Fundamentals of Pressure Transducers

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Pressure is a key factor in almost every fluid-power circuit. Pressure transducers can interface that factor with the control system.

Pressure transducers, when connected to an appropriate electrical source and exposed to a pressure source, will produce an electrical output signal (voltage, current, or frequency) proportional to the pressure. Most transducers are designed to produce output that is linear with the applied pressure and independent of other system variables — the most important of these being temperature. Most outputs are mV, V, mA, and, sometimes, as a frequency.

Pressure transducers have a sensing element of constant area and respond to force applied to this area by the fluid pressure. This force deflects a diaphragm, bellows, or Bourdon tube. In turn, these deflections, strains, or tensions are converted to electrical outputs through any of a variety of different transduction methods. Figure 1 illustrates three of these.

Electrical input/output

To operate, most pressure transducers require an electrical input (usually called excitation). Many operate from a 5- to 10-Vdc input and produce full-scale outputs from, say, 0 to 20 mV and 0 to 100 mV. Transducers that produce high level voltage outputs operate from voltage sources. Typical outputs are 0 to 5, 1 to 5, 1 to 6, and 1 to 11 Vdc. Digital control circuits can be interfaced by routing transducer output through an analog-to-digital (A/D) converter or by using a transducer with a frequency output. This allows pressure to be monitored by microprocessors, programmable controllers, computers, and similar electronic instruments.

Pressure transducers that generate a current output usually are called transmitters. By definition, they are variable-current devices and produce 4- to 20-mA outputs with supplies of widely varying voltage.

Outputs are chosen with the following factors in mind:

- the type of device that will receive the transducer's output signal (programmable controller, panel meter, signal conditioner, etc.)
- the distance between the transducer and its receiving device
- presence of electromagnetic interference (EMI) in the environment, which can come from sources such as power lines, welding equipment, solenoid valves, motors, 2-way radios, etc., and
- cost as it relates to the entire installed system (not just the transducer).

Measurement error
Pressure transducers are mechanical structures made from more than one material. Because of this, they respond not only to changes in pressure, but to changes in temperatures as well. These changes can affect both the zero and full scale output (FSO) of the transducer, regardless of its type. The term temperature effect upon zero refers to the change in output at constant pressure as temperature is varied over a stated range. Extreme temperature fluctuations may change a transducer's output signal even though pressure remains constant.

Many other characteristics — such as linearity, hysteresis, repeatability, etc. — help to determine the measurement accuracy of a pressure transducer, Figure 2. Additional factors, equally important, are more elusive; these include packaging, configuration, construction materials, and internal design. Each of these can be appraised on the basis of field testing and/or experience.

Overall, the best pressure transducer for one application is not necessarily the best for another. In fact, a transducer with the second best performance may be the best choice for an application if its price is significantly lower.

**Pressure transducer terminology**

The following definitions are used to put a quantitative value on transducer performance.

**Range** refers to minimum through maximum pressures that can be accurately measured by a transducer. Usually transducers are selected so that system operating pressure is 50 to 60% of the transducer’s maximum rated pressure. For example, a hydraulic system, normally operating in the 2500- to 3000-psi region, would usually use a 5000 psi transducer. In addition to providing a safety margin, this practice also makes a good compromise among performance characteristics.

**Over-range capability** is the maximum magnitude or pressure that can be applied to a transducer without causing a change in performance beyond specified tolerance.

**Burst pressure** refers to fluid pressure at which mechanical failure and/or fluid leakage from the transducer is expected. Do not confuse burst pressure with over-range capability. Exceeding over-range capability can affect a transducer’s ability to function; exceeding burst pressure can destroy it.

**FSO (full-scale output)** refers to the variation in the output signal as the transducer performs over its calibrated range from minimum to maximum pressure at a specified temperature. A tolerance and a temperature are generally given. Output, with maximum pressure applied and rated excitation, is FSO. Example: 5 Vdc ± 0.05 Vdc at 77° F
**Zero unbalance** is the residual output of an excited transducer that has no pressure applied. For a sealed gage transducer, tolerance must account for temperature and atmospheric pressure. Examples are 0.0 V ± 5mV at 77° F and ± 0.4 mA at 77° F.

If zero unbalance is large in respect to FSO, the user may have to zero a transducer through an external zero-adjust circuit. This ensures that the transducer will produce no output signal when no pressure is present. Depending on accuracy requirements, the user also may have to calibrate the transducer's output circuit to correct for deviations from nominal value at FS.

Most manufacturers specify **accuracy** as plus or minus a percentage of FSO, including the mathematically combined effects of linearity, hysteresis, and repeatability errors. Note that this accuracy does **not** include the effects of environment - especially temperature - and system dynamics. Operation at a constant temperature is implicit in this concept of accuracy.

**Resolution** refers to the smallest change in pressure that can be detected in the transducer's output. It is usually expressed as a percentage of FSO. For example, if two transducers each have a resolution of 0.1% of FSO, a 100 psi (6.8 bar) transducer could detect a pressure increase or decrease of 0.1 psi (0.007 bar). A 5000 psi (340 bar) transducer could detect a pressure change of 5 psi (0.34 bar).

Resolution generally is not constant throughout a transducer's range. Manufacturers may publish values for maximum resolution or average resolution. Users should be aware of the difference between them when comparing one transducer's performance with another.

Maximum resolution describes the best resolution that can be expected. Average resolution represents a value between the best and worst values throughout a transducer's range. Even though a pressure transducer may have infinite resolution, electrical noise — contained in power supplies and introduced by other sources — can limit resolution. Also, instrumentation, such as analog-to-digital (A/D) converters, can limit resolution.

**Pressure spikes**

Pressure spikes are microsecond to millisecond bursts of pressure that can reach 15 times the normal system operating pressure. For example, if a valve shifts abruptly to block flow, a shock wave can be generated within the system. Likewise, if a hydraulic system is moving a load and the load suddenly stops, the system may react with a brief surge of pressure.

System control electronics — such as PLCs with millisecond scan times — are not fast enough to detect spikes of such short duration. Often, the first indication that a system is generating pressure spikes is a positive shift in a pressure transducer's zero output. System control electronics commonly indicate the shift in transducer output as a pressure out-of-range condition, which could cause the system controller to shut down.

Pressure transducers are the components most vulnerable to damage from pressure spikes. Transducers, with much quicker response than mechanical gauges, react to spikes and can show signs of having been overpressurized. This is not because the transducer is less durable than the mechanical gauge it replaced. Actually, a transducer designed for severe service should have been specified. Spikes also damage the machines that generate them. The erratic flow of liquid, common in systems that generate spikes, reduces efficiency and accelerates wear on valve ports and seals.

(Note that pressure spikes do not pose serious problems in pneumatic systems because the air is
compressible, which tends to dampen shock. Cyclic pressure surges, caused by pulsation from compressors, pose a greater potential problem because the pressure surges — while not as sharp — occur repeatedly and frequently.

Pressure spikes usually can be detected with an oscilloscope through a transducer of, say, five times the normal operating pressure range. Once it is determined that spikes exist in a system, any of several practices can be used to prevent them from damaging the transducer. A transducer with a higher pressure rating can be used. However, doing so sacrifices accuracy in the normal operating range because a transducer with a wider operating range has poorer resolution.

As an alternative, a snubber can be used to dampen the spike. A snubber is an orifice installed in piping between the transducer and the source of the spike. A potential disadvantage of this practice is that it slows the response of the measurement. If neither measurement resolution nor response can be compromised, a transducer that can tolerate spikes should be specified. Obviously, these transducers cost more.

**Big impact from temperature**

Temperature is a major consideration in the performance of pressure transducers. As temperatures change, different materials expand or contract at different rates, which creates residual stresses within the structure. These stresses can change the output of the transducer by changing its geometry, mechanical properties, and electrical characteristics. While manufacturers take great care in selecting materials and determining how they are put together, these changes are inevitable. Transducer manufacturers compensate for these changes in a variety of ways - generally, by electrically adjusting the transducer's output circuit.

Transducers are specified to have a **compensated temperature range**. Within this temperature range, the transducer will perform within published specifications. Transducers also have an **operating temperature range**. Transducers will continue to perform within this range, but an operating error likely would exceed published specifications. For example, a transducer's typical compensated range might be 30° to 130° F (1° to 54° C), while its typical operating range could as great as 60° to 200° F (51° to 93° C).

The degree of compensation is expressed by two specifications:

**Thermal effect on zero** gives the boundaries within which the zero value of the transducer is compensated to stay. This is usually published as ±x% of FSO within the compensated range. Some transducer manufacturers may publish the same value as ±x% of FSO/°F within the compensated range; this makes the numbers look smaller. Graphically, the thermal effect on zero can be expressed as shown in Figure 3.

**Thermal effect on span** gives the boundaries within which the full scale output of the transducer is compensated, to stay. This is usually expressed as ±x% of reading within the compensated range. Here, too, some manufacturers may publish the same value as ±x% of reading/°F within the compensated range. Graphically the thermal effect on span can be expressed as shown in Figure 3.

Thermal errors are separate from other errors affecting total transducer accuracy (linearity, repeatability, and hysteresis). These errors must be accounted for and specified separately. Accuracy over the compensated temperature range must include the thermal effects on zero and FSO.

It is important to realize that the performance specifications of transducer manufacturers refer to ambient temperature - that is, the temperature of the air surrounding the external case of the transducer. Users also
must be aware of media (fluid) temperature, because it can have a significant effect on the actual operating temperature of the transducer and, therefore, its performance.

**Physical considerations**

Materials of construction are usually selected by the transducer manufacturer, but they also are clearly important to the user. Material in contact with media (or wetted materials) includes all materials exposed to the pressurized fluid. These may include any of a variety of stainless steel, bronzes, epoxies, plastics, elastomers, glasses, and silicon. Users must satisfy themselves that the pressure medium will not adversely affect any of these materials. If this does occur, the calibration of the transducer will certainly change. Ultimately, its sealing integrity will fail as well.

Environmental specifications tend to be difficult to relate to actual working environments. OEMs often test their components through actual usage in the working environment to carefully and accurately determine operating parameters - shock and vibration levels, temperature excursions, moisture levels, etc. These approaches require time and money, but they are recommended. If lack of time or money prevents exhaustive testing, follow these steps:

1. Look at manufacturers’ published environmental specifications.
2. Ask around. Chances are that associates may have had experience with similar applications and components.
3. Talk to transducer suppliers who have extensive experience in similar fluid power applications. No test is better than actual product usage in a real-world working environment.

**Electromagnetic interference**

Electromagnetic Interference (EMI) can affect transducer performance. High field strengths tend to affect transducer outputs. In some cases, these fields can completely saturate internal amplifiers to the point where erroneous outputs are produced regardless of the pressure input.

There are shielding and grounding techniques that are remedies for the effects of EMI. Also, wires should be carefully routed from the transducer to its receiving device so as to avoid EMI areas. Solutions are specific to each problem presented.

Only a few transducer manufacturers specify EMI protection. This is stated as: percentage of full scale error divided by a frequency range up to a maximum field strength. Example: Full scale output error typically is less than 1% over the frequency range of 20 kHz to 2 GHz at field strengths up to 100V/m. While these specifications are difficult to relate to the real world, the fact that manufacturers supply EMI data in their specifications indicates they have had some experience dealing with this interference.

**Other specifications**

There are many design features that may not appear in published specifications that can be important over the life of the application.

- is the transducer sensitive to mounting orientation (attitude)? Will pressure readings be consistent if the attitude changes when the equipment moves?
are special wrenches or tools needed to install the transducer?
will external design and materials of construction stand up to physical abuse? In mobile equipment, a protruding transducer can make a convenient step for maintenance personnel climbing on equipment. Moreover, falling debris is another potential source of physical damage. When possible, transducers should be accessible, but in areas not subjected to potentially damaging conditions, and

can electrical connections be made in a reliable and fool-proof fashion? Can leads come to the transducer from any direction? Is reverse polarity protection provided?

Summary

It should now be evident that no one transducer is better than all others. An ideal transducer for one application could be unsatisfactory for another. With the wide variety of transducer products to choose from, knowing what features to look for and how to interpret specifications for a particular application will help you choose transducers with confidence.

The checklist above is designed to help users organize application information that has an effect on transducers. However, even when the checklist is completed, it still may be difficult to select a specific transducer for a specific application. For example, one transducer may cost five or ten times more than another, but offer comparable performance characteristics. This cost difference can usually be attributed to additional capabilities built into the more expensive transducer. Immunity to electrical noise or the ability to sustain pressure spikes are two characteristics that add cost to a transducer without improving basic performance parameters. However, specifying a transducer without these characteristics, in an application clearly needing them, ultimately will result in an unsuccessful application.

Furthermore, the more expensive transducer may actually cost less when considering economics of an entire system. This is because the less expensive transducer may require additional components that make it function in an otherwise unacceptable environment.

In general, capabilities that add cost to a transducer, so it can perform under less than ideal conditions, can be divided into four categories:

- special performance capabilities that make a standard transducer compatible with a special application
- the environment, both the fluid and of that surrounding the exterior of the transducer
- electrical requirements, both of the input and output signals, and
- physical and mechanical requirements, regarding size strength, etc.

In general, as the number of these capabilities increases, so does cost of the transducer. Some characteristics substantially add to a transducer’s cost while others do not. This means it is important to evaluate each application to decide what characteristics are absolutely essential to an application and which are desirable, yet cost effective.

Types of pressure measurement

Selecting a pressure transducer goes beyond choosing one with acceptable performance. It must be configured to measure any of four common forms of pressure.

Gauge pressure (psig) (bar₉) quantifies fluid pressure relative to ambient air pressure. In the case of a diaphragm-type transducer, Figure (a), the fluid side of the diaphragm sees the measured pressure; the
other side sees ambient air pressure. Because a transducer measuring gage pressure is vented to the atmosphere, it could be exposed to atmospheric contamination and condensation unless precautions are taken.

**Absolute pressure (psia) (bar\textsubscript{a})** measures pressure relative to a vacuum. In the case of a diaphragm-type transducer, Figure (b), one side of the diaphragm sees fluid pressure, the other sees a full vacuum.

**Sealed reference pressure (psis) (bar\textsubscript{s})** is measured relative to a reference pressure whose magnitude is at, or close to, standard atmospheric pressure. In the case of a diaphragm-type transducer, Figure (c), one side of the diaphragm is exposed to the fluid pressure while the other side is exposed to a chamber sealed from the atmosphere and containing pressurized gas at standard atmospheric pressure. The pressure transducers recommended for hydraulic service are sealed gage to ensure that the units sensitive internal components remain moisture and dirt free.

**Differential pressure (psid) (bar\textsubscript{d})** quantifies the pressure difference between two points within a system. The measurement also must consider the magnitude of the system’s line pressure. Measurements usually are taken from two different fluid inputs within the system using a transducer designed specifically for differential-pressure calculations, Figure (d), or by installing a separate transducer at each of the two fluid inputs. (Output from each transducer is routed to a common signal processor that produces a signal proportional to line pressure as well as the difference between the two pressures.)

Line pressure is important not only for monitoring system operation, but also for making differential pressure measurements more meaningful. For example, an 8 psi (0.544 bar) pressure drop across a filter may be acceptable for a system operating at 120 psi (8.16 bar), but unacceptable for one operating at 80 psi (5.44 bar).

Standard atmospheric air pressure (zero gage pressure) is 14.7 psia (1 bar). Actual atmospheric pressure normally ranges from 14.2 to 15.2 psia (0.966-1.03 bar). Recognizing the small variations from nominal, the user realizes that in the range of hydraulic pressures, the possible difference between a vented gage and sealed gage transducers output would be extremely small. In the order of less than 0.5 psig (0.034 bar) in 2000 psig (136 bar), there is an error of only 0.025%. Because most pneumatic systems operate at pressures much lower than hydraulic, the difference between vented gage and sealed gage measurements
may be more significant.

**Application checklist**

<table>
<thead>
<tr>
<th>Performance</th>
<th>Electrical</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure range: ____ psig/psia/psis/psid</td>
<td>Input (excitation): AC ___ DC ___ Oth ___</td>
<td>Handling during installation and use:</td>
</tr>
<tr>
<td>Maximum pressure: ______________ psi</td>
<td>Output require: ___ mV ___ V ___ 4-20mA</td>
<td>careful ______ avg ______ rough ______</td>
</tr>
<tr>
<td>Pressure spikes: ______________ psi</td>
<td>Zero adjust: yes □ no □</td>
<td>Replacement without recalibration y □ n □</td>
</tr>
<tr>
<td>Frequency: Intermittent ______</td>
<td>Full scale adjust: yes □ no □</td>
<td>Maximum size:</td>
</tr>
<tr>
<td>Regular ______ Duration ______ msec</td>
<td></td>
<td>Weight: ______ x ______ x ______ in.</td>
</tr>
<tr>
<td>Desired accuracy: ______ ± % FSO</td>
<td></td>
<td>Port mounted ______ oz.</td>
</tr>
<tr>
<td>Resolution: ______ psi or % FSO</td>
<td></td>
<td>Pressure port: yes □ no □</td>
</tr>
<tr>
<td>Dynamic response: ______ Hz or msec</td>
<td></td>
<td>Termination: ____________________</td>
</tr>
</tbody>
</table>

**Environment**

<table>
<thead>
<tr>
<th>Type of application:</th>
<th>type of fluid: ______</th>
<th>Terminal: ______ type ______</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ industrial □ mobile</td>
<td>Lo ___ med ___ hi ___</td>
<td>terminals ______ type ______</td>
</tr>
<tr>
<td>□ laboratory □ other</td>
<td>Lo ___ med ___ hi ___</td>
<td>connector ______ type ______</td>
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<tr>
<td>Pressure Media:</td>
<td>EMI:</td>
<td></td>
</tr>
<tr>
<td>Vibration:</td>
<td>Humidity:</td>
<td></td>
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<tr>
<td>Shock:</td>
<td>Operating temp</td>
<td>cable ______ length ________ in.</td>
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<tr>
<td>EMI:</td>
<td>of fluid: min ______ max ______</td>
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<tr>
<td>Humidity:</td>
<td>Extreme temp</td>
<td>terminals ______ type ______</td>
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<tr>
<td>Operating temp</td>
<td>of fluid: min ______ max ______</td>
<td>connector ______ type ______</td>
</tr>
<tr>
<td>of fluid:</td>
<td>of surroundings: min ______ max ______</td>
<td></td>
</tr>
</tbody>
</table>

*Checklist provided by National Fluid Power Association*