The double-opposed piston rack and pinion actuator is often chosen for actuating rotary valves—suitable in both on-off and modulating control applications.

As rack and pinion actuator technology has been developed over the years, it has been proven reliable because of durability and cycle life. Other styles of actuators have features with merit, but they comprise a smaller fraction of the quarter-turn actuator market.

Rack and pinion actuators, despite common misconceptions of issues dealing with mechanical backlash and internal friction, are well suited for modulating control applications as well as commonly accepted applications in on-off service.

Before modern rotary valves were introduced, fluid flow in piping systems was controlled by rising-stem valves. The plug valve was around, but it was not automated. The closest thing to a butterfly valve was a damper, and any mention of a ball valve before World War II pertains to ball-check valves. When rotary valves were introduced, they caused an upheaval in the market.

Ball and elastomer-seated butterfly valves, which were invented in 1949 and 1951 respectively, proliferated because they were easier to manufacture, inexpensive compared to gate and globe valves, and they had high capacities and tight shutoff.

Soon, commercially available pneumatic cylinders on fabricated brackets were introduced, which achieved the remote actuation of rotary valves.

Commonly, a cylinder was used that had a pivot on one end and a clevis on the piston rod, so that the whole actuator floated to track the arc of the crank arm. While this method was a clever adaptation of the components available at that time, it put both shear and bending loads on the valve shaft, so only flexible hoses for the air lines could be used. By modern standards, this was difficult to instrument and awkward to set travel stops. Furthermore, the exposed mechanisms invited contamination and posed injury hazards to personnel.

When major control valve companies entered the market, typical actuation strategy was to use existing off-the-shelf (globe-valve) spring-diaphragm actuators driving a linear-to-rotary linkage. Over the years, other configurations and actuator designs have been developed, and many of them are still available today, including scotch yoke, vane and electric. Each of these has its place in the market, but this article investigates the development, limitations and design characteristics of rack and pinion actuators.

**ORIGINS**

While rack and pinion mechanisms themselves date back to the dawn of gearing history, an important development for actuators was helped along by the Norris brothers, successful investors and fabricators from Southern England. The brothers set out to make a purely rotary valve actuator—without preconceived notions of how the actuator should look or without using a stock of existing components. The pivotal moment came when the Norris brothers realized that they could oppose two pistons in a single cylinder (Figure 1).

With two pistons, torque was doubled for a given-sized cylinder, and most importantly, the linear piston forces cancelled one another so that the output of the actuator was purely torsional with no side-load on either the valve components or the internal actuator bearings. Internal forces exist, including contained or balanced gear separation forces. However, this arrangement made for a more compact and efficient actuator, and canceling the side loads on the shaft allowed seals and bearings to last longer, both in the valve and in the actuator.
spring-return rack and pinion actuator positioned with the valve in the full open condition with pressure applied to P2. Pressure at P2 pushes out the pistons, rotating the pinion counterclockwise and compressing the springs on the outside of the pistons. Most designs can be reversed by flipping the pistons. Some designs are reversible by turning them top-side down, but it is complicated by the fact that one end of the pinion may be configured to drive the valve and the other end may have a NAMUR-compliant drive for accessories. There is a piston-effect on most pinion designs in which one end (usually the bottom) must be large enough for the pinion to be inserted into the case and the other end is customarily smaller (illustrated in Figure 3). Pressure in the actuator, acting against different upper and lower areas, causes an axial load on the piston. In this case, an inverted actuator would have a greater chance of pinion blowout; if the actuator is installed conventionally, the pinion would be secondarily retained by the valve stem.

This cutaway differs from the Norris Brothers’ design, which uses rods for guiding the piston. Almost all rack and pinion actuators produced since the original design use thrust pads to absorb the side load on the skirts. Since the faces of the rack and pinion teeth have slope, a small component of the force exerted by the pistons acts to lift the racks off the pinion. The thrust pad keeps the racks properly meshed with the pinion. These thrust pads are commonly molded of an engineering resin with a large portion of dry lubricant such as 25% MoS2, which helps reduce friction. Another notable difference between the designs is that the actuator pictured in Figure 2 uses con-
MECHANICAL BACKLASH
Some engineers are concerned about the mechanical backlash between the racks and pinion, which they fear could decrease precision when using a rack and pinion actuator for modulating control with a positioner. However, the mechanical lash between the racks and pinion is extremely small. Also, the position of the valve is not inferred from the position of the pistons but from the position of the spindle, because it is mechanically coupled to the positioner, not the pistons.

All components of the valve assembly move together. A ball control valve has a close and lash-free connection between the ball and the shaft. Frequently, these are splined, pinned or precision-fit, but whichever is used, the fit needs to have no lost motion. Butterfly valve shafts are pinned, and eccentric rotary valves have splined connections or the proprietary Polygon coupling. Plug valves have a one-piece plug and stem. A control valve must have no lash between the shaft and the active control element.

The connection between the actuator and the valve shaft is a clamped fitting. Some manufacturers use a split coupling while others use a clamping collar or setscrews. The clamping device ensures no mechanical play between the actuator pinion spindle and the valve shaft. Actuators with female output shafts require a precision fit. Some assemblers use threadlocker on these components. The goal for all of this is to avoid lost motion in the drive-train.

At the top of the shaft is the NAMUR connection that engages the positioner feedback shaft: a pilot bore to center the connection and a slot to drive the positioner. Analog positioners have cams and feedback springs, and the action of the spring on the cam causes a continuous torque on the shaft, which preloads the positioner shaft and prevents any backlash in the connection.

Any tolerance between the spindle and the positioner shaft is closed by the torque, and the relationship between the spindle and positioner shaft never changes. Early digital positioners did not employ biasing springs; however, today these springs are almost universal. The biasing spring applies a continuous torque so that the relationship between the positioner shaft and the actuator spindle is fixed.

The position of the final control element (e.g., ball, disc or plug) is transmitted through a fitted, splined or pinned joint, through a clamped coupling and through a spring-biased coupling, allowing the valve positioner to know the exact position. The piston-pinion connection falls outside the connections involved with the positioner so it has no effect on the precision of the steady-state control using these actuators. “Steady-state” applies if there is lash between the rack and pinion and if the control valve is a butterfly valve buffeted by system turbulence, which means the valve position could chatter. This is unlikely to occur, but because it’s possible, it should be considered in the specification stage.

FRICTION
Another issue with rotary valve and actuator systems is friction. However, the friction of the valve/actuator package is primarily a function of the valve, not the actuator. A rack and pinion actuator that has been inactive for a long period may take 5 psi (.34 Bar) differential to begin moving, while a recently cycled rack and pinion actuator has a breakout pressure of about 1 psi (.07 Bar). Considering these actuators typically operate with air supplies in the range of 60 to 80 psi (4.1 to 5.5 Bar), this is a small offset.

Overcoming valve friction is the primary function of the actuator. Ball valve seats are always in contact with the ball, causing significant friction throughout their operation, although the torque drops off as the valve is opened. Plug valves inherently have very high friction, yet plug valves using rack and pinion actuator assemblies have met Entech specifications for precision modulating control valves.

Butterfly valves have considerable breakout torque, much higher than the force required to operate the actuator. High seating torque is required to proper-
ly seal against the seats that touch the disc only when closed. Given the nature of the torque generated by rack and pinion actuators, butterfly valves can be precisely positioned by an appropriately sized unit. Limitations are likely to appear at extremely small openings, where the disc progressively engages the seat, and the steep slope of the torque/rotation curve may be reflected by some torsional windup of the valve stem.

By design, eccentric rotary plug (ERP) valves have particularly low static and dynamic torque requirements and are well served by comparatively small rack and pinion actuators. The ERP design is stable in either flow direction, and therefore not likely to chatter.

It is important to note that a positioner should always be used for modulating control. The positioner should be judiciously mounted to take feedback from the actual position of the valve, not the actuator pistons. Any potential lash between the pinion and the racks is thus made irrelevant because the responses of the positioner are based on the true valve position.

Another reason for using a positioner on a rack and pinion actuator is that the air supply pressure used to drive that actuator is incompatible with the customary, universally familiar 3 to 15 psi instrument signal range. Modern positioners, particularly contemporary digital positioners, are incredibly stable. However, they may vary, a properly selected, well-built rack and pinion actuator can offer a six-digit cycle life if properly installed and maintained.

Several factors can impact the performance and reliability of a rack and pinion actuator, including:

**Dirty air:** A system that is not blown down diligently when constructed or has wet air causing rust in supply pipes can lead to particulate contamination of the actuator. Grit lodges in the seal rings and the guide pads, scoring the cylinder wall. Because the contamination is admitted into the volume between the pistons, the dirt may directly damage the racks. Once the cylinder wall is scored, the actuator is no longer serviceable or repairable. Rack and pinion actuators are lubricated for life, and clean air will maximize their service.

**Heat:** Heat causes accelerated aging of the O-rings and can break down the lubricating grease. The primary heat path into a rack and pinion actuator is from the valve stem, through the coupling, and into the bottom seal of the pinion spindle. An issue with a leak at the bottom seal is characteristic of a heat-related problem. Viton O-rings and high-temperature lubricant generally solve this problem, and a good practice is for valves intended for high-temp services to supply extended brackets and couplings to lengthen the heat path.

**Corrosive environment:** Caustic chemicals dripping on an aluminum actuator housing can destroy the actuator in days, if not hours. However, several solutions exist, including repairing process leaks, adding a corrosion-resistant coating such as a TFE-based deposition polyester powdercoat, or epoxy, and using corrosion-resistant actuator material such as stainless steel.

**Corrosive atmospheres:** Particularly with spring-return actuators, when the air is released and the valve strokes to its failsafe position, the spring-chamber inhales a volume of exterior air equal to the piston displacement. If this air is corrosive, salty or humid, the actuator may corrode internally. Rust flakes from the springs can cause abrasive damage to the cylinder bore or the springs may pit from corrosion, leading to fracture. Generally, the most effective remedy is to use a rebreather vent, which vents the exhaust air over the vent port so it can be inhaled (preferentially to the ambient atmosphere). If the supply air is at 80 psi, the exhaust expands more than six times as it vents to atmosphere, so the available supply to the vent port is sufficient to keep the corrosive atmosphere purged.

**DESIGN CONSIDERATIONS**

With so many manufacturers supplying rack and pinion actuators, it is important to consider several aspects of an actuator’s design before making a selection. Some considerations include:

**Housing:** Hard anodizing or other surface treatments can increase abrasion resistance, and using materials such as stainless steel increases corrosion resistance.

**Fasteners:** Corrosion-resistant options, such as stainless steel, can ensure longer life.

**Springs:** Two main spring configurations are available: concentrically nested springs and parallel springs. No significant differences exist in performance, but there are considerations on parts inventories. For example, it may be attractive to
have the same housing with or without springs to simplify inventory if both spring-return and double-acting actuators are used throughout an installation. Also, multiple parallel springs might have merit in both stocking and configuration because it is possible to load in enough springs to achieve the required closing torque. Long fasteners allow the spring to be relaxed fully before removal.

Travel stops: As discussed earlier, adjustable travel stops are beneficial if the actuator is being used with a position-seated valve and fully adjustable-travel stops are beneficial if the valve must never close or must never open past a certain point.

NAMUR and ISO mounting dimensions: These standard mounting options readily accept a wide range of accessories. They also ensure adaptability for use in any application.

Replaceable components: Replaceable pinion journals and guide pads simplify maintenance.

Rack and pinion design: The actuator design should ensure gear engagement is full-length between the racks and pinion to maximize the contact area and minimize wear and specific loading of the teeth surfaces. Surface treatments such as nitriding will harden the gear’s surface and decrease wear.

High-temperature options: Heat can cause premature actuator failure so special elastomers and lubricants can be used in severe service applications not possible with standard construction.

Pistons: Quality piston materials and manufacturing ensures reliability in standard applications while stainless steel offers maximum corrosion resistance for severe applications.

BEYOND ON-OFF APPLICATIONS

Rack and pinion actuators are a proven technology well suited for modulating control applications as well as traditional on-off applications. Though many success stories of these actuators for modulating control have been told, in general, they are underused in these applications. The compact and efficient design of rack and pinion actuators has advantages for many installations, and these actuators can meet facilities’ control needs with reduced cost but increased reliability.

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