A new method for detecting vacuum leakage of a pressure sensor using a pulse discharge technique

A new method for detecting vacuum leakage of a pressure sensor using a pulse discharge technique

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Abstract. A new method for estimating the degree of vacuum of a pressure sensor has been proposed and demonstrated to be applicable for detecting vacuum leakage. The principle of this method is based on the discharge characteristics of Paschen's law. The shielding body case and the electrode terminals in the sensor are employed as the electrodes for the discharge. The discharge potential is measured under a linearly increasing voltage supply, and from this value the pressure in the sensor is estimated. This method is very simple, offering nondestructive testing quality. The measurable range is between 80 and 200 Pa, which is an important pressure range for judging the occurrence of vacuum leakage in pressure sensors.

1. Introduction

One of the most serious problems of a vacuum apparatus is leakage of air into the vacuum tube. In particular, for long life (a few tens of years) apparatus—such as a pressure sensor used to control firing time in automobile engine operation—the leak rate should be suppressed within a limited value. The maximum allowable leakage rate for the pressure sensor used in a car is about 1.0×10^{-5} Pa cm^3 s^{-1}.

Many methods have been suggested to detect leakage of pressure sensors and some of them are now in practical use [1–3]. One method is the detection of He gas leaked out from the inner side of the pressure sensor. For this purpose He gas must be used to fill intentionally the pressure sensor during the production process. This method is very effective because of its high sensitivity. However, there are some disadvantages in actual industrial applications because simultaneous detection on many samples is essentially difficult and the gas itself is rather expensive.

Another method now in practical use is based on radiochemistry. In this method, completed pressure sensors with an internal vacuum are confined for several days in a high-pressure chamber containing Kr radioisotope gas. After such a treatment any possible leakage of the Kr radioisotope into the pressure sensor via a leak point can be detected. The leak rate can then be obtained from counting the rate of γ rays coming from the pressure sensor. This method is very simple to operate and can be applied to many samples simultaneously. However, there are potential serious problems to the environment and to the health and safety of factory personnel who use this method. The necessary preventative action makes the total cost of such a pressure sensor expensive.

We propose here a new method for measuring degrees of vacuum and leakage. The principle of this method is the application of the discharge characteristics of Paschen's law, where the breakdown voltage of the discharge changes depending on the pressure. It should be emphasised that this method is quite unique compared to other methods because not only the leak rate but also the absolute pressure in the pressure sensor can be measured.

2. Principle and experimental method

As is well known from Paschen's law, the breakdown potential of a discharge changes with vacuum pressure when the electrodes are identical in both interelectrode distance and their shape. There is therefore the possibility to determine the pressure of a pressure sensor by measuring breakdown potential of its discharge.

Figure 1 shows the electric circuit employed in this experiment to measure the pressure dependence of the discharge potential. The pressure sensors used in this experiment were commercial ones used in cars, and they contain an integrated circuit (IC) in the shielding case to amplify the signal of the pressure sensor. The sensors have electrode pins on the bottom to transmit the signal. These electrode pins were used as one of the electrodes for inspecting the discharge. The shielding body case was used as another electrode. In order to avoid the occurrence of breakdown in the IC when a high voltage supply was

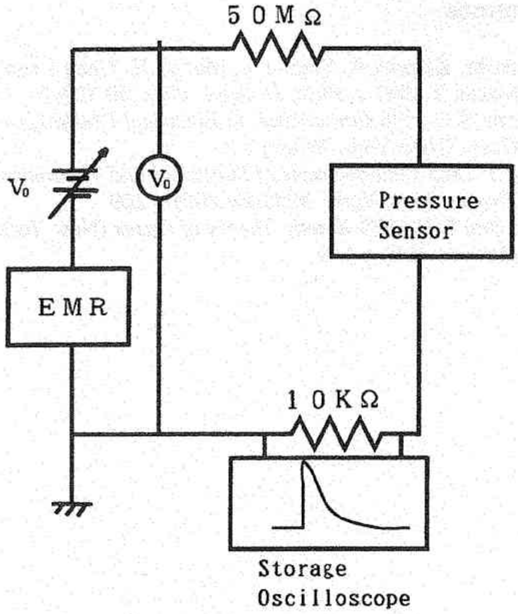


Figure 1. Electric circuit for the discharge characteristics of a single shot discharge.

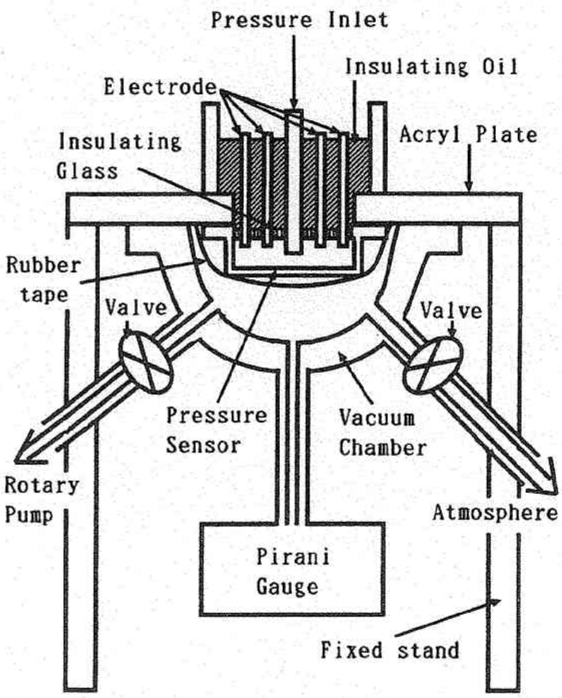


Figure 2. Experimental set-up used to obtain the pressure-controlled simulation experiment.

used, two devices were employed. In one of them all the electrode pins were connected to each other to keep the same electric potential in order to avoid the generation of a potential difference in the IC. In the other device only a single pulse discharge was allowed so as to suppress the total electric charge flowing during inspection of the discharge. The essential point for the single shot discharge is the employment of a high resistance R (50 MΩ) and an electromagnetic relay (EMR) which were connected in series in the circuit. Once the discharge takes place the EMR begins to work to shut the circuit off. The response

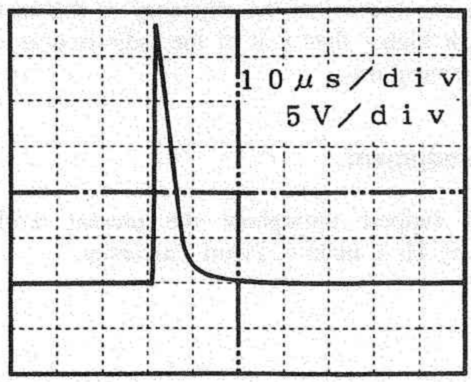


Figure 3. An example of a voltage waveform of a pulse discharge through a 10 kΩ resistance.

time of the EMR is about 2 ms. These methods enabled us to measure the discharge characteristics with a high accuracy and high reproducibility with no damage to the sensor.

Simulation experiments were performed in order to determine how the discharge potential changes with changing pressure of the inside of the pressure sensor. Figure 2 shows a schematic representation of the chamber used in this experiment. The pressure sensors used in this experiment were not complete, but were collected before fixing of the cap in the production stage in the factory, i.e. the shielding cap and the body base of the pressure sensor were disconnected. The body base of the pressure sensor was embedded into an acrylic plate so that the inside of the pressure sensor was enclosed in the vacuum chamber and all the leading out electrode pins were external to the chamber. The removed cap was re-connected to the sensor body base using rubber tape so that electric contact between them was ensured.

The pressure inside the shielding case was supposed to be the same as that of the vacuum chamber because gaps between the shielding cap and the body base were still present and gas circulation can easily take place between them. The pressure of the vacuum chamber was controlled by a rotary vacuum pump.

The imitation sensor was considered to have almost the same features in the electric field distribution as that of the practical pressure sensor when a high voltage was supplied. The pressure sensor had eight electrode pins which were insulated from each other with glass material. These eight electrodes were connected to be at the same potential as mentioned above. The pressure inlet tube of the pressure sensor—a metal pipe with a small internal diameter—was electrically connected to the body base of the sensor. The positive terminal of a high-voltage power source was connected to the eight electrode pins and the negative terminal connected to the sensor body base. Silicone oil was used to insulate these eight electrodes from the pressure inlet tube.

In measurements of the discharge characteristics, we increased the voltage of the power supply automatically to avoid measurement errors since the discharge is a very complicated phenomenon. The room temperature and the humidity of the laboratory were kept constant. The

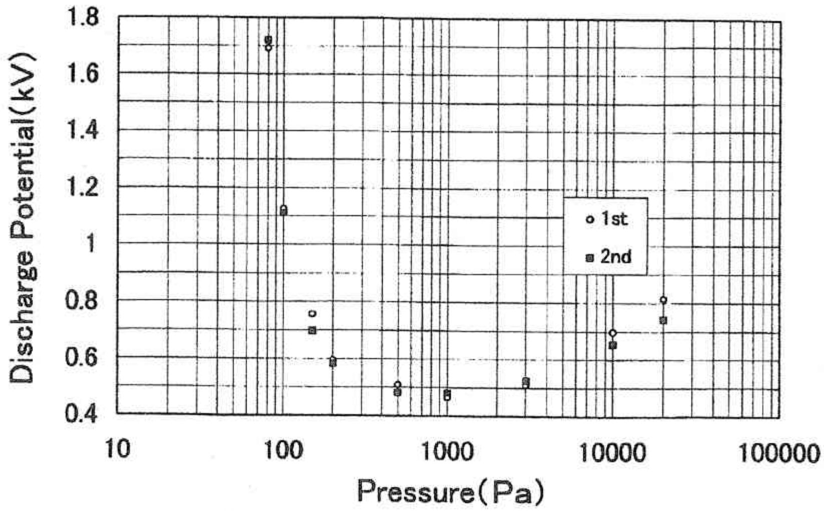


Figure 4. Discharge characteristics for a sample sensor.

maximum voltage was limited to 1800 V because of the dielectric strength between the electrodes.

3. Experimental results

Figure 3 shows an example of a voltage waveform due to a pulse discharge which was detected through a 10 kΩ resistor in the circuit shown in figure 1. The peak voltage is about 25 V and the peak current is 2.5 mA. The total electric charge flowing in the discharge is estimated to be as low as 10 nC, considering the time duration of about 4 μs as half maximum.

Figure 4 shows an example of the discharge characteristics for a sample sensor used in the simulation experiment. Two measurements were done for each vacuum pressure with an interval of about 5 min between them to avoid the influence of residual charges in the shielding case of the sensor.

Figure 5 shows how the discharge characteristics change for nine different samples: (*a*) for the whole pressure range, 80–20 000 Pa, considered in this experiment; and (*b*) a detailed account for the lower pressure range, which is of practical importance. The slight difference in the characteristics of these samples may be mainly due to structural unevenness introduced during factory production, though at this stage we have no idea where the discharge takes place in the shielding case of the pressure sensor. By using these results on the relationship between the pressure and the discharge potential we can identify the pressure in the shielding case of a pressure sensor to an accuracy of about 20 Pa in the pressure range 80–200 Pa.

In addition to the pressure-controlled simulation experiment shown in figure 5, a similar experiment was performed using actual pressure sensors. That is, the discharge potential was measured with the use of the experimental set-up shown in figure 1. Table 1 shows the discharge potential measured at 1.5 months and 3 months after production in the factory. Measurements were made on four actual samples. It can be seen that the discharge potential hardly changed during this time, indicating that there is practically no leakage in these samples. The vacuum pressure of these sensors can be estimated to be 80–100 Pa on the basis of the results shown in figure 5(*b*).

Table 1. Discharge potential (in kV) with time lapse for four actual samples of sensor.

Sensor No.	After 1.5 months	After 3 months
1	1.590(kV)	1.650(kV)
2	1.256	1.416
3	1.692	1.749
4	1.343	1.328

4. Discussion

The method presented in this paper can be used to estimate the inner pressure of a pressure sensor directly. However, it can also be applied to obtain the leak rate of the vacuum.

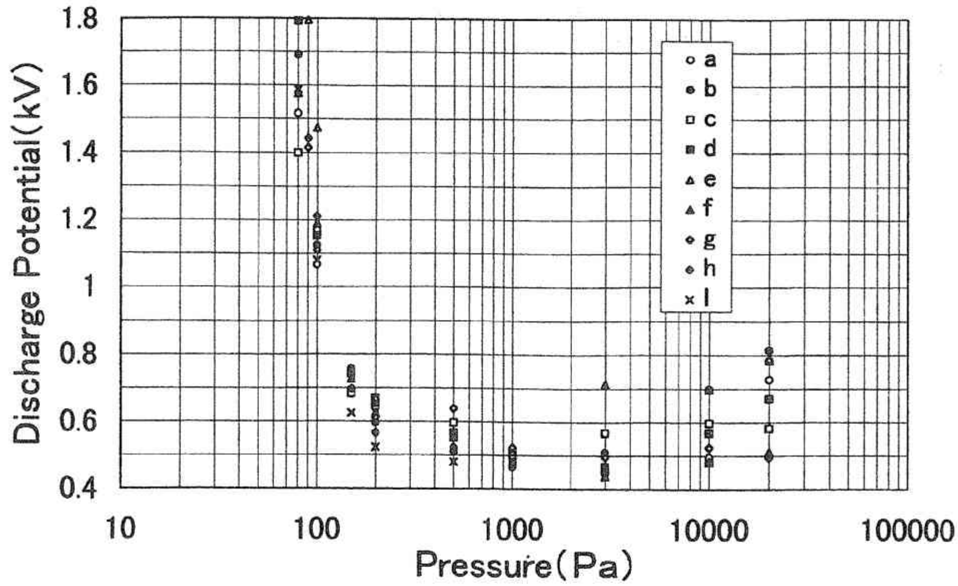
The inner pressure of the sensor changes with time when there is a small leak point in it. The inner pressure P is expressed as a function of time t as

$$P = P_A(1 - e^{St/P_A V}) \tag{1}$$

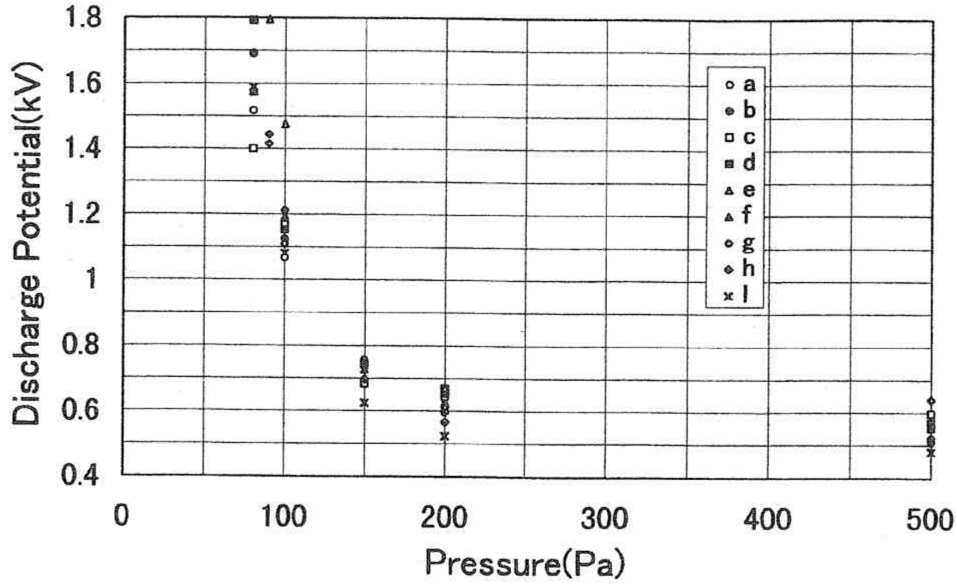
where P_A is atmospheric pressure, S the leak rate and V the volume of the shielding case of the sensor. In the actual case of $P \ll P_A$, the leak rate S can be expressed in a simpler form as

$$S = (P_m - P_0)V/t_m \tag{2}$$

where P_m is the measured pressure at $t = t_m$, and P_0 the initial pressure at $t = 0$, i.e. the pressure of the vacuum chamber in which the sensor was shielded in the factory. Using equation (2) we can easily obtain the leak rate from P_m because the values of P_0, V and t_m are known. Even if P_0 is unknown, we can estimate the leak rate S by two measurements of P_m at $t = t_1$ and $t = t_2$.



(a)



(b)

Figure 5. Discharge characteristics for nine sample sensors: (a) for the whole measured pressure range (80 Pa–20 000 Pa); (b) for the practical range of 80 Pa–500 Pa.

The standard criterion for an allowable leak rate of the pressure sensor used in a car is 1.0×0^{-5} Pa cm^3 s^{-1}, determined from the life of a car. Figure 6 shows how P_m changes with time when S is the allowable leak rate. The volume of the pressure sensor was 0.5 cm^3, and 6.7 Pa was used for P_0. Figure 6 shows that the internal pressure of the sensor increases by 50 Pa in a month. For example, if the initial pressure of the sensor is 30 Pa, the inner pressure of the sensor becomes about 80 Pa after a month, and the discharge potential will be around 1800 V when referred to the experimental results shown in figure 5(b). If the initial pressure is 100 Pa, it becomes about 150 Pa after a month and the discharge potential will reduce to around 700 V.

Fortunately, as shown in figure 5(b), the curve of the pressure–discharge potential shows a very dramatic change in the pressures range around 100–150 Pa. Therefore it is possible to measure the pressure in the pressure sensor with fairly high accuracy. Furthermore the leak rate can be obtained even when only one measurement is made, provided that the initial pressure of the pressure sensor is always fixed at around 100 Pa during production in the factory.

Usually almost all sensors have practically no leakage, and the probability of producing a sensor with leakage over the allowable leak rate is extremely low. Therefore in order to find serious leakage the supply voltage should be set at a higher value than that derived from the characteristic curve as shown in figure 5. Namely, the supply voltage should be fixed at 800–900 V, instead of 700 V, taking the error of the discharge potential into account when inspecting the discharge. Then, if discharge occurs under such a voltage, the sensor is defective.

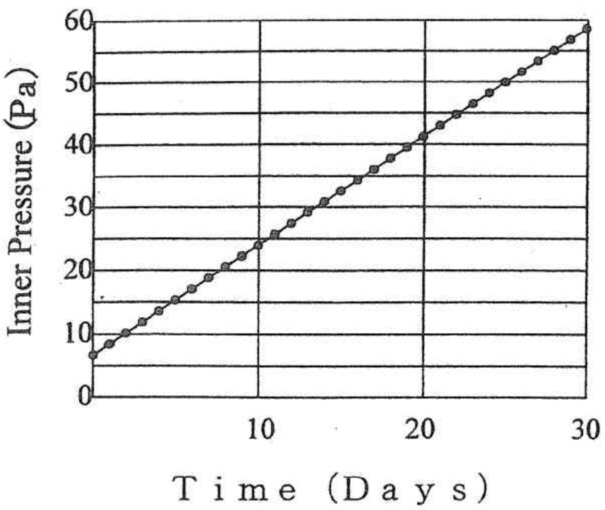


Figure 6. Pressure increase with timer under the conditions of an allowable maximum leak rate $S_m = 1.0 \times 10^{-5}$ Pa cm^3 s^{-1}, an initial pressure $P_0 = 6.7$ Pa (0.05 Torr) and sensor volume $V = 0.5$ cm^3.

5. Conclusion

A new method has been proposed to estimate the degree of vacuum in pressure sensors and its validity has been proved experimentally. The applicable pressure range is limited from 80 to 200 Pa. However, this is enough for practical applications. The method has the following advantages.

(1) It is nondestructive with an accuracy of around 20 Pa in the pressure range between 80–200 Pa.

(2) The leak rate can also be obtained by two measurements taken with a proper time interval between.

(3) It is simple and rapid, taking only about 1 min for the measurement.

(4) Testing can be performed on many sensors simultaneously.

Although further studies are required to improve the reliability of this method by reducing the error in inspection of the discharge, this method could be used in many industrial fields as an alternative to present methods.

Acknowledgment

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