Intrinsically-Safe Fiber Optic Sensors Reduce Cost and Improve Process Control

John W. Berthold III
Technical Director
Davidson Instruments
4800 Research Forest Drive
The Woodlands, TX 77381

Richard L. Lopushansky
President
Davidson Instruments
4800 Research Forest Drive
The Woodlands, TX 77381

KEYWORDS

Fiber Optic Sensors, High Temperature Pressure Sensors, High Temperature Vacuum Sensors, Differential Pressure Sensors, Flow Sensors, Density Sensors, Level Sensors, Strain Gages, Vibration Sensors, Turbine Sensors, Strain Sensors, Acoustic Sensors, Accelerometers.

ABSTRACT

After years of research and development, intrinsically safe, fiber optic sensing technology has matured to the point that it is now ready for use in industrial applications where it has the potential to significantly reduce installation and maintenance costs and offers substantial improvements in process control. This paper will describe the basic principles and components that make up a fiber optic sensing system, the results of an extensive characterization program performed on temperature and pressure transducers, the multiplexing approach and communications options. This paper will also describe specific applications of this technology that are being developed for the process industry.

INTRODUCTION

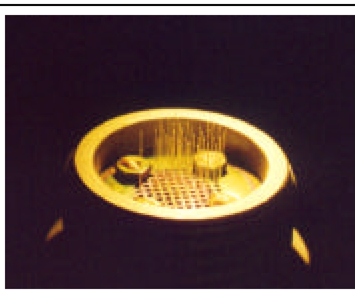


Figure 1 – Optical Fibers

Low power fiber optic process control instrumentation is ideal for use in refineries, chemical plants, power plants, oil production facilities, or in other hazardous environments because the sensors pose no danger even in hazardous areas where explosive vapors may exist. The fiber optic sensors described in this paper operate with less than 1% of the power level deemed intrinsically safe by safety standards. An independent evaluation of the safety level of the fiber optic sensing systems will be performed to assure that high energy levels cannot be placed on the fiber through a malfunction of the system.

Instrumentation installation and maintenance costs can be significantly reduced because low-power fiber optic sensing systems do not require explosion-proof conduit and containment.

Fiber optic sensors can be designed for operation at temperatures up to 1000°F and down to –55°F. This allows fiber optic sensing technology to make direct and accurate measurements of process conditions that simply cannot be made with conventional electronic sensing technology. It also allows fiber optic sensors to be used in severe cold where need for impulse lines, capillary tubes and the associated weatherization programs can be eliminated. Significant process improvements and increased margins of safety will be realized through the application of this enabling technology.

Fiber optic sensors are immune to electromagnetic interference and are suitable for use near high voltage electrical systems. Because optical fibers cannot conduct current, fiber optic sensors eliminate problems associated with lightning and ground loops. They are tolerant of high concentrations of hydrogen and corrosive environments. The small size and lightweight characteristics of fiber optic sensors make these sensors ideal for most industrial applications.

Fiber optic sensors can be used for measuring temperature, pressure, differential pressure, vacuum, linear and rotary position, strain, vibration, and acceleration. The signal conditioners can be designed for high resolution, quick dynamic response, and/or for long transmission distances. The signal conditioners can be designed to communicate with any open architecture ranging from digital to 4-20mA analog. The signal conditioners can be dedicated to a single sensor for high-speed data acquisition or they can be multiplexed with a variety and large number of sensors to drive down the installed cost of a system.

Ruggedized cabling and multipoint connectors are used to transmit the optical signals from the harsh environment to non-hazardous locations where the signal conditioners can be located and operate safely and reliably. Safe, economical, and reliable -- fiber optic instrumentation is rapidly becoming recognized as the best technology for industrial process control.

BACKGROUND

Fiber optics has become the standard for the telecommunications industry because of the many technical advantages that fiber optics offer. For many of the same reasons, fiber optic sensing systems will also become the standard in the future for industrial process control. The fundamental advantages that fiber optic sensors offer over conventional electronic sensors include the following:

Safe in Class I, Division 1 Explosion Hazardous Areas
Immune to Electromagnetic Interference (EMI)
Lightweight with a Small Cross-Section
Insensitive to Lightning Strikes and Grounding Problems

While most fiber optic based systems enjoy the preceding advantages, the systems described in this paper also enjoy the following additional advantages:

Low Installed Cost and System Life Cycle Cost
Transmission Ranges of 500 Meters
Tolerant to High Temperatures and Corrosive Environments
Insensitive to Hydrogen-Rich Environments
High Resolution and Long-Term Stability
Absolute, Static, and Dynamic Measurements
Insensitive to Light Losses and Power Fluctuations
Seamless Interface with Existing Digital and 4-20mA Control Systems

SENSING TECHNOLOGY

All of the sensors described in this paper are based on Fabry-Perot displacement sensor technology. In its most basic form, a Fabry-Perot optical sensor is formed when two reflective surfaces are closely spaced and parallel creating a Fabry-Perot gap. With a fiber optic Fabry-Perot sensor, one of reflective surfaces is typically on the end of the fiber; the other reflective surface can be a second fiber, a diaphragm, of a vibrating beam. At the sensor, two reflections occur, one from each reflective surface. These reflected signals travel to the opposite end of the fiber where they are detected and processed.

For each individual measurement parameter such as temperature or pressure, the transducer is designed to measure displacement that results from a change in that parameter. For example, a temperature sensor is designed to take advantage of the difference in the coefficient of thermal expansion between two materials for its displacement mechanism while the pressure sensor is designed to minimize the thermal effects and uses a deflecting diaphragm as its displacement mechanism. One can quickly see that temperature, pressure, vacuum, density, strain, acceleration, rotary and linear position, and vibration can all be measured by designing the sensor to have a change in displacement in response to a change in the environment.

The full-scale displacement of these fiber optic sensors is less than five ten-thousandths of an inch. Since these displacements are so minute, the stress on the sensor components is well below the strength of the materials and results in sensors with little hysteresis and very good repeatability. The deflection is so small that for most pressure sensors, the maximum stress at design pressure is less than 25% of the elastic limit of the diaphragm material. The optical interrogators inside the signal conditioners are capable of resolving nanometer displacements over a range of displacements exceeding 12,000 nm. This resolution gives the systems great dynamic range and accuracy

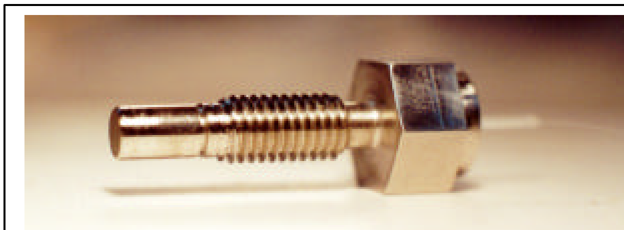


Figure 2 - Miniature Temperature Compensated Pressure Sensor

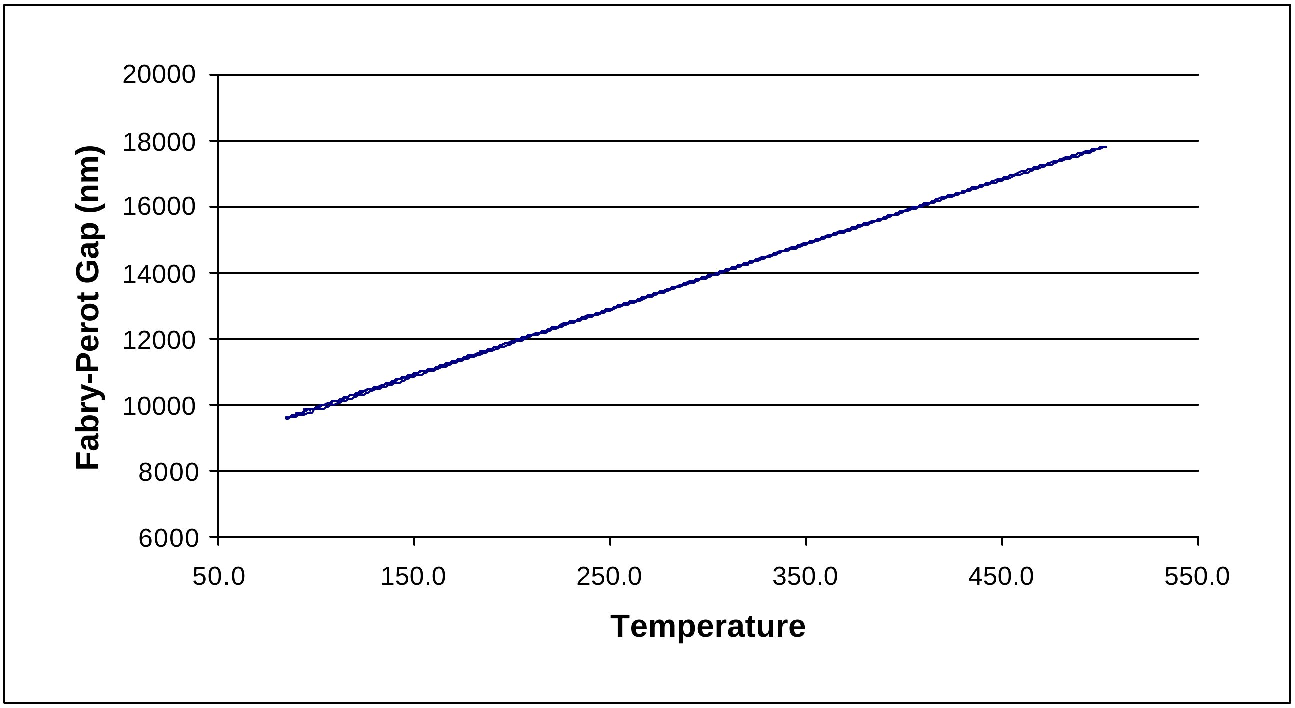
that is more than adequate for most industrial applications, i.e. 1:10,000.
Electronic sensors use a variety of technologies to affect a measurement. For example, thermocouples that produce a thermal electromotive force (EMF) require a different signal conditioner than a strain gage that produces a change in resistance or a piezoelectric crystal that produces a change in dynamic voltage. Since each of the fiber optic sensor/transducers described in this paper contains the same basic Fabry-Perot displacement sensor, the same signal conditioner can be used for any sensor by simply defining the type of sensor along with the calibration constants at the time of system setup. This allows a variety of sensors to share a single signal conditioner greatly reducing the overall cost while increasing the reliability of the sensing system. It also allows compensation for thermal effects to be built into a pressure sensor increasing the effective operating temperature range and improving the accuracy of the sensor.

The fiber optic sensing systems described in this paper use a white light source or a narrow band LED depending on the application. The source light is injected through a power splitter into a delivery fiber. At the sensor, two reflections occur – one on either side of the Fabry-Perot gap. The reflected light signals return to the power splitter where they are routed to a linear variable filter and a detector. In all cases, changes in displacement between the reflective surfaces are measured through a phase shift of the modulated light. Once the displacement measurement is made, the displacement or absolute measure of the gap is converted into engineering units such as temperature or pressure based on the calibration constants for a given sensor. Finally the signal is transmitted by the signal conditioner to a control system via a variety of standard communication protocols.

A variety of signal processing schemes are employed for various applications. Some applications require dynamic measurements with update rates exceeding 10kHz while others sacrifice speed for high resolution. Still other systems require ultra high resolution at transmission distances greater than 10km. This requires a variety of light sources, detectors, and related hardware.

TEST RESULTS

Extensive testing of the fiber optic sensing systems has been performed. Initial tests were performed on fifteen temperature transducers mounted in a thermal mass with reference thermocouples. The thermal mass was placed inside a furnace, which was cycled three times between ambient and 500°F.



Typical test results are shown in Figures 3 and 4 for temperature and pressure transducers.

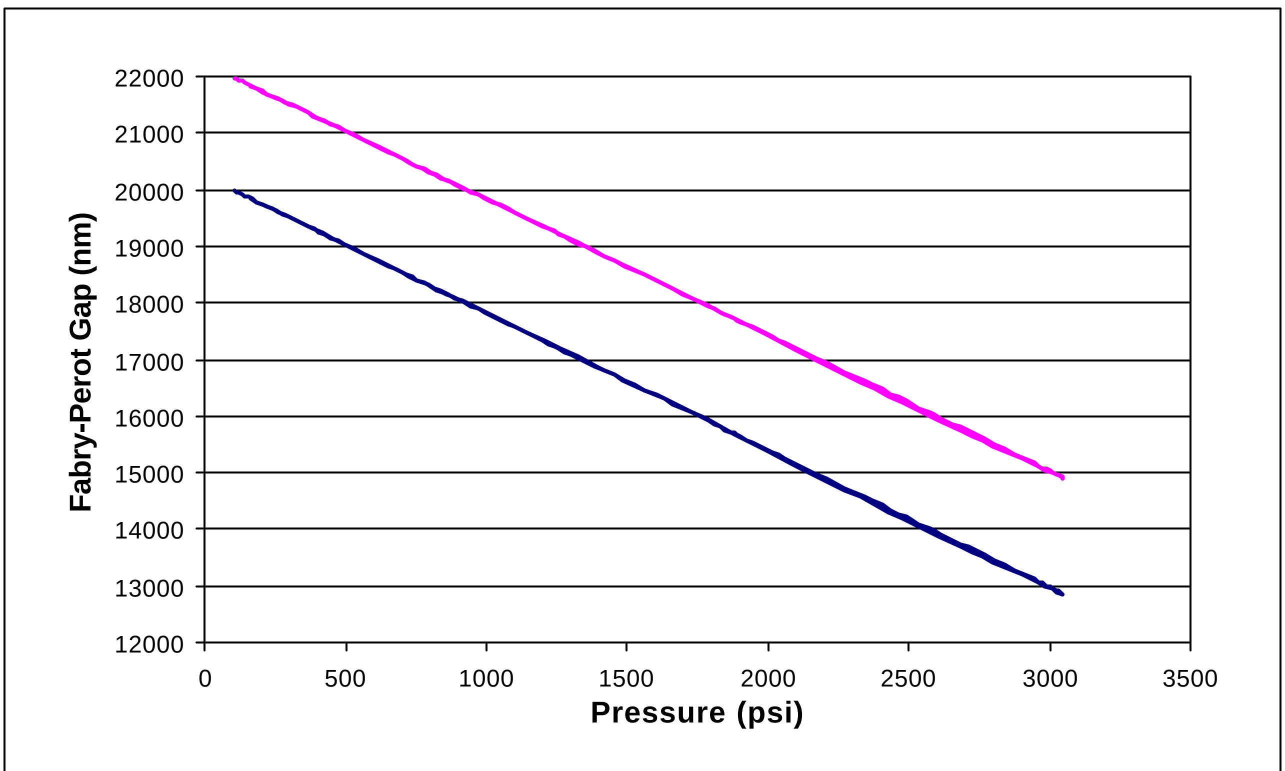


Figure 4 – Response from Two Pressure Sensors

APPLICATIONS

Low-power fiber optic sensors can be used in refineries, chemical plants, power plants, oil production facilities, or in any hostile environment because the sensors pose no danger even in hazardous areas where explosive vapors may exist. Instrumentation installation and maintenance costs can be significantly reduced because low power fiber optic sensing systems do not require explosion-proof conduit and containment. The fiber optic sensors can operate at elevated temperatures in hydrogen rich environments

Temperature – Fiber optic temperature sensors can be designed for measuring temperatures that range from -100°F to 1400°F. The sensors can be packaged in stainless steel sheaths that range from .050" to 1/4" diameter. Single point sensors can be a direct substitute for conventional thermocouples and RTD's. Multipoint temperature sensor probes can have up to thirty-two sensors. Multipoint temperature sensor probes are ideal for monitoring the temperature profile of catalyst in tube reactors or along the length of furnace tubes. The probes can range in length from several inches to more than fifty (50) feet and can be packaged in probes as small as 1/8" in diameter. The individual temperature sensors can be spaced 1" apart. The multipoint sensor probes can be connected directly to the signal conditioner or via a ruggedized multipoint connector.

Pressure Sensors – Fiber optic pressure sensors can operate at temperatures up to 1000°F with maximum pressures to 20,000 psi and be designed as gage or absolute sensors. Inconel-718 is typically used for diaphragms because of its high strength and corrosion resistance but other materials can be used if conditions warrant. Each sensor is manufactured with stainless steel armor jacketing to protect the fiber where it exits the transducer body. If conditions warrant, a temperature sensor can be integrated into the transducer to provide thermal compensation for changes in the pressure sensor gap due to changes in temperature over the operating temperature range of the transducer. Miniature pressure sensors can be as small as 0.180 inch in diameter. Because the fiber optic gage pressure sensors do not contain any fill-fluid, they are immune to drift and failure due to service at high temperatures in hydrogen-rich environments.

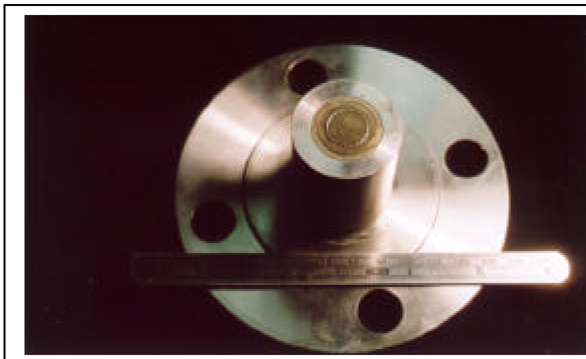


Figure 5 – Extended Flange Pressure Transducer

Differential Pressure (dP)/Density/Level/Flow Sensors – Fiber optic differential pressure sensors can operate at temperatures up to 500°F and measure 0-400 inches of water with static pressure of 3000 psi. These fiber optic differential pressure sensors are fluid-free and can be integrated with a temperature sensor. The differential pressure sensors can be used to measure density or level if defined as such in the signal conditioner set routine. In many cases, the fiber optic dP sensor can be designed to eliminate capillary tubes and impulse lines.

Linear/Rotary Position Sensors – Fiber optic linear position sensors have an operating range of up to 4" and can resolve 0.001 of an inch. These sensors are designed to operate at temperatures up to 500°F. Rotary position sensors have an operating range of 360° and can resolve 0.5°. These sensors are designed to operate at temperatures up to 500°F.

Strain Sensors – Fiber optic temperature-compensated strain sensors are designed to operate at temperatures up to 1000°F with a range of 0-5000 microstrain. These high temperature strain sensors can be configured with a stainless steel shim that allows the sensor to be welded to a vessel or pipe. These fiber optic sensors remain accurate through the rated temperature range because of the innovative design that provides automatic temperature compensation. As with all of the other sensors, the temperature compensated strain sensor has two reflective surfaces, one of which is the end of the fiber. The other reflector is a material that matches the thermal expansion of the work piece. For example, if the work piece is stainless steel, then a stainless steel wire is used for the second reflector. Since both the work piece and the wire are the same material, the Fabry-Perot gap is not sensitive to temperature changes and is only sensitive to changes in strain.

Accelerometers and Vibration/Acoustic Sensors – Fiber optic accelerometers and vibration/acoustic sensors are designed to operate at temperatures up to 500°F with a wide range of sensitivity. Because the sensors contain no electronic components, they can be quickly welded to a vessel or pipe using conventional stud welding equipment. Two variations of the vibration/ acoustic sensors exist. The first is a microelectromechanical systems (MEMS) based design with an "H" shaped accelerometer beam. The second is a resonant sensor that is tuned for high sensitivity to a narrow band of acoustic frequencies. The range of frequency response for these sensors is 2Hz to 100kHz and performance is comparable piezoelectric accelerometers.

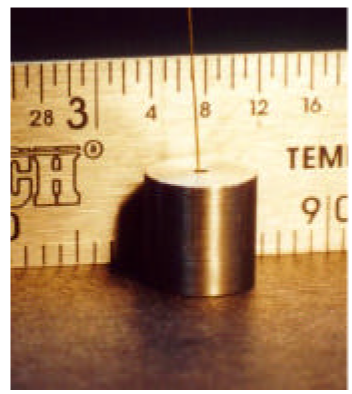


Figure 5 – Resonant Acoustic Sensor

CONCLUSION

The advantages of fiber optics for industrial process control instrumentation are great. The technology is mature; the infrastructure to support industrial fiber applications is in place; and the cost of critical components continues to fall while technical performance improves. Fiber optic sensing systems offer a number of benefits over conventional electronic sensing systems:

- Lower installed cost than conventional sensors used in hazardous locations because no explosion proof containers and conduct is needed.
- Inherent safety and suitability for use in Class I, Division 1 explosion hazardous environments.
- Tolerance to high temperatures, e.g. 1000°F and hydrogen-rich, corrosive environments.
- Immunity to EMI, grounding, and lightning problems and isolation from high voltage circuits.

Fiber optic sensing systems are being designed and packaged to address the harsh environments of industrial process control. Sensors and signal conditioners have been tested under field conditions and have demonstrated seamless interface with existing distributed control systems. Integrated families of fiber optic sensors and signal conditioners are available to measure most physical parameters and systems are being used in refineries, chemical plants, power plants, and in oil and gas production facilities.

Over the next few years, the reliability and economic advantage of fiber optic sensing will be proven in a wide variety of industrial applications. There is a bright future in the field of industrial process control.