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Current developments in magnetostrictive position sensors

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Abstract.

A magnetostrictive position sensor with a flexible sensing element simplifies the installation in a hydraulic cylinder. Such a sensor should achieve the same performance as a sensor with a rigid sensing element. In addition, a magnetostrictive position sensor should provide further information in addition to the position, as data can be recorded directly on site in the hydraulic cylinder.

Keywords. Magnetostriction, position sensor, flexible sensing element, hydraulic cylinder.

1. INTRODUCTION

Hydraulic cylinders are used for many purposed, such as to open and close lock gates (Fig. 1), feed rolls in a rolling mill, move the arm of an excavator, or orient the wheels of a vehicle according to the steering angle. All these movements require the position of the piston rod to be detected and transmitted to the control system. Magnetostrictive position sensors have proven themselves in applications such as these.

Figure 1.1: Hydraulic cylinder for moving a lock gate

2. What is Magnetostriction?

A magnetostrictive position sensor uses the principle of magnetostriction to determine a position. Magnetostriction is a magnetic effect in which the mechanical dimensions of a ferromagnetic material such as nickel, iron, cobalt, or their alloys change under the influence of a magnetic field. This is known as the Joule effect. The reverse of this effect is also possible: The magnetic properties of a material, such as permeability, change when its mechanical dimensions are altered. This behavior is known as the Villari effect.

When a current flows through a wire made of magnetic material, this current generates a magnetic field that surrounds the wire. If this magnetic field encounters an external axial magnetic field, a torsional force is generated at this location, which causes a slight mechanical twist. The external axial magnetic field is generated by a permanent magnet that surrounds the wire or is located very close to it. This behavior of a wire made of magnetostrictive material is known as the Wiedemann effect.

These properties are used to determine a position with a magnetostrictive sensor.

3. What is a Magnetostrictive Position Sensor?

Fig. 2 shows a magnetostrictive position sensor. This type of sensor measures the distance between the pickup system and the position magnet. To do this, a short current pulse is generated in the sensor electronics and applied to the waveguide. This current pulse travels through the waveguide and creates a radial magnetic field. The position magnet, which marks the position to be measured, generates an axial magnetic field. The momentary interaction of these two magnetic fields generates a torsional wave in the waveguide, which propagates as an ultrasonic wave at a speed of approximately 2800 m/s. This wave travels in both directions, toward the end of the waveguide and toward the pickup system. The wave traveling to the end of the waveguide is extinguished by damping elements. This eliminates disruptive reflections of this wave.

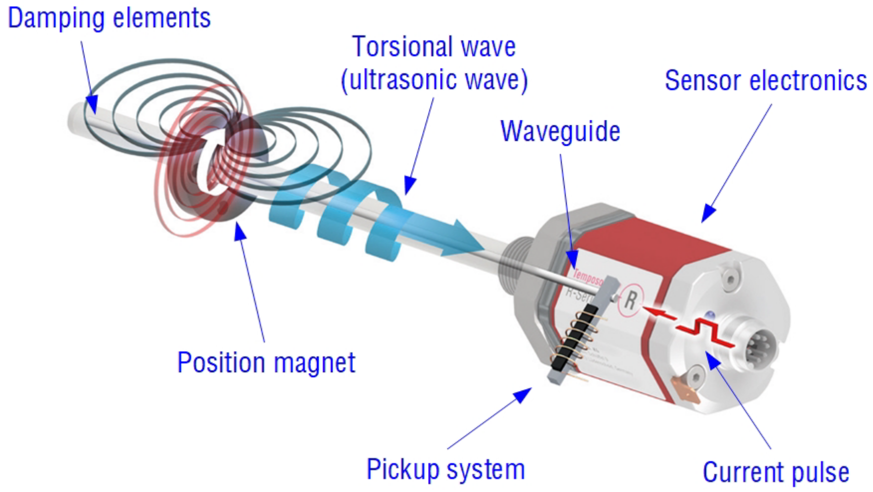

Figure 3.1: Design of a magnetostrictive position sensor

The wave traveling to the pickup system is converted into a voltage signal. When the current pulse is sent, a time measurement is started, which is stopped when the wave arrives at the pickup system. The speed at which the wave moves along the waveguide is called the gradient. The gradient of each position sensor is known, so that the position of the magnet on the waveguide can be determined based on the time measurement. The following applies:

Position = gradient × travel time

The main components of a magnetostrictive sensor are:

- Waveguide
- Position magnet
- Pickup system
- Sensor electronics

The waveguide can be described as the heart of a magnetostrictive position sensor. It is a thin wire with a diameter of 0.25…1 mm. The properties of the waveguide have a significant influence on the performance of the sensor. Important characteristics of a waveguide are:

- Magnetostriction coefficient: The coefficient indicates how far the magnetostrictive material expands when a certain field strength is applied.
- Wave attenuation: The amplitude of the wave is attenuated as the distance along the waveguide increases.
- Variation in propagation speed along the length: For accurate position measurement, it is necessary that the speed at which the wave travels along the waveguide is identical at every point along the waveguide.

These characteristics depend on the intrinsic properties of the material and the microstructure. They can be influenced by the material composition and manufacture of the waveguide. A nickel-iron alloy or similar is often used as the material for the waveguide. However, the exact composition of the material and the manufacturing process are a trade secret of the manufacturers, just like the recipe for Coca-Cola.

A permanent magnet is used as the position magnet. When using a magnetostrictive position sensor in a hydraulic cylinder, a rod-type sensor with a ring magnet is used in most cases, as shown in Fig. 2. The ring magnet surrounds the waveguide on all sides, ensuring a uniform magnetic field.

The pickup system detects the torsional wave and converts it into a voltage signal. The design and functionality of a pickup system are not relevant to this work. Interested readers can find more information in [Nyce, 2004].

The sensor electronics generate the current pulse that is applied to the waveguide and perform the time measurement. The time measurement signal is processed and made available at the output. The user can choose between different configurations such as analog, SSI, IO-Link, EtherCAT®, or PROFINET.

A magnetostrictive position sensor is an absolute measuring sensor that is characterized by high precision and repeatability. The measurement is contactless because the position magnet hovers above the rod. It is not necessary for the magnet to touch the rod. Such a sensor meets the requirements of both industrial and mobile hydraulic environments in terms of reliability and robustness in harsh environments.

4. INTEGRATION OF A MAGNETOSTRICTIVE POSITION SENSOR INTO A HYDRAULIC CYLINDER

A magnetostrictive position sensor is integrated into a hydraulic cylinder by inserting the sensor rod into the drilled piston rod (Fig. 3). The cylinder is sealed via the flange so that no hydraulic fluid can escape. The position magnet is mounted at the bottom of the piston rod so that the position of the piston can be detected at any time. The pressure-resistant sensor rod contains the sensing element with the waveguide. Only the flange with the sensor electronics housing is located outside the cylinder. This offers the advantage that no large attachments are required on the outside of the cylinder.

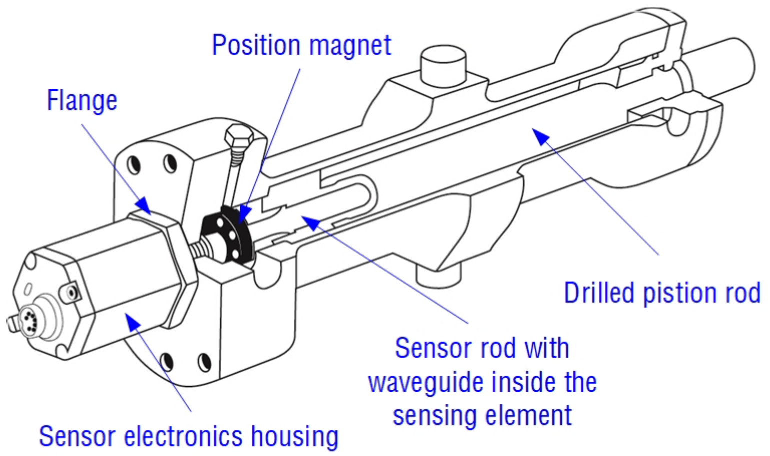

Figure 4.1: Integration of a magnetostrictive position sensor into a hydraulic cylinder

As described, a magnetostrictive position sensor measures the distance between the pickup system and the position magnet. The maximum distance that a sensor can measure is referred to as stroke length and can be selected in the range of 25…7620 mm for a rod sensor. When installing a magnetostrictive sensor in a hydraulic cylinder, the stroke length is usually slightly greater than the piston stroke of the cylinder. This ensures that the sensor can detect the entire travel path of the piston. The sensor rod usually has an outer diameter of 10 mm and a wall thickness of 1.5 mm. It protects the internal waveguide and withstands the hydraulic pressure inside the cylinder.

5. SENSOR WITH FLEXIBLE SENSING ELEMENT

As explained the stroke length of a magnetostrictive position sensor is slightly greater than the piston stroke of the hydraulic cylinder, and the sensor rod with the internal waveguide is rigid due to its compressive strength. Therefore, when installing the sensor, one piston stroke of space is required behind the cylinder. While this is usually possible when constructing the cylinder, there is often not enough space available after the cylinder has been integrated into the final application. If the sensor needs to be replaced, the lack of space behind the cylinder poses a challenge.

To reduce the space required for removal and reinstallation, the sensing element – essentially consisting of a waveguide and an enveloping protective tube – would have to be bent.

However, bending the waveguide impairs the propagation of the torsional wave. The more the waveguide is bent, the more the amplitude of the torsional wave is weakened. A weakening of the torsional wave makes detection at the pickup system more difficult and thus a reliable and precise position determination. If the waveguide is bent so much that it is plastically deformed, the microstructure of the waveguide is damaged. In this case, the propagation of the torsional wave is stopped at the damaged location. A position determination is no longer possible.

The following conditions therefore apply to a flexibly designed sensing element:

- Bending of the sensing element must not impair the function of the sensor: As described, bending of the waveguide weakens the signal of the torsional wave. The sensing element with waveguide must therefore be designed in such a way that this weakening does not affect reliable position determination.
- It must be possible to insert the flexible sensing element into the pressure-resistant sensor rod with an outer diameter of 10 mm and a wall thickness of 1.5 mm.
- The performance of the sensor with a flexible sensing element must be the same as that of a sensor with a rigid sensing element: In addition to reliable position detection, this applies in particular to linearity as well as shock and vibration resistance.

To meet these conditions, the interaction between the sensing element and sensor electronics must be adjusted. The choice of protective tube is also crucial: The protective tube must be stable enough to protect the internal waveguide, yet flexible enough to allow bending. After testing various tubes, a stainless-steel protective tube covered with a PU sheath was selected. The structure of this tube is shown in Fig. 4. It protects the internal waveguide from mechanical stress and, with the PU sheath, provides the necessary flexibility so that the waveguide can only be elastically deformed.

Figure 5.1: Schematic presentation of the structure of the protective tube in a bent state

As described, the amplitude of the torsional wave is attenuated when the waveguide is bent. With a suitable combination of sensing element and sensor electronics, reliable position measurement can be achieved even with a weaker torsional wave signal. Tests were conducted to determine the degree of bending of the flexible sensing element at which the position of the magnet on the measuring rod can still be reliably determined by adjusting the sensor electronics.

For example, a sensor with a flexible sensing element was wound in a curve of 100 mm and 165 mm and the linearity was measured (Fig. 5.2). Fig. 5.3 shows the linearity diagram of the sensor with flexible sensing element in a straight state after unwinding from a diameter of 165 mm. A laser interferometer is used as a reference to determine linearity. Despite the bending of the flexible sensing element, the internally set linearity limits of ± 0.1 mm are only minimally exceeded.

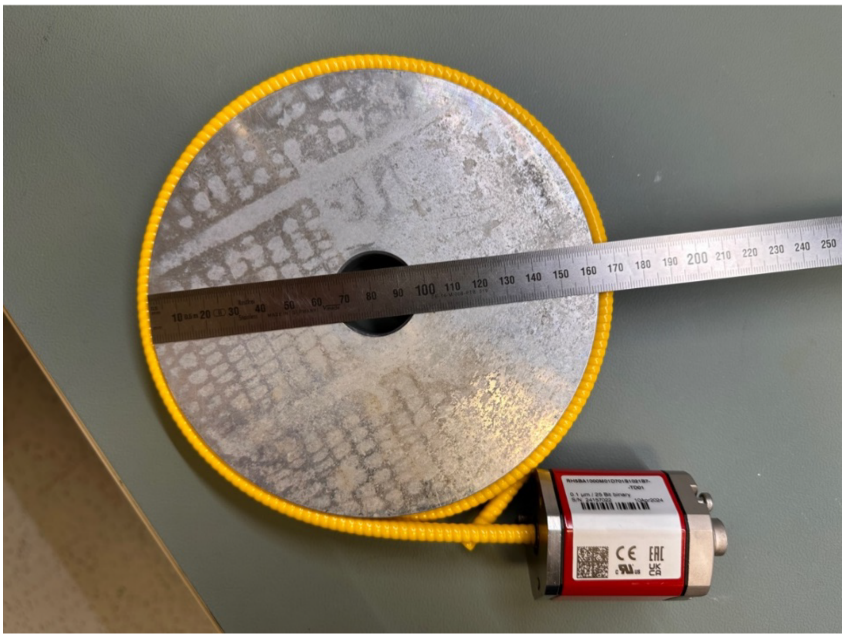

Figure 5.2: Sensor with flexible sensing element wound up in a diameter of 165 mm

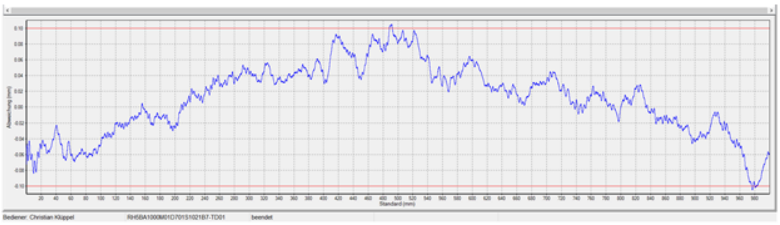

Figure 5.3: Linearity diagram of a sensor with flexible sensing element after unwinding from a diameter of 165 mm

Another test examined how different bending radii affect the amplitude of the torsional wave. To do this, the flexible part of such a sensor was pushed through devices with defined bending radii. The sensing element was pushed through the device up to the sensor electronics in order to assess how different bending radii dampen the torsional wave when it reaches the pickup system (Fig. 5.4). Table 5.1 shows how the signal strength changes as a percentage compared to the unbent state as the bending radius increases. By adjusting the sensor electronics, the signal strength decreases by only 3% even with an increasing bending radius. It should be noted that these tests were carried out under laboratory conditions. In harsh industrial environments, the permissible minimum bending radius must therefore be provided with a safety factor.

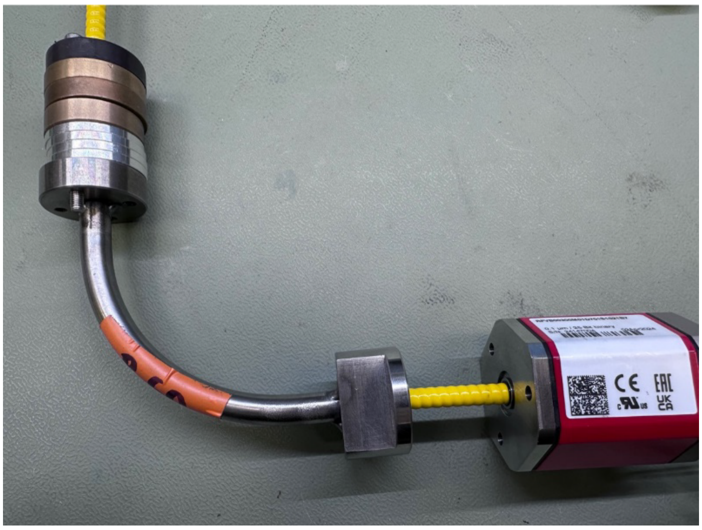

Figure 5.4: Sensor with flexible sensing element inserted into a device with a defined bending radius

Bending radius R	Amplitude of torsional wave
R = 0 mm (reference)	100 %
R = 80 mm	100 %
R = 75 mm	100 %
R = 70 mm	100 %
R = 65 mm	97 %
R = 60 mm	97 %
R = 55 mm	97 %
R = 50 mm	97 %

Table 5.1: Damping of the amplitude of the torsional wave depending on the bending radius

The tests show that a reliable magnetostrictive position sensor with a flexible sensing element can be constructed using a suitable combination of metal protective tube, waveguide, and sensor electronics. As shown in Fig. 5.5, the base unit of a magnetostrictive sensor, consisting of sensor electronics and sensing element, can be separated from the pressure-resistant sensor rod. While the pressure-resistant sensor rod remains in the cylinder, the base unit can be replaced. With a sensor with a flexible sensing element, only a space of approximately 150…200 mm behind the cylinder is required when installing and removing the base unit in the pressure-resistant sensor rod, regardless of the stroke length of the sensor. This means that a sensor with a flexible sensing element is a great simplification in comparison to a sensor with a rigid sensing element regarding removal and reinstallation on site.

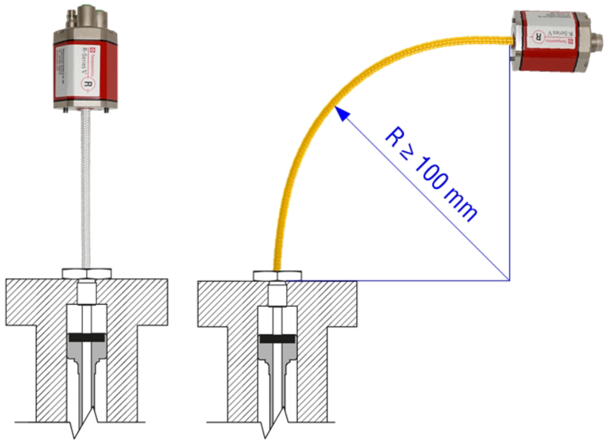

Figure 5.5: Installation of a base unit with rigid sensing element (left) and with flexible sensing element (right)

6. Sensor with Additional Information

In the context of Industry 4.0, a sensor should not only provide its actual data, but also transmit additional information [Anderl et al. 2015]. The actual data of a magnetostrictive sensor is the position of the piston in the cylinder and, if applicable, the velocity of the piston movement. In addition, such a sensor can transmit further information to the control system, such as:

- the total distance traveled by the piston,
- the number of cycles performed by the cylinder,
- the current, minimum, and maximum power supply to the sensor, or
- the quality of the measured sensor signal.

The total distance traveled by the piston and the number of cycles provide information about the operating life of the hydraulic cylinder and can be used to analyze maintenance intervals. The information on the sensor's power supply and the quality of the sensor signal describes the current status of the sensor. Users can use all this information to check both their system and the sensor during operation, thereby enabling predictive maintenance.

One aspect of development trends in sensor technology is the functional integration of different sensor components [Wertschützky 2018]. When integrated into a hydraulic cylinder, a magnetostrictive position sensor offers the advantage of being able to collect data "directly on site," i.e., inside the cylinder. For example, the temperature of the hydraulic oil or the pressure inside the cylinder can be recorded by extending the magnetostrictive sensor. Currently, in order to record additional data, holes must be drilled and sealed in the cylinder, further sensors must be installed, and cables must be laid. Combining data recording in a single sensor reduces the cost of mechanical processing of the cylinder. In addition, by linking the data, conclusions can be drawn about the condition of the cylinder and thus the application. On the other hand, there are the costs of such an adaptation. In order for the expansion of a magnetostrictive position sensor to be of interest to cylinder manufacturers and users, the costs must not exceed those of a separate sensor.

According to [Drese et al., 2025], sensors will become smarter in the future. Such smart sensors not only collect data, but also process it. In this context, a magnetostrictive sensor can be enabled to prepare the data currently collected for analysis and decision-making:

- By recording the piston travel, it is possible to process how often the piston moves in which area of the cylinder stroke.
- The number of cycles driven can be used to determine how smoothly or gently the piston moves through the cylinder (detection of stick-slip effects).

In this respect, this article is also a call to users, manufacturers, and scientists to work together to clarify what can and should be implemented and how.

7. References

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Biographies

Olaf Kissing received his diploma in industrial engineering from the University in Siegen in 2002 and his doctorate degree in engineering from the University of Siegen in 2010. He has been working as a product manager at Temposonics GmbH & Co. KG in the industrial sensors division for more than 10 years.