

Solid State Replacements for Electro-Mechanical Potentiometer Type Pressure Transducers

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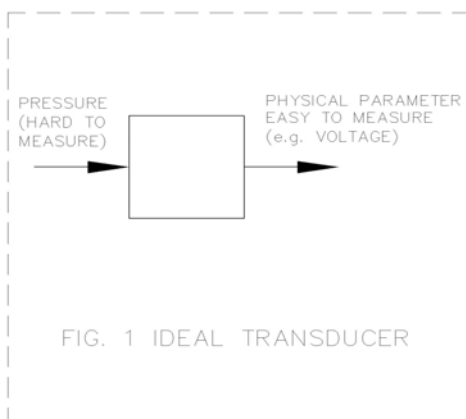
Abstract

This article describes traditional pressure transducers using potentiometers and their modern replacements using solid-state technology. The inherent limitations of the electro-mechanical device are compared with the superior performance and reliability of the solid-state transducers using piezoresistive sensors. Several implementations using potentiometers are described, as well as their form, fit and function replacements.

Introduction

Pressure is one of the most widely measured physical parameters. Pressure transducers are extensively used in aircraft, industrial and chemical installations, power plants, medical applications, oil exploration, trains, ships, automobiles, trucks and racing cars, house appliances, etc. In fact, a vast majority of the advances in technology would not have been possible without accurate measurement of pressure. The modern jet engine is a typical example of a system that will simply not work without pressure transducers. Equally important, the reliable and accurate measurement of pressure rendered a significant increase in the reliability of all of the above applications.

Historically, the design engineer wanted something like in the fig. 1. At times however, this was an ideal impossible to achieve; therefore the engineers settled for more practical solutions.



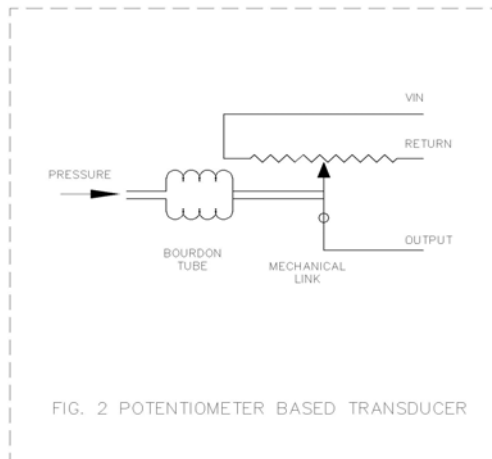
In the past such practical implementations of pressure transducers used potentiometers, LVDTs (Linear Voltage Differential Transformer), synchros, variable reluctance systems, etc. All these used a Bourdon tube moving a mechanical part of a system, which resulted in a change of the electrical output. Some of these early transducers employed mechanical designs comparable in complexity and ingenuity with the most expensive Swiss watches. Unfortunately, none of these types of transducers escaped the inherent

disadvantages of mechanical systems with moving parts.

Modern transducers employ a different approach. The pressure-sensing element is a solid-state component, to which an electronic circuit is added which produces a normalized, compensated output. Most widely used types of sensing element are either a piezoresistive bridge, a capacitive sensor, or a piezoelectric sensor. In the following, we will describe how a piezoresistive bridge with an adequate electronic interface can replace electro-mechanical transducers. Solid-state devices have distinct, significant advantages over their electro-mechanical counterparts, which will be discussed below.

1. Potentiometer based transducers.

Such transducers, shown in fig. 2, use a Bourdon tube mechanically attached to the wiper of a potentiometer. The pressure applied to the Bourdon tube causes it to deflect, which



in turn moves the wiper of the potentiometer. By applying a constant voltage to the end terminals of the potentiometer, the wiper voltage will change as a result of the applied pressure.

Although simple, simple to use, and inexpensive, these transducers have significant shortcomings which makes them ideal candidates to be replaced by solid state devices. Most of the problems arise from the mechanical contact between the

wiper and the resistive layer and the mechanical linking between the Bourdon tube and the wiper. In order for the contact to withstand even moderate levels of vibration, a spring pushes the wiper against resistive layer. The force of the spring is determined by two very contradictory requirements:

- a. This force has to be as strong as possible to maintain the contact under vibration or high acceleration
- b. This force has to be as small as possible in order not to wear the resistive layer or interfere with the action of the Bourdon tube.

Clearly any compromise will result in a device not able to withstand harsh environments or with a poor reliability.

Another common failure of such devices is due to the very frequent situation when a relatively constant pressure, but with small fluctuations, is applied to the transducer. Under these conditions, the wiper will constantly rub against one spot on the resistive layer, resulting in the rapid wear of this layer and ultimately failure of the transducer.

Other disadvantage of these devices is that they “stick”, i.e. there is no change in the output for small changes in the pressure. This effect is due to the friction between the wiper and the resistive layer, which is overcome only when enough force is exercised by the Bourdon tube. Also, the bandwidth of potentiometer transducers is very low, making them inappropriate for dynamic measurements.

To summarize, these devices have the following disadvantages:

- Very poor reliability
- Poor accuracy
- Unable to handle high vibration, shock, or acceleration
- Large hysteresis, i.e. they “stick”
- Slow response, unsuitable for fast dynamic measurements

Solid-state piezoresistive type replacements of potentiometer type transducers have none of the above disadvantages, while being very cost competitive. Furthermore, even when the cost differential is large, this difference is recouped very fast as a result of the high cost of replacement of the potentiometer-based devices. The advantages of piezoresistive transducers are:

- Significantly better reliability and longer MTBF
- Much better stability
- Much higher operating temperature capability
- Vibration, shock, and acceleration insensitive
- Practically no hysteresis – less than 0.1% of full scale
- Fast response, wider bandwidth – by three orders of magnitude typical.
- Cost competitive, even cheaper than potentiometers, depending on the application

Solid state replacement of potentiometer based transducers

The key component in the solid-state transducer is the sensing element, shown in fig. 3a. The sensing element is made by micromachining a monolithic piece of silicon, on which four piezoresistors are deposited. The resistors form a piezoresistive bridge, which when supplied with a constant voltage, produces an output voltage proportional with the applied pressure. The micromachining of the silicon substrate into the shape shown in the fig. 3a is done in order to maximize the strain of the sensor in the areas of the four resistors, thereby maximizing the piezoelectric effect.

The sensors manufactured by Kulite employ a proprietary process, which results in the bridge being deposited on a thin silicon dioxide (SiO₂) layer, which electrically isolates the bridge from the semiconductor substrate, and the resistors from each other.(US Patent #5,286,671) This isolation is essential in making sensors stable in time and over a very wide temperature range.

Due to the monocrystalline structure of the silicon substrate, which is an ideal elastic material, the sensor does not exhibit wear, fatigue, or hysteresis, which are unavoidable in mechanical structures.

Fig. 3b shows the classical mounting of a piezoresistive sensor, where the bridge is connected to pins via gold bonding wires. The entire structure is closed by a very thin (1mil) elastic steel diaphragm, and then filled with silicone oil. The pressure is transmitted through the diaphragm to the oil, which, due to its incompressible nature, transmits the same pressure to the sensing element, which produces an output voltage proportional to the pressure. This construction insures that the piezoresistors do not come in contact with the pressure media, making possible the measurement of a wide range of media.

Fig. 3c shows a new way of making pressure sensors (US Patent #5,955,771), where the oil filling, steel diaphragm, and wire bonding are eliminated. In this structure, called leadless, the contact between the Piezoresistive Bridge and pins is made through conductive frit glass. The pressure media comes in contact only with the back of the silicon sensor, which is chemically inert for a wide range of media. This novel structure has numerous advantages over the traditional one, especially in the much wider operating temperature range, limited previously by the freezing or burning of the oil.

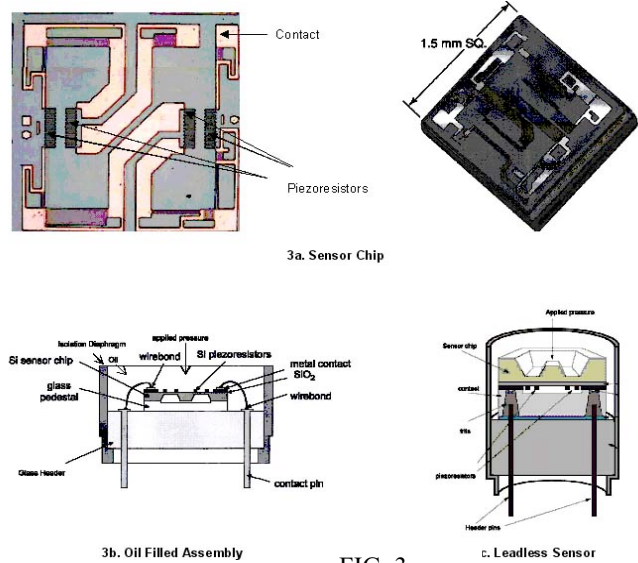


FIG. 3

The basic diagram of a solid-state transducer implementation is shown in fig. 4. The Piezoresistive Bridge is supplied by the input voltage, producing an output proportional with the pressure, and ratio metric versus the input voltage. The bridge output is compensated for thermal errors by the resistors RSPAN1 and RSPAN2, and amplified by the instrumentation amplifier U1, producing an output identical to that of a potentiometer based transducer.

The electronic circuit is mounted in a TO-8 hermetic metal case. A capacitor array is mounted directly underneath the TO-8 case, such that each pin has a capacitor connected to the case, providing a very efficient EMI/RFI filter. The output of the transducer is normalized using fixed resistors for gain and balance to compensate for the differences between individual sensors. Additional components (transzorbs, resistors, diode) protect the circuit against lightning and power

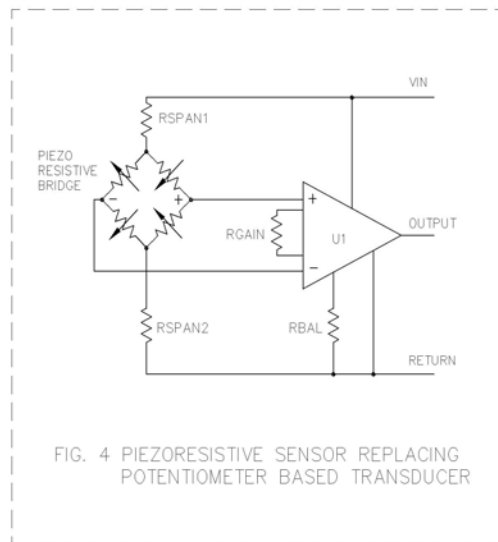


FIG. 4 PIEZORESISTIVE SENSOR REPLACING POTENTIOMETER BASED TRANSDUCER

transients. A second capacitor array of lower capacitance value protects the entire transducer against EMI/RFI. The entire transducer is enclosed in an all steel electron beam welded case, insuring an excellent resistance to the most severe environmental conditions.

The typical specifications as well as performance data are shown in the tables and graph below.

Typical Specifications.

Pressure Range	800psia
Proof pressure	2000psia
Burst pressure	4000psia
Input voltage	5V
Nominal output voltage	0 to 5V, or 0.5V to 4.5V
Total error band	1% of full scale
Temperature range	-55°C to +125°C
Non-linearity	Max. 0.1% of full scale
Hysteresis	Max. 0.1% of full scale

These transducers are available in many pressure ranges, from 2psi to 20,000psi, for many measurement modes: gage, absolute, differential, in a wide range of mechanical configurations: ports, mounting, connectors, and different supply and output voltages.

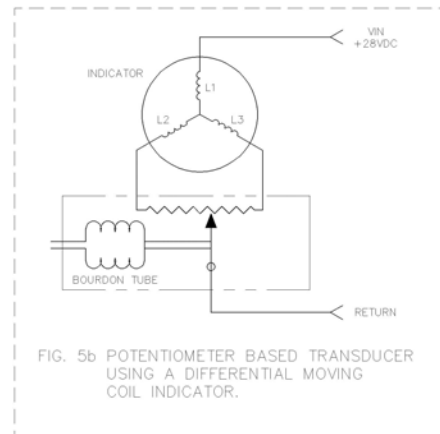
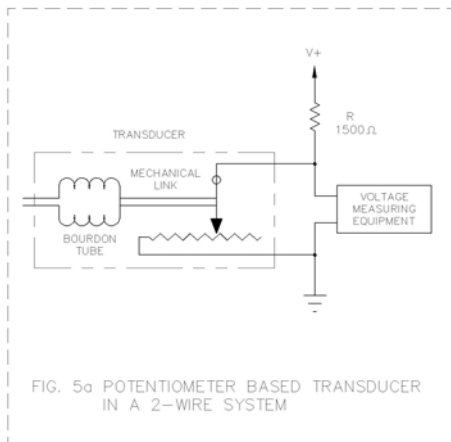
Performance data. Supply voltage = 5.000V, nominal output = 0.5V to 4.5V

Temperature	-55°C	+20°C	+125°C
Zero pressure output	0.511V	0.518V	0.529V
Full scale output	4.508V	4.517V	4.515
Total error band	0.75% of FS		
Linearity	0.08% of FS		
Hysteresis	0.08% of FS		

This transducer does not have any of the shortcomings of the electro-mechanical device. In addition, depending of the application and customer’s requirements, the electronic circuit can provide additional functions difficult or impossible to implement with potentiometer-based transducers, like:

- Regulated supply voltage
- Low pass filter
- Low output impedance

In addition to the standard potentiometer type transducers, our company successfully replaced other configurations, using our piezoresistive sensors and different electronic interfaces. Such configurations, requiring more complex electronics, are 2-wire potentiometers (see fig. 5a), or the ground connected wiper driving a differential moving coil indicator as shown in fig. 5b. In all cases, the solid-state transducer is a Fit, Form and Function replacement of the original device.



The piezoresistive sensor in conjunction with the electronic circuit makes possible the implementation of combined devices, like a transducer and a switch. One such device, which replaced a potentiometer type transducer, was significantly cheaper than the original transducer. In fact, the original transducer required expensive refurbishments every few months, due to the wear of the potentiometer. The solid-state replacement was significantly cheaper than the cost of one refurbishment, while the MTBF was better by many orders of magnitude.

Kulite has successfully replaced potentiometer-based transducers on numerous aircraft, missile, helicopter, shipboard, and industrial applications, with significant benefits for the customers in all these programs. One among many notable examples is the case of a transducer on a military helicopter. The original device, with an operational life of a few hundred hours, was replaced with one with more than 100,000 hours effective MTBF.

Another example is a series of transducers used on a rocket engine, subject to vibration levels of 140g. The devices covered a wide range of pressures, from a few psi to 10,000psi. Besides the benefit of much better withstanding the vibration levels, the much higher bandwidth of the solid-state devices revealed unknown before transient effects in the engine, enabling the engineers to improve its performance.

Kulite manufactures a wide range of pressure transducers, with numerous types of outputs: voltage, current, LVDT, frequency, etc.