a more rigid structure, suitable for a high range of strain measurements that meter high external pressures. A nonideal gas with high compressibility will afford a less rigid structure suitable for a low range of strain measurements that meter low external pressures. Calibrations and detailed studies are ongoing in our lab.

4 Conclusion

A Rayleigh backscattering-based SMF distributed pressure sensor is proposed and demonstrated in this paper. Multiple Bourdon tubes were employed as mechanical pressure transducer surrogates, and an SMF was attached to the inside surfaces of the Bourdon tubes to form high-fidelity SMF-Bourdon tube pressure-sensing structures. The sensor was interrogated with an OFDR system to achieve spatially distributed and real-time monitoring of hydrostatic pressure changes applied to the Bourdon tubes. In a demonstration experiment, three Bourdon tubes were placed at three different positions along the SMF: 2.00, 3.65, and 5.25 m. A series of hydrostatic pressures ranging from 0 to 0.5 MPa were simultaneously applied to the three Bourdon tubes using a hydraulic test pump and a homemade hydrostatic pressure chamber. The responses of the three SMF sections were tested to verify the capability of distributed sensing of the proposed sensor device. The results demonstrated that the sensor could be used to simultaneously measure multipoint pressure variations by monitoring the local Rayleigh backscattering spectral shifts. The proposed method and SMF-Bourdon tubes device, with proper calibration, have wide applications in various fields requiring distributed pressure measurements. For instance, the system can be used to detect the leakage of gas or liquid in pipelines, or used for distributed liquid-level sensing based on hydrostatic pressure measurements. We anticipate that another application for the SMF-Bourdon tube sensor is in diagnostic monitoring of the pressure modulations of the fluid flow in systems under elevated pressures, such as the water cooling systems and the oil in the crankcase of automobile engines. Pressure modulations that do not match known patterns for proper engine operations can indicate the onset of premature failure pathways of engine components. The high sensitivity of the SMF-Bourdon tube system can be used to record pressure modulations during scheduled automobile maintenance services and compare them to established standards for diagnostic purposes. Similarly, the compressed air pressure system in a building could be monitored by an SMF-Bourdon tube system to indicate the onset of problems with the compression pump as well as signature pressure changes that correlate with excessive releases of gas from ruptured pipes and leaking valves.

In addition to the C-shaped Bourdon tubes used in the construction of the prototype sensor, spiral or helical Bourdon tubes can also be employed for fabricating the SMF-Bourdon tubes structure. In fact, the SMF-Bourdon tubes motif provides a sensing scheme to combine a structure that has a mechanical response to pressure (e.g., expansion or deflection) with an optical fiber for distributed pressure sensing. Therefore, by judiciously designing the pressure sensitive structure, it is envisioned that distributed internal and external pressure sensing can be realized.

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