Designing With Metal Bellows

Metal bellows have long been a key component in demanding sensing and sealing applications. In fact, they've become so familiar that many engineers now think of bellows as generic items: Just specify a few key dimensions, pick a metal alloy and you're good to go.

The reality, however, is that not all bellows technologies are created equal. Different manufacturing methods and material grades can have profound effects on how metal bellows will perform in terms of their stroke, pressure capabilities, spring rate and temperature response.

Manufacturing methods and materials will also determine how long your bellows will last in the field. The wrong bellows may work for a short time but not achieve your expected lifecycle.

To be successful with metal bellows, start with an understanding of the basic design and sizing inputs. Bellows have some specification requirements that you probably didn't cover in engineering school.

Next, pay close attention to the distinction between different welded and seamless constructions. Each type strikes a different balance between cost and performance, and each has its own application sweet spots.

Finally, consider the type of materials. Sometimes the choice of bellows materials will be obvious. But more often you'll be confronted with choices between different metal alloys, any one of which could meet your requirements.

Here's a closer look at what you need to know to pick the right type of bellows for your application:

DESIGN CONSIDERATIONS

Think of bellows as a combination of a piston and a spring. Like a piston, bellows can convert changes in their internal or external pressure into an applied force. Like a spring, bellows deflect elastically in response to an applied force and exert a reactive force. And like a spring, bellows exhibit hysteresis and linearity effects that you'll need to account for in your designs (see Force vs Deflection chart).

Having the characteristics of both a piston and spring makes bellows a very versatile component. Bellows are used in dozens of different sensing, fluid handling and actuation applications. In general, these applications fall into four broad categories—sealing, temperature, evacuation and pressure. We use the acronym *STEP* for these categories (see sidebar, *How Do I Use Metal Bellows?*).

The versatility of bellows, however, also creates some design challenges. Bellows behave differently, depending on how you load them. A given bellows, for example, can have one set of lifecycle, pressure and stroke characteristics when compressed under an axial load and an entirely different set when expanded with an internal pressure.

When choosing a bellows for your application, there are some fundamental application details you'll want to start with. Most obvious are the dimensional specifications. You'll need a bellows with an outside diameter and free-height length that will fit your package constraints.

Things will start to get more complicated when you need to reconcile those packaging constraints with the bellows' functional requirements. Both diameter and length have a bearing on two important performance attributes—*spring rate* and *mean effective area*.

- **Spring Rate** (SR) refers to the resistance force a bellows exerts in response to an axial load. Its defined as:

  SR = Axial Load/Deflection

  The wall thickness, material, OD and ID of the convolutions, and number of convolutions determine the SR.

- **Mean Effective Area** (MEA) relates changes in pressure to changes in force. You can determine MEA empirically by measuring a bellows' initial and final force and pressure values. Or you can calculate the MEA using this formula based on the bellows outside and inside diameters:

  $$MEA = \pi/12(OD^2+OD\times ID+ID^2)$$

Along with your pressure and stroke requirements, both SR and MEA form the basis of lifecycle and force calculations that will determine whether a given bellows will meet your functional requirements. You'll also want to take your operating environment's thermal, chemical and vibration conditions into account as they can influence performance and lifecycle.

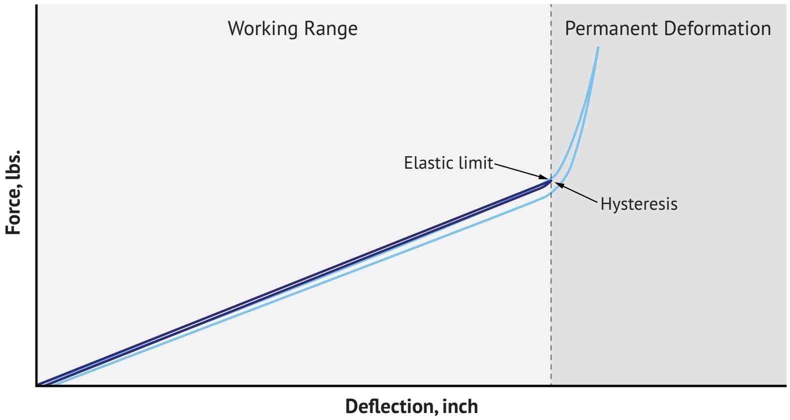
A typical bellows data sheet will, at first glance, present all the information you need to pick the right bellows. You'll find values for length, wall thickness, convolutions, SR and MEA as well as maximum stroke and pressure. But given the complex relationships between bellows loading, environmental conditions and performance, take the data sheet values with a grain of salt. It's not so much that the data sheet values are inaccurate as that the values are based on load cases that may not jibe with real-world conditions. So it's a good idea to review the finer design details of your application with an experienced bellows supplier early in your design process.

MANUFACTURING METHODS

With metal bellows, you can't begin to talk about performance without considering the manufacturing method. All of the key performance parameters we just reviewed depend heavily on the way the bellows is formed or welded. The most common manufacturing methods include:

Seamless hydroformed bellows. As their name suggests, seamless metal bellows have no welded joints. Instead, they are produced in a multi-step deep drawing process. A secondary hydroforming step forms the convolutions. The deep drawing and hydroforming processes can hold extremely consistent dimensional tolerances. For example, wall thickness variation from a well-controlled deep drawing process is typically within +/- 0.0001 inches.

Force vs. Deflection



Metal bellows have negligible hysteresis as long as you keep deflection beneath the elastic limit as shown by the dark blue line. Above the elastic limit, there's permanent deformation and more significant hysteresis as indicated by light blue line.

This dimensional consistency translates directly to a tight spring rate tolerance, and a precise response to applied forces and pressure. (See sidebar, Seamless Bellows Offer Consistent Performance). And because they're drawn and formed, seamless bellows avoid the potential leak paths and internal stresses of welded joints. Seamless production methods also allow the bellows to be closed at one end, allowing the integration of connection points or other design features.

Seamless bellows do have some package size limitations. Their sweet spot for OD lies between 0.25 to 3 inches. Seamless bellows also have a higher initial tooling cost than seam-welded bellows. At production volumes, however, the tooling costs of bellows all but disappear.

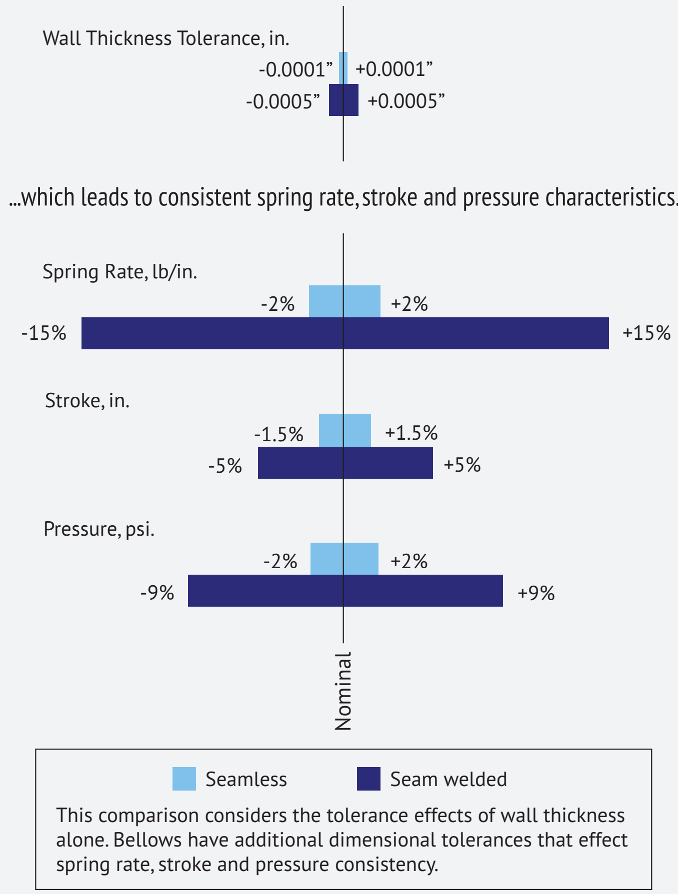
In high-volume applications requiring a small package size and a precise spring rate, seamless bellows are by far the most popular choice. These applications include many kinds of appliance, HVAC and industrial controls and sensors.

Seam-welded formed bellows. Made from rolled, welded and formed sheet metal stock, seam-welding excels at producing large diameter bellows cost effectively. Diameters up to eight inches are not uncommon and would be cost prohibitive with seamless deep draw production methods. Seam-welded bellows can also be fabricated to any required length. And they have low initial tooling costs.

So seam-welded bellows have a lot going for them in applications that need a large, cost-effective bellows. These applications include expansion joints or other connections that compensate for the movement of mating components.

Seamless Bellows Offer Consistent Performance

Compared to seam welded bellows, seamless hydroformed bellows have five times better wall thickness tolerance...



Seam-welding bellows, however, do not lend themselves to applications that require a very precise spring rate. The reason is that their wall thickness tolerances are determined by the sheet metal stock, not the precision deep drawing process. Typical wall thickness variation for seam-welded models is ± 0.0005 inches, or about five times greater than a seamless bellows.

With wall thickness tolerances influencing spring rate and mean effective area, seam-welded bellows inherently have a less precise response to pressure and applied forces, which rules out many sensing and control applications.

Seam-welded bellows have other limitations as well. For one, the welding process limits your material choices, ruling out brass and bronze. For another, seam welded bellows have to be open at both ends, which limits their design flexibility. They're typically used in applications that require less than 10,000 full stroke cycles.

Edge-welded bellows. Production of edge-welded bellows requires a combination of stamping and welding processes. The stamping process first turn out a set of ring-shaped diaphragms. The diaphragms are then joined with welds along their inside and outside diameter.

All that welding makes edge-welding one of the more expensive production methods, but the costs can be worth it because edge-welded bellows will tend to have the smallest package size for a given set of lifecycle and stroke requirements. They also offer the ability to dial in a specific mean effective area value because the stamping process offers tight control of ID and OD.

Edge-welded bellows are typically used in applications where package size is at a premium and cost is less of a factor. These applications include aircraft engines, semiconductor equipment and medical devices. Edge-welding does not lend itself to high-volume production.

Electro-formed bellows. Formed by the electro-deposition of nickel onto an aluminum mandrel, these bellows aren't subject to the geometry limitations of formed or welded bellows. They offer very tight control of wall thickness, convolution shape and diameters, which allows you to fine tune the spring rate, mean effective area and stroke. Electro-formed bellows are also compact, with package sizes down 0.125 inches across.

Though not as costly as edge-welding, electro-forming is significantly more expensive than hydroforming. For this reason, electro-formed bellows are used primarily in low-volume, high-performance applications such as aerospace and defense.

BELLOWS MATERIALS

The tensile, chemical and physical properties of the bellows material also play a crucial and obvious role in bellows performance. And one key to the versatility of bellows in so many different applications is that they can be made from a wide variety of metals, including:

- **Brass.** A traditional and popular bellows material with a low manufacturing cost, brass solders easily even with today's lead free solders. Brass is usually used in applications that involve an air medium and can withstand operating temperatures up to 300°F.
- **Bronze.** With a slightly higher tensile strength, better corrosion resistance and better electrical conductivity than brass, bronze also offers a low manufacturing cost. Bronze solders as easily as brass, but can also be brazed for use in high temperature applications. Bronze bellows are often used in high-volume applications such as appliances and HVAC equipment.
- **Beryllium Copper.** Beryllium copper (BeCu) is ideal for seamless metal bellows. It features a high tensile strength and electrical conductivity. Beryllium copper can be soldered or brazed. When age hardened, beryllium copper holds length tolerances better than any of the alternative bellows materials. Beryllium copper bellows are often favored in applications that require a small package size and demanding lifecycle requirements. Among these applications are aerospace systems and instruments.
- **Monel.** Monel is a nickel alloy that offers better corrosion resistance than brass, bronze or beryllium copper. Monel is routinely welded, though it can be brazed too. With similar mechanical performance to bronze, Monel is often used in corrosive environments, such as those containing steam or salt water.
- **Stainless Steels.** Bellows can be manufactured from a variety of stainless steels, with 316L and 321 steels being the most common. Stainless steel has excellent tensile strength, making it easier to maximize stroke and minimize package size. Stainless steels also have excellent corrosion resistance in multiple environments and media. Typically brazed or welded, stainless steel bellows withstand high operating temperatures. Stainless steel bellows applications include electrical interrupters, power transmission systems and industrial controls.
- **Nickel.** Nickel is a hard material with excellent corrosion resistance. Electro-deposited bellows are made from nickel, but the material is also useful as a corrosion resistant plating for other types of bellows. Nickel is widely used in aerospace applications.

For more information on designing with metal bellows, visit sigmanetics.com/metal-bellows/metal-bellows-overview

How Do I Use Metal Bellows?

SEALING

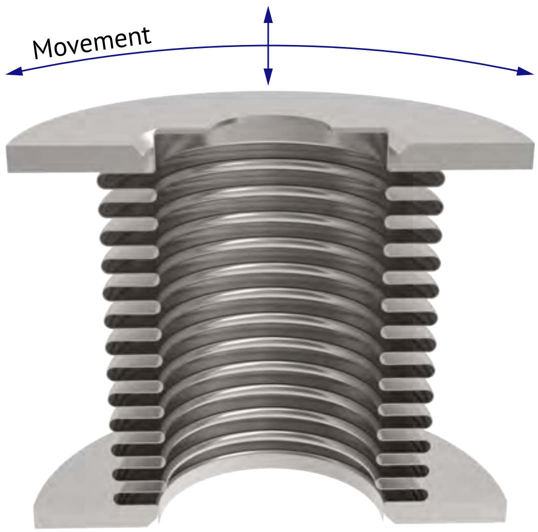
Bellows create a sealed, flexible connector capable of multi-axis movement.

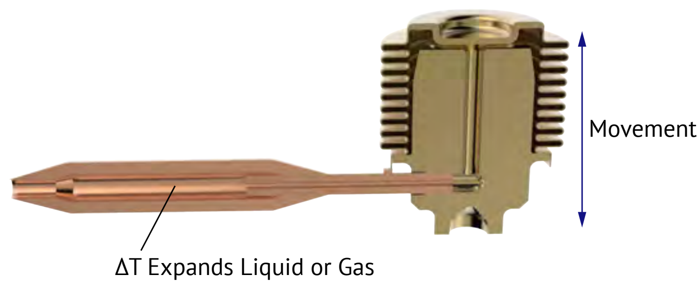
- Electrical Interrupters
- Expansion Joints

TEMPERATURE

Liquid-filled bellows assemblies expand and contract in response to temperature changes.

- Control Valves
- Temperature Switches





EVACUATION

The aneroid will expand or contract due to changes in altitude.

- Fuel to Air Mixture
- Pilot Oxygen Masks

PRESSURE

When pressurized, bellows exhibit a linear response.

- Pressure Switches
- Gauges