

# A New Pressure Sensor Structure with Minimal Enclosed Oil

Tatsuo Tanaka

Technology Development Headquarters  
Azbil Corporation

## Keywords

pressure sensor, enclosed oil, pressure sensor structure, diaphragm

We have developed a pressure sensor structure for small pressure transmitters that we believe will benefit process automation, factory automation, and various markets such as the sanitary market. The pressure sensor structure is equipped with a new pressure sensing element with built-in overpressure protection. The new pressure sensing element has a pressure introduction chamber both on the top and the bottom of the pressure detector, and contains only a very small amount of enclosed oil as the pressure transmission medium. Minimizing the amount of oil minimizes the degradation of characteristics caused by the ambient temperature, allowing higher precision. The amount of enclosed oil is reduced to less than 10 % compared with the existing structure.

## 1. Introduction

Pressure is a physical quantity that serves as one of the fundamental indicators enabling us to understand physical phenomena. Research and development of relevant measurement methods and equipment have been repeatedly carried out for many years. The importance of measuring pressure continues to increase, and technical improvements are made on an ongoing basis. Azbil Corporation initially began business operations by developing and selling pneumatic pressure gauges, and we have been successfully developing and marketing pressure transmitters for approximately 60 years. In the mid-1980s, we converted our sensor detectors to incorporate semiconductor elements, and controlled the output of these elements using an electric module containing a microcomputer, enabling us to develop and market high-precision products. Since then, we have built up a track record as a leader in the sale of semiconductor piezo-resistive pressure sensors in Japan. Currently, we provide products like the examples shown in figure 1 to a wide range of markets, such as process automation (PA), factory automation (FA), and the sanitary market, and we have received high praise from numerous customers.



Figure 1. Azbil Corporation Pressure Transmitters

In order to address a wide variety of conditions related to measurement subjects and to stabilize the atmosphere around the sensor detector, these products have sensor detectors surrounded by enclosed oil, and pressure is measured by means of a barrier diaphragm.

In spite of having the above-mentioned advantages, however, the enclosed oil expands and contracts due to temperature changes, causing deformation of the barrier diaphragm and affecting the output of the pressure sensor. Therefore, if the volume of the enclosed oil is reduced, the temperature characteristics are improved.

Generally, the space filled with enclosed oil can be classified into two areas: a space that maintains the range of motion of the barrier diaphragm, and a space that transmits the pressure to the sensor detector. Their ratio is approximately 1:1. The space for pressure transmission can ideally be reduced to a minimal amount that can still ensure a transmission path. As a result, the proportion for the range of motion of the barrier diaphragm increases. The diameter of the barrier diaphragm can be reduced, and the volume of the enclosed oil can be greatly reduced.

Based on the above-mentioned ideas, we have developed a pressure sensor structure with a barrier diaphragm which is smaller in diameter than conventional models and which requires a minimal volume of enclosed oil. We believe that this development will provide greater value to a wide range of markets.

## 2. Conventional Pressure Sensor Structure

Prior to describing the newly developed pressure sensor structure, we would like to explain the typical pressure sensor structure that utilizes a semiconductor piezo-resistive method (figure 2).

The structure of the conventional pressure sensing element is shown in the center of figure 2. A sensor detector is formed on the top of a silicon layer, and a glass layer is bonded to the bottom of the silicon layer in order to insulate it from the diaphragm base, which is a metal housing.

The sensor detector and the pin are connected by wires. The output of the pressure sensing element is sent out through this pin. The pin is insulated from and supported at the diaphragm base by glass beads. Also, the enclosed oil is insulated and shielded by a hermetic seal.

One of the components of the pressure sensing element is the glass layer. The coefficient of linear expansion of the glass layer differs greatly from the coefficient of linear expansion of the stainless steel that the diaphragm base is made of. Therefore, if these two parts are directly bonded using epoxy adhesive or something similar, when the temperature changes, strain may be generated in the sensor detector due to the difference in the coefficient of linear expansion. Consequently, if the temperature changes significantly, measurement accuracy will be degraded.

To alleviate this effect, various types of structural ingenuity have been devised. In many cases, a method to reduce the thermal strain propagation to the sensor detector is used. A buffer whose coefficient of linear expansion is intermediary to that of these two parts is mounted between them. For this purpose, materials with a low coefficient of linear expansion such as KOVAR and 42 alloy are widely used.

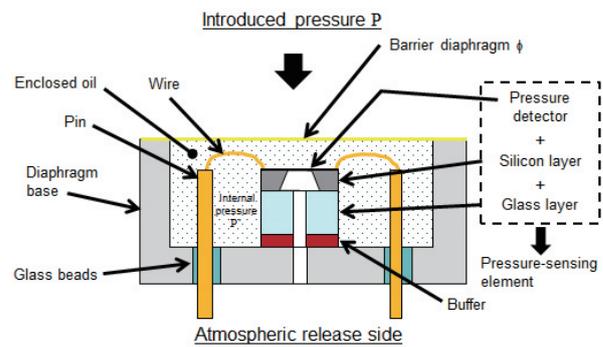


Figure 2. Conventional pressure sensor structure

The enclosed oil is filled around the pressure sensing elements. The enclosed oil works as a pressure transmission medium, transmitting the process pressure to the sensor detector. If the process pressure is  $P$  and if the pressure of the internal enclosed oil is  $P'$ , the following relationship (1) is established between pressure difference  $\Delta P$  and the change in volume  $\Delta V_1$  due to the displacement of the diaphragm (that is, the volume change due to compression of the enclosed oil).

$$\Delta P = P - P' = \Delta V_1 / \phi \quad (1)$$

Here, the value  $\phi$  is a physical amount that indicates the percentage of volume change per unit pressure change, and this is expressed as the compliance of the barrier diaphragm.

$$\phi = Kd^6/t^3 \quad (2)$$

In expression (2), "K" is a constant that is determined by the shape of the barrier diaphragm, "d" is the diameter, and "t" is the thickness.

The volume of enclosed oil also changes as it expands or contracts due to changes in the ambient temperature. In this case, if the change in the volume is  $\Delta V_2$ , the volume of the enclosed oil is "V," the coefficient of expansion is " $\alpha$ ," and if the change in ambient temperature is  $\Delta T$ , the following (3) is obtained.

$$\Delta V_2 = \alpha V \Delta T \quad (3)$$

Also, in this case:

$$\Delta P = P - P' = \Delta V_2 / \phi \quad (4)$$

can be obtained.

The design concept of the pressure sensor structure is to reduce the value  $\Delta P$  by reducing  $\Delta V_1$  in expression (1) and the value  $\Delta V_2$  in expression (4), or to reduce the value  $\Delta P$  by increasing the value  $\phi$  in expression (1). The value  $\phi$  is greatly affected by the diameter and thickness of the barrier diaphragm, as shown in expression (2). In other words, if the barrier diaphragm is larger in diameter and thin, the value  $\phi$  increases, and the pressure loss due to values  $\Delta V_1$  and  $\Delta V_2$  decreases. Consequently, higher precision can be achieved for the output of the pressure sensor structure.

As described above, the conventional pressure sensor structure has a hermetic seal structure and a pedestal with a low coefficient of linear expansion. Although degradation in the output accuracy of the pressure sensing element can be suppressed by the above-mentioned measures, but due to the special structure and special materials used, in terms of cost significant ingenuity is required at the time of application. In addition, the output accuracy level of the pressure sensing element greatly depends on the balance between the diameter of the barrier diaphragm and the volume of enclosed oil.

Incidentally, characterization of  $\Delta P$  can be accomplished by the electrical module that is connected to the latter stage of the pressure sensor structure. Therefore, even if there is a large volume of enclosed oil, there may be no problem if the reproductivity of the barrier diaphragm is normal. However, increasing the volume of enclosed oil causes the displacement range of the barrier diaphragm to increase, while also inducing an increase in pressure hysteresis and thermal hysteresis. Since the hysteresis cannot be removed by correction, the smaller the hysteresis is, the more it contributes to the high-precision output of the pressure sensor.

### 3. Newly developed pressure sensor structure

We have developed a new pressure sensing element and pressure sensor structure based on the conventional structure described in section 2. A diagram of this structure is shown in figure 3.

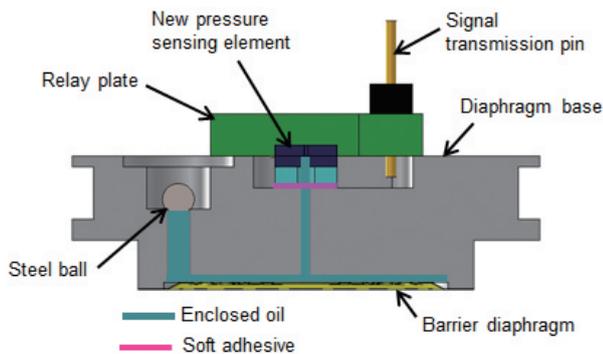


Figure 3. New pressure sensor structure

In the new pressure sensor structure, the enclosed oil fills only a small space, as shown in Figure 3. The new pressure sensing element is directly bonded to the diaphragm base, which acts as a pressure vessel. After the oil is enclosed, it is sealed using a steel ball attached by resistance welding. The relay plate is a component that is used to send the output from the new pressure sensing element to the outside via the signal transmission pin. The relay plate is directly bonded to the diaphragm base.

The new pressure sensing element has two main features in terms of the structure. The first structural feature is a minimal volume of enclosed oil filling the space between the pressure diaphragm and the sensor detector. The second structural feature is the pressure sensing element directly bonded to the diaphragm base using an adhesive with ultra-low Young's modulus.

The following explains the first feature, the minimum volume of enclosed oil. The new pressure sensing element has a stacked structure as shown in figure 4, and has pressure introduction chambers 1 and 2 on both sides of the sensor detector. With this structure it is possible to limit the presence of enclosed oil to within the pressure sensing element. That is, unlike the conventional pressure sensor structure, there is no need for the wiring section where the output of sensor detector is read to be submerged in the oil. As a result, we can minimize the area for pressure transmission between the barrier diaphragm and the sensor detector, consequently reducing the volume of oil used.

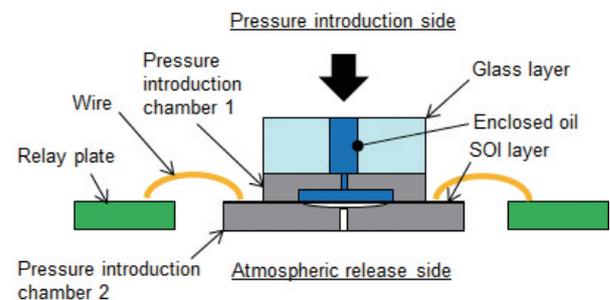


Figure 4. Structural drawing of new pressure sensing elements

Thanks to this effect, we were able to reduce the size of the barrier diaphragm in the new pressure sensor structure by approximately 20 % compared to that of our conventional products. We were also able to reduce the volume of enclosed oil to 1/10th of that of conventional products. As a result, the amount of expansion or contraction due to changes in ambient temperature has been minimized, and zero-point change of the sensor output has been suppressed to within  $\pm 0.6$  % FS. In addition, we do not need to fill the enclosed oil to include the electrode lead-out portion or wires. Therefore, the hermetic seal structure, which is widely used in many products, is no longer required, and subsequently production cost are reduced.

The second feature of the new pressure sensor structure is the bonding process of the pressure sensing element and the diaphragm base component.

For the new pressure sensor structure, we have adopted the direct bonding method and a soft adhesive with ultra-low Young's modulus after curing. The soft adhesive layer suppresses the generated thermal stress as well as the strain due to this stress. As a result, the buffer shown in figure 2 is not required, and consequently production costs are reduced. Figure 5 shows the stress-strain curve of this soft adhesive.

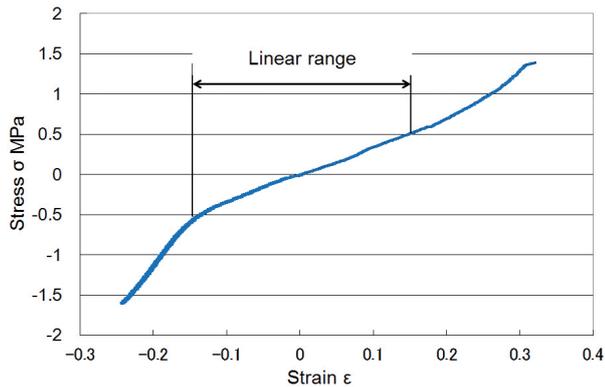


Figure 5. Stress-strain diagram of soft adhesive

Figure 5 shows that the area where the relationship between stress and strain is linear has a level of strain within  $\pm 15\%$ . The tilting of the curve indicates that the Young's modulus of the soft adhesive is approximately 3.6 MPa. Because this value is very small compared to that of conventional adhesives, we concluded that it was appropriate for this soft adhesive to be used for adhesion purposes in the new pressure sensor structure.

On the other hand, because the soft adhesive has ultra-low Young's modulus, the pressure resistance of the package structure is limited by the pressure resistance of the adhesive layer. We achieved a pressure resistance of 10 MPa or higher by making the ratio of the cross-sectional area of the glued area to the pressure transmission area to be 20 or higher, so that even if excessive pressure is applied, the stress on the adhesive layer is maintained within the linear range shown in figure 5.

As described above, we were able to produce a new small pressure sensor structure that has two main features. By adopting this pressure sensor structure in a pressure transmitter product, we are able to create the performance characteristics of a high-precision industrial instrument that can be installed in a unit to be used indoors, which was not a viable option for conventional products due to their large size. Also, its compact design reduces the amount of materials required for its production, which helps reduce environmental impact.

## 4. Performance evaluation of new pressure sensor structure

This section discusses the results of evaluating the new pressure sensor structure that was described in section 3. In order to confirm the effects of the reduced volume of enclosed oil, we also evaluated with the volume of enclosed oil equivalent to that of conventional products, and compared the two. The subjects of evaluation were the temperature characteristics and the temperature hysteresis characteristics at the zero point of pressure sensor structure output, which are major error factors. The results are described below.

### 4.1 Zero-point temperature characteristics

Figure 6 shows the results of evaluating the zero-point temperature characteristics of the pressure sensor structure output.

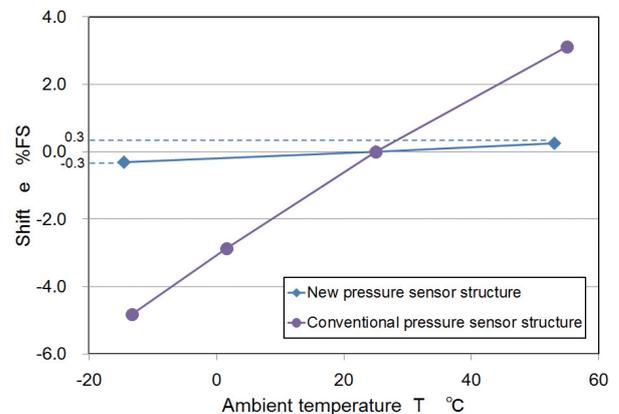


Figure 6. Zero-point temperature characteristics of new pressure sensor structure

In this figure, the horizontal axis shows the ambient temperature, the vertical axis shows the amount of shift based on a temperature of 25 °C. The zero-point error at each temperature point is shown as a percentage of the full scale. In the new pressure sensor structure, the calculated value of the zero-point shift due to the impact of enclosed oil was a maximum of  $\pm 0.55\%$  FS, but the actual value was no more than  $\pm 0.3\%$  FS. Regarding this difference, in order to clarify the influence of temperature characteristics of the enclosed oil, we compared the zero-point temperature characteristics before and after oil was enclosed in the new pressure sensor structure. The results are shown in figure 7.

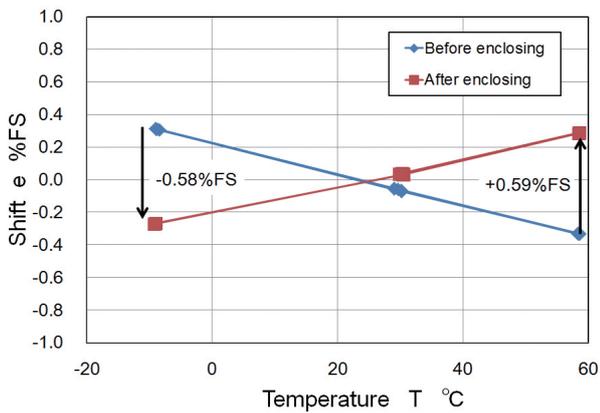


Figure 7. Change in output characteristics before and after oil was enclosed

In figure 7, the horizontal axis shows the ambient temperature. The vertical axis is the amount of shift as shown in figure 6. When we checked the difference in characteristic values before and after oil was enclosed, it was  $\pm 0.59\%$  FS. This was almost the same as the calculated value of the zero-point shift amount due to the impact of the enclosed oil.

In figure 6, the new pressure sensor structure has a very small amount of zero-point shift when the ambient temperature is changed when compared with that of conventional products. Therefore, it may be possible to simplify the characterization function that will be implemented when the product is marketed.

#### 4.2 Temperature hysteresis characteristics

To enable high-precision pressure measurement, the temperature hysteresis of the pressure sensor structure needs to be small. In this development, we have determined the target value of the temperature hysteresis to be  $\pm 0.01\%$  FS. To help us achieve this, we checked the hysteresis of the displacement amount by intentionally changing the barrier diaphragm before oil was enclosed. The results are shown in Figure 8.

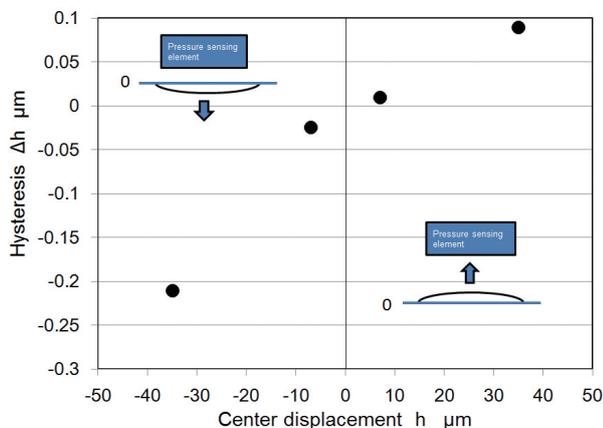


Figure 8. Hysteresis of barrier diaphragm

In Figure 8, the horizontal axis is the center displacement of the barrier diaphragm. The vertical axis shows the difference in center displacement (that is, the hysteresis) before and after applying the displacement load. Here, the negative value side of the horizontal axis shows the status after oil was enclosed when the ambient temperature was high and the enclosed oil had expanded. The positive value side of the horizontal axis shows the status after oil was enclosed when the ambient temperature was low and the enclosed oil had contracted.

From figure 8, it can be seen that the hysteresis of the barrier diaphragm increases more when the enclosed oil expands. Based on this result, we determined the allowable volume of enclosed oil in this pressure sensor structure, and evaluated it.

To maintain the temperature hysteresis of the pressure sensor structure within  $\pm 0.01\%$  FS, we determined that it is necessary to limit the hysteresis of the barrier diaphragm to no more than  $0.23\ \mu\text{m}$ . Figure 8 shows that when the hysteresis of the barrier diaphragm reaches  $0.23\ \mu\text{m}$ , the center displacement, which is calculated from the volume of enclosed oil, is approximately  $40\ \mu\text{m}$ . On the other hand, in the newly developed pressure sensor structure, when the ambient temperature changes from  $25\ ^\circ\text{C}$  to  $55\ ^\circ\text{C}$ , the center displacement of the barrier diaphragm is  $11\ \mu\text{m}$ . Thus, a sufficient level of accuracy can be guaranteed.

The results of evaluating the temperature hysteresis are described next.

Figure 9 shows the results of temperature hysteresis of the new pressure sensor structure.

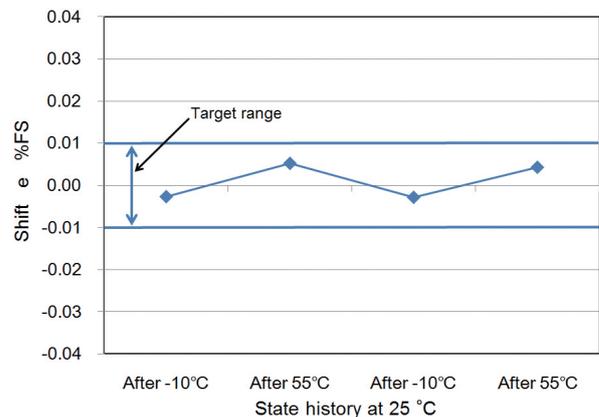


Figure 9. Temperature hysteresis evaluation results

The procedure for evaluation involved observation of the status transition of zero-point output at the standard temperature when the ambient temperature was changed. The standard temperature was set at  $25\ ^\circ\text{C}$ , and the ambient temperature was changed as follows:  $25 \rightarrow -10 \rightarrow 25 \rightarrow 55 \rightarrow 25\ ^\circ\text{C}$ . This sequence was considered to be a single cycle of temperature change, and we repeated two cycles continuously for evaluation purposes.

In Figure 9, the plot for “After -10 °C” indicates the difference in zero-point output at 25 °C before and after the ambient temperature was changed to -10 °C. The plot for “After 55 °C” indicates the difference in zero-point output at 25 °C before and after the ambient temperature was changed to 55 °C. The vertical axis shows the zero-point shift amount in % FS. As shown in figure 9, the temperature hysteresis after change to -10 °C is suppressed to 0.003 % FS. Furthermore, the temperature hysteresis after change to 55 °C is 0.005 % FS. Although a difference in the amount of shift of 0.002 % FS occurred after change to -10 °C and after 55 °C, this was caused by the trend of the hysteresis of the barrier diaphragm before oil was enclosed as shown in figure 8.

Consequently, we were able to realize a pressure sensor structure that achieves the target design values.

## 5. Conclusion

We have developed a pressure sensor structure containing a minimal volume of enclosed oil, and achieved a level of performance within  $\pm 0.6$  % FS for ambient temperature characteristics and within  $\pm 0.01$  % FS for temperature hysteresis. We will incorporate this new pressure sensor structure in our new products, and in order to satisfy various specification-related requirements and to provide value to our customers, we will improve, for example, response speed and expand our product range to include products with differential pressure systems.

Registered trademarks:

Bravolight and SuperAce are registered trademarks of Azbil Corporation.

Patents:

The pressure sensing elements and the new pressure sensor structure that have been described in this document have patents pending.

Reference publications:

- (1) T. Tokuda, et al., “A Novel Pressure Sensor with Built-In Overpressure Protection Utilizing Three-Dimensional Etching and Wafer-Level Stacking Technology,” *The 29th IEEE International Conference on Micro Electro Mechanical Systems (MEMS2016)*

Author affiliation:

Tatsuo Tanaka, Fundamental Technology Development Department, Technology Development Headquarters