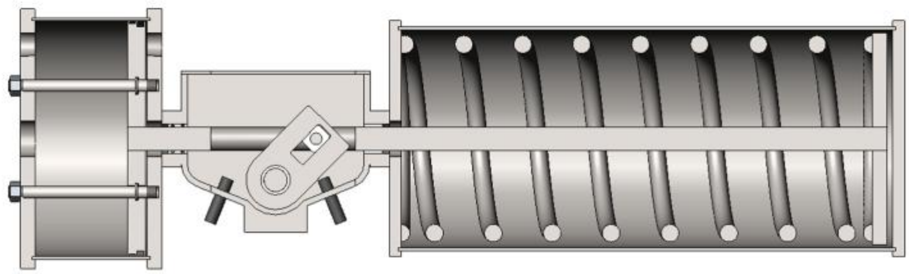
SCOTCH YOKE ACTUATORS

Design Review, Assessment and Theory
SYADR030410-1

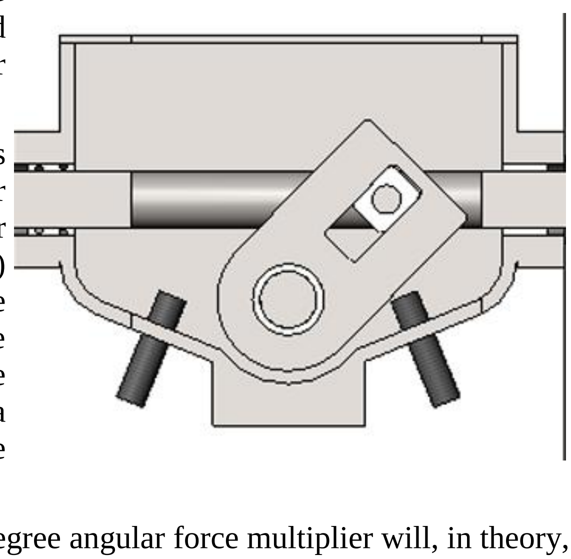
Introduction: Scotch Yoke type actuators are made by numerous companies and are sold under even more names (as some simply rebrand what they buy from others). While produced in a wide range of torque outputs, the most common usage is on valves and other devices that require higher torque values - roughly 8,000"# and above.



The scotch yoke mechanism provides a torque characteristic with higher values at the two ends of travel, or stated another way, a torque characteristic that is lower at mid-travel than at the ends of travel. This characteristic is especially beneficial on certain valves that exhibit high end of travel torque requirements, but less so on plug valves and others that require roughly equal torques throughout the entire range of travel. Regardless, scotch yoke actuators tend to cost less per unit of torque output than competing products using other type mechanisms and are therefore popular on all types of higher torque valves.

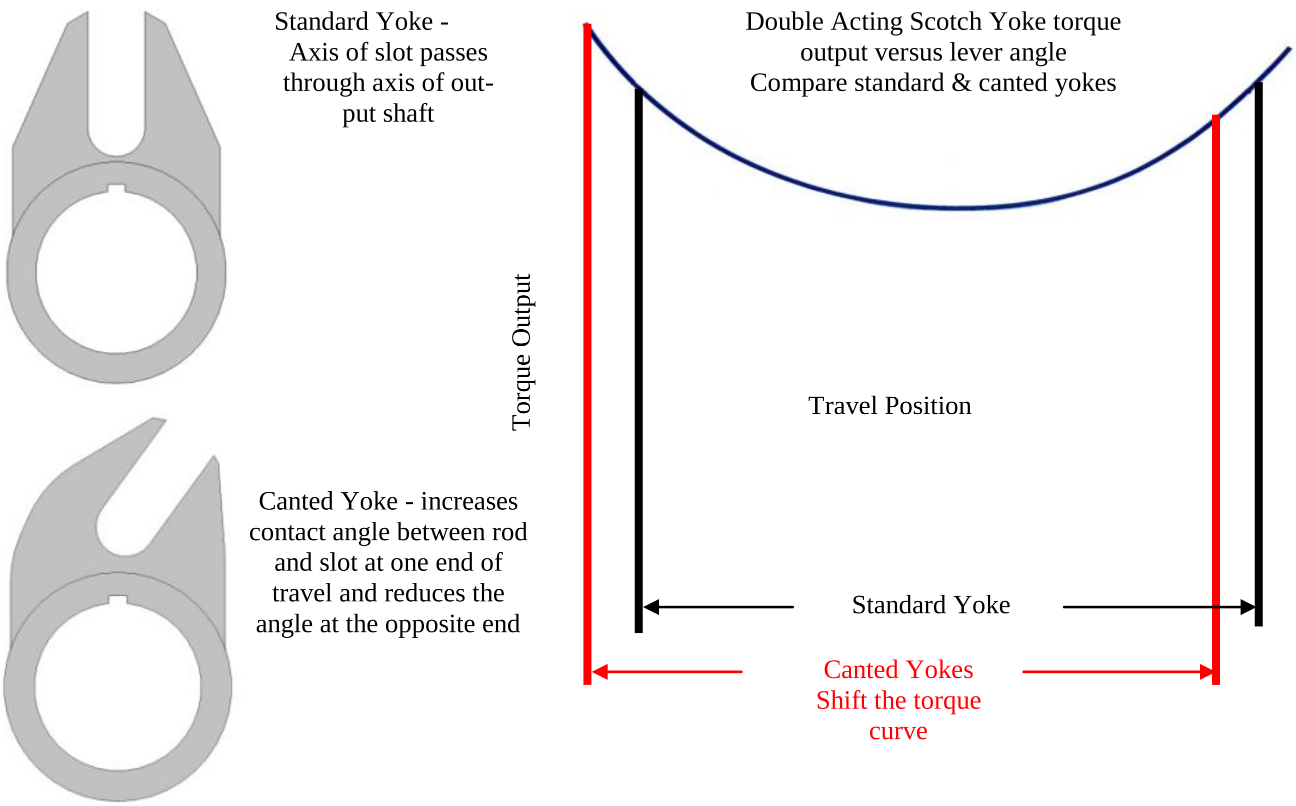
Purpose: The purpose of this paper is to review various scotch yoke designs and to make honest evaluations of the concepts and implementation in comparison to available alternatives, including the QTRCO FLAT YOKE™ actuator

Basics: A scotch yoke mechanism includes a slotted lever and a means to impart force to the lever. Typically the force is applied via a rod that moves to the left and to the right as shown in the accompanying image. A means is provide to connect the rod and the lever slot such that lateral motion of the rod causes rotational motion of the shaft to which the lever arm is attached.



As mentioned above, torque output is greater at the ends of travel than at mid travel. This is because the lever length is longer when the lever is fully clockwise or counter clockwise than when at the center (vertical) position. Also however, the lateral force applied by the rod acts at an angle to the lever slot. The greater the angle, the greater the effective magnification of the force that acts on the lever. (If the lever were able to rotate to a nearly horizontal position, the force multiplier would be nearly infinite.)

Combining the same force on the longer lever with a 45 degree angular force multiplier will, in theory, absent friction, yield an end of travel torque that is twice that obtained at the mid travel position. The multiple will be even greater if the lever were rotated to 50 degrees or more. Most manufacturers offer a 'canted' lever which effectively 'cants' or 'tilts' the yoke slot so as to increase the angle to achieve even higher torque at one end of travel, while decreasing the torque at the opposite end of travel. (As shown by the torque curve, this has the effect of rotating the lever past the normal zero degree travel position without actually rotating the lever.)



Note a terminology definition at this point. Normally one would be told that the beginning angular position of the lever is zero degrees and that the angle increases to 90 degrees as the actuator travels over the full stroke. Any excess travel would be defined in minus degrees at the start and 90+ degrees at the end of stroke. At QTRCO we prefer to use the mid-travel position as the zero degree angle. The start angle is therefore –45 and the end of travel angle is +45 degrees. The reason should become obvious as you read further.

At mid travel, the torque output is equal to the applied force multiplied by the lever arm length at mid travel. (Example: A 100# force acting on a 2" lever arm produces 200"# of output torque). At each end of travel, the torque output is equal to the longer lever length multiplied by the applied force and the angular force multiplier.

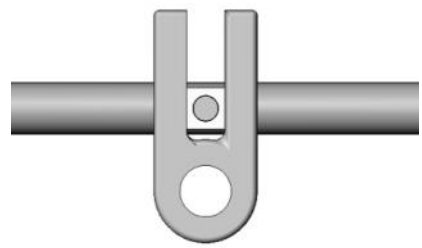
From the image it can be seen that the lever is longer when at the (QTRCO terminology) -45 degree position than when at the mid-travel 0 degree position.

DESIGNING THE SCOTCH YOKE ACTUATOR

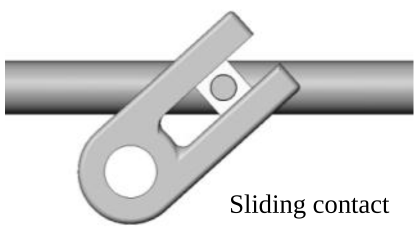
The basics:

- Define torque desired
- Double acting or spring return (not critical at this stage)
- Shaft drive male or female
- Interface between rod and lever (yoke) slot
    - Sliding contact or rolling contact (surface area versus friction)
    - Temporarily we'll use the slider method in our images

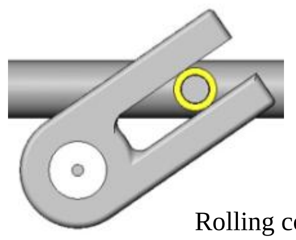
Lever at 45 degrees off of mid-travel center position (defined as zero degrees by common terminology but as –45 degrees using QTRCO terminology



Lever at mid-travel center position (defined as 45 degrees by common terminology but as 0 degrees using QTRCO terminology



Sliding contact



Rolling contact

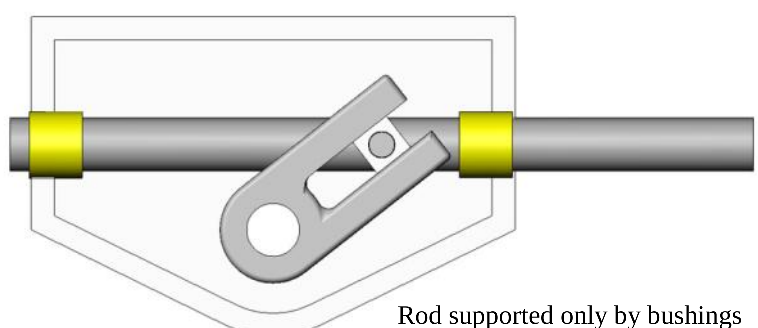
Forces encountered:

As previously discussed, the lateral forces applied by the rod translate into torque output by acting upon the yoke slot. This also applies loading onto the rod, trying to cause bending either upward or downward depending upon the direction and position of travel.

Side loading forces can be quite high. Consider an actuator that has 80 psig pressure acting on a piston of 10" diameter. The piston force is 6,283#. At a lever angle of 45 degrees, the bending force acting on the rod is equal to the piston force, or 6,283#. If the yoke is canted, the angle may be 10 degrees greater, or 55 degrees, and the side load force acting on the rod = 8,966#

Only at the mid travel position is there no side load acting on the rod.

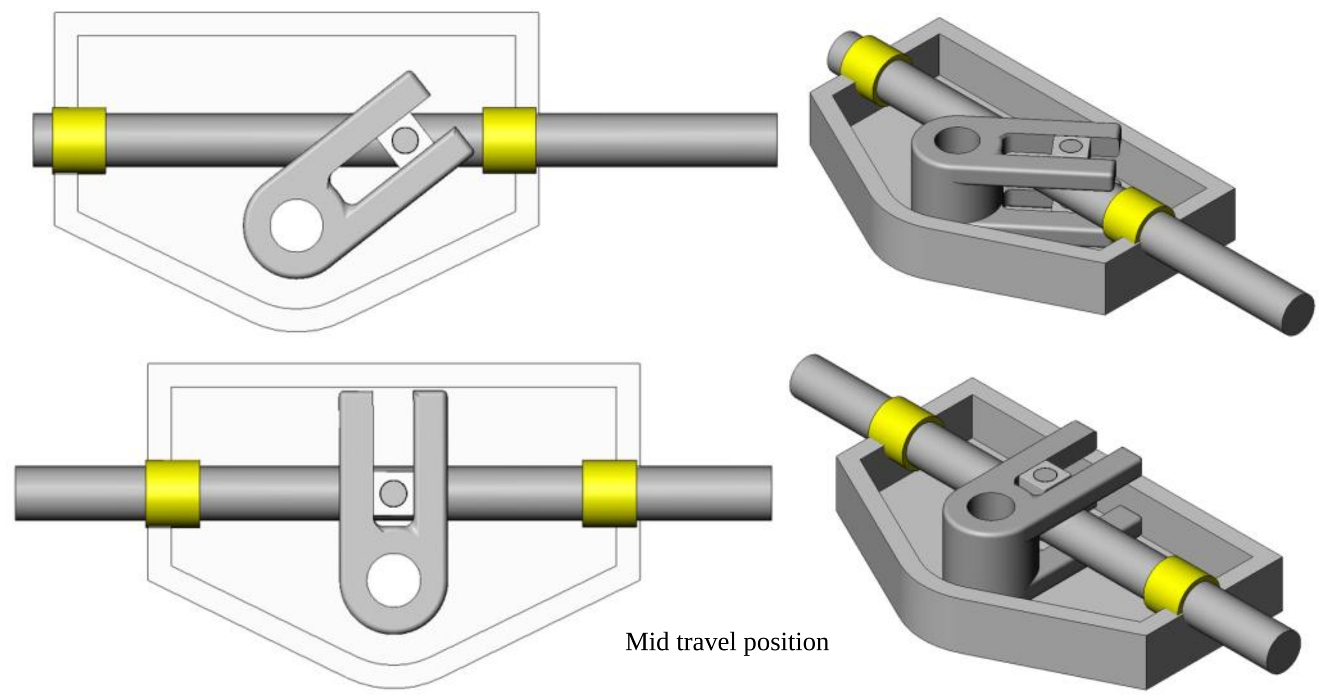
Given side loading on the rod, we want to prevent rod bending. The simplest, and least effective means is to support the rod with bearings located in the body. One deficiency lies in the loads which are placed



Rod supported only by bushings allows more rod bending on the bushings (high) and the relatively great distance between the source of the force and the bushing support, thus allowing some bending to occur, which leads to edge loading on the bushings and possible bushing wear and failure. Later we will discuss pressure seals that may also be located in these bushings and are thus more subject to wear and failure.

A second deficiency is that rod only support does not assist in preventing rod rotation. When springs compress, there is a rotational moment from end to end. One end rotates with regard to the other end. A torsional load is thus applied to the piston and thereby the rod. Rod bushings have no effect in resisting this rotation, thus the design depends upon the angular engagement between the slider and lever as the sole means of rotational resistance. Thereby additive (and unnecessary) loads are imparted onto the slider (or roller) and lever. At mid travel, the angular engagement is zero, thus the rod is free to rotate allow the sliders to misalign with the lever, thereby binding somewhat as the rod travels further and the angular engagement is reestablished. Observation indicates a higher degree of pin failure

At travel positions other than mid travel, rod rotation is resisted solely by the engagement between the slider and the lever but at mid travel, the slider to lever engagement does not resist rod rotation

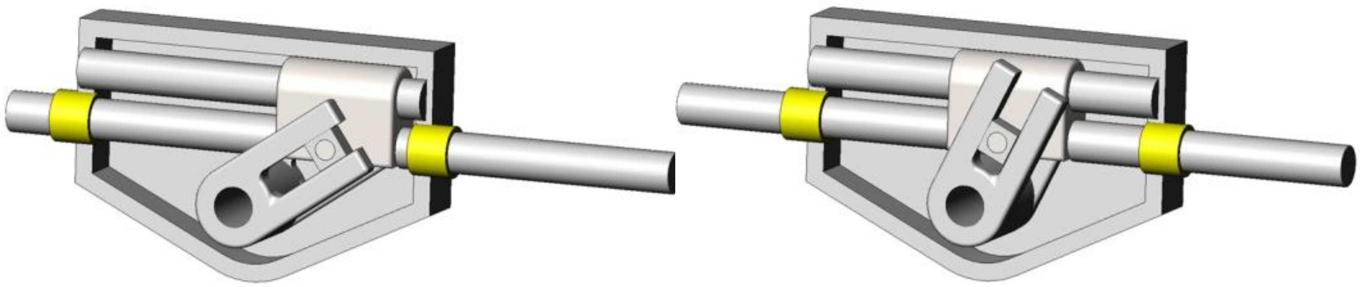


Mid travel position

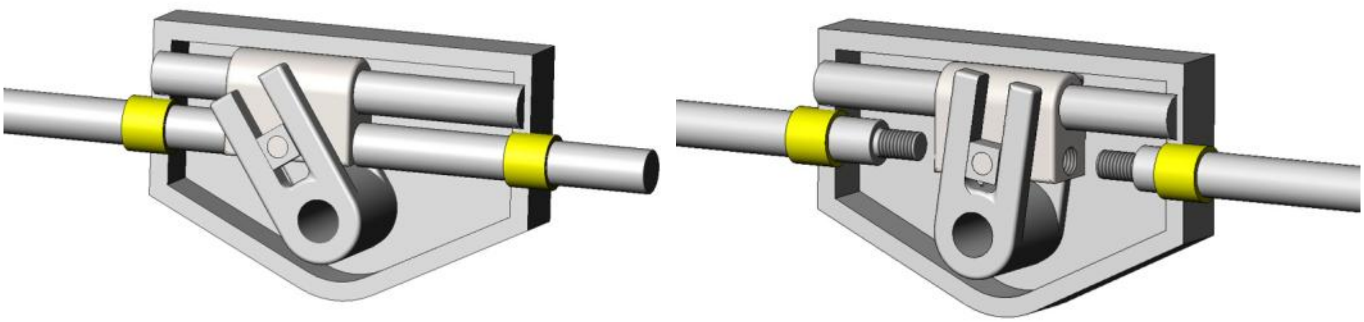
More concerned manufacturers add substantial primary supports to resist bending of the rod and while they typically also have rod bushings, their rod bushings experience far less side loading and importantly, the additive rotational loading on the slider and lever are eliminated.

The following images portray an improved and more substantial means of rod support. Notice that a separate carrier is employed and that the rods from the various force modules are threaded into (or otherwise attached) to the carrier. Side loading is supported by the outer rod and rotation is resisted by the carrier rather than the slider and lever. One can see that this design is superior to one using only the rod bushings for support but the added components do add to the production cost, leaving the manufacturer to convince the user of the benefit value (it is substantial).

Because of the design superiority, we will use this design as the basis of further discussion.

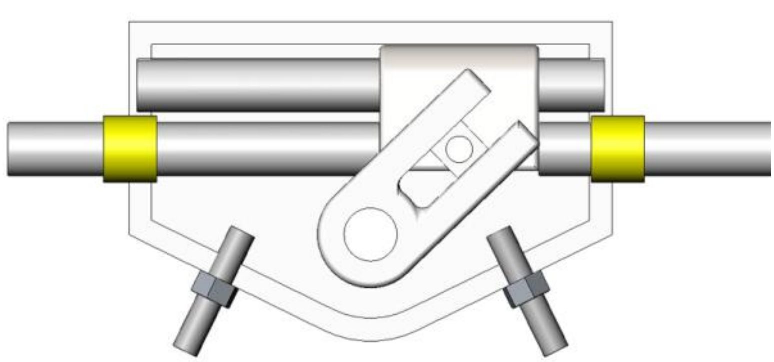


The force module rods push the carrier which then engages the lever to cause actuator shaft rotation



Travel stops:

Various travel stops designs exist but there are two predominant designs. One design acts in line with the piston and rod axis to stop the pistons directly (we will show images later). The second acts to stop lever rotation. Stopping the lever allows added stress on the slider, lever and shaft bushings.

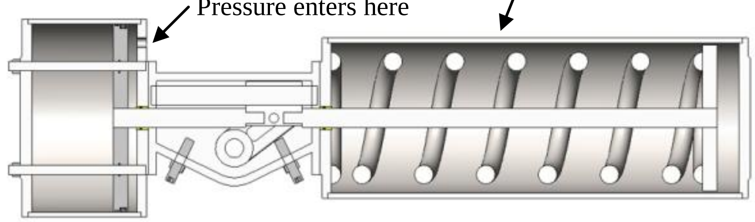


Given the previous example of a 10" piston with 80 psi pressure, the piston force equals 6,283# and at the end of travel (45 degrees from mid travel) the force acting perpendicular to the lever is also 6,283#.

Let us, for example, assume that this piston force will produce an actuator output torque of 20,000"#. Normally the valve torque will be less than the maximum actuator torque. For this example assume the end of travel valve torque is 15,000"#, therefore the required force acting on the lever is only 4,712# to fully operate the valve.

If piston stops are used, the force acting on the sliders and lever will never exceed 4,712# but if lever stops are used, the force applied will equal the maximum possible from the piston. Consider that some users build a safety factor into their stated air supply, the 6,283# force might be 25% greater, or 7,853#.

Why use lever stops? Certainly they should be avoided. But a close look at many actuator designs show that their tie rods would not have sufficient strength to withstand the forces associated with piston stops and therefore they employ lever stops.



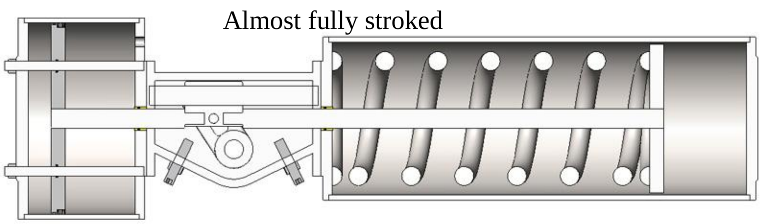
This image shows a typical scotch yoke actuator with piston on one end and spring on the opposite end. (Note weight imbalance)

Why are the modules on opposite ends rather than equal on each end for weight balance? This is because the rod requires support and passing it trough the body allows support on each end as well as the travelling guide. Once the rod passes through the body, there is insufficient space on the ends to place balancing modules.

Key positives of this approach:

- Pressure is applied to the inward side of the piston, thus reducing the number and size of the tie rods that secure the air module end cap
- Fastener size and quantity to retain the modules to the body are reduced

Key negatives of this approach:



- Weight imbalance - Both laterally and longitudinally. (also center of gravity moves as the actuator strokes)
- Force imbalance - the shaft bushings must withstand the full force of the piston and spring as they serve as pivot points for the rotating shaft (frictional losses and wear result)
- The rod bushing must contain a seal that is subject to wear. Should wear occur, the actuator must be removed from the valve, then disassembled to replace this seal. (Likely this is a proprietary seal that will be sold as one component of a very costly kit - nice profit margin if you are the manufacturer)

- Another point of frictional loss is from the module rods sliding against the rod bushings and also the rod support guide sliding along the supporting rod.
- And finally, a very important issue arises when assembling the force modules to the body because the module rods must be treaded (or by some other means) into the guide. Because the modules are usually large and extremely heavy, they must be externally supported while also carefully aligned to prevent thread crossing and unrecoverable actuator damage.
    - It may seem unlikely you will have to worry about module mounting but consider, they must be removed and remounted if seals are replaced - or - if you do something as seemingly simple as change the direction of action (fail closed to fail open)
    - It is also claimed by nearly every supplier that THEIR scotch yoke actuators are modular. As you will see as you read further, there are modular designs and then there are MODULAR designs. A module may be a module but if you cannot perform the process of mounting without special training and equipment, how truly modular is the design? Make your own evaluation.
    - Manufacturer's instruction manuals warn that only well trained and properly equipped personnel should perform work on their actuators .. and they mean WELL TRAINED.

Air module design:

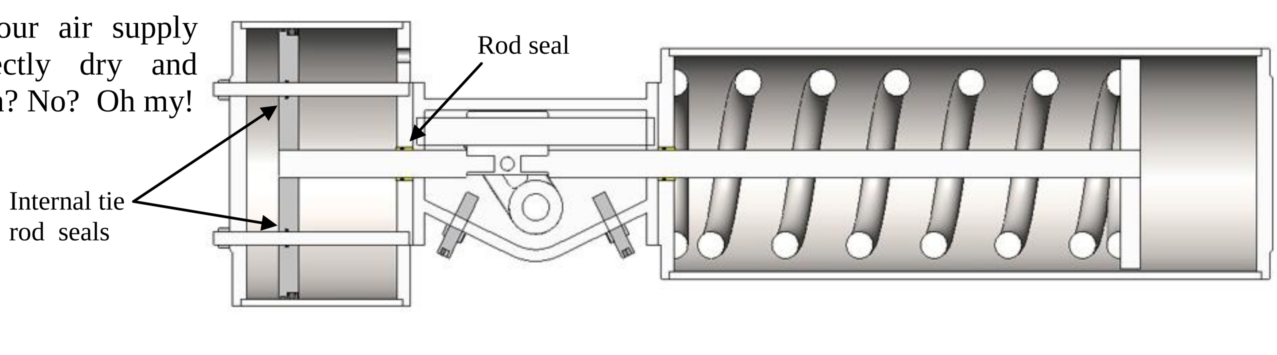
There are two common air module designs. The obvious has external tie rods to secure the end cap, cylinder and base. In this design, the tie rods would normally be designed to have the strength required to withstand the maximum outward force of the pressured piston.

But, because air is normally applied to the inboard face of the piston, in theory, the end caps do not experience these forces. Some designers take advantage of this by reducing the number and size of the tie rods. This is acceptable but it does not permit locating piston travel stops in the end caps and thereby forces use of the inferior lever stop design.

An even lighter, lower cost approach is to place the tie rods internal to the cylinder, passing them trough the piston. The positive aspect of the design is weight and cost due to fewer tie rod quantity. The downside is that there are no at least two more critical, difficult to access, seals that drag on the tie rods. Why add these seals that are additional reasons for failure? Initial cost!

… and perhaps … added sales of high margin replacement part kits?

Is your air supply perfectly dry and clean? No? Oh my!



SCOTCH YOKE ACTUATORS

Design Review, Assessment and Theory
SYADR030410-3

Expectations;

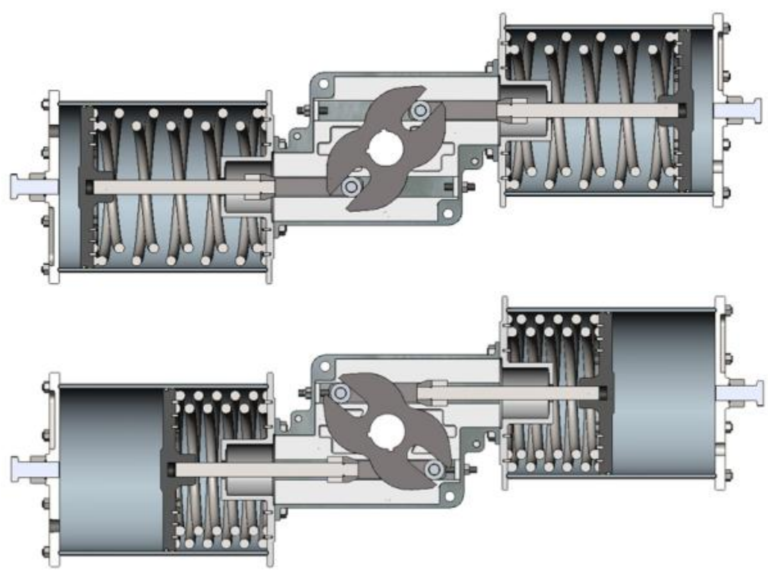
Given that scotch yoke actuator design are basically the same, users understand and expect friction and wear failures. Not that these are truly bad designs, no, they just are not as good as they could be. They meet expectations because expectations have acclimated to reality. If there is nothing better from which to choose, then choose the actuator you are most familiar with or were convinced the minor differences warranted your faith. But, what if there is now something better?

No rod bushings
No rod seals
Zero rod side loading
C.O.G. on shaft axis at all travel positions
'Canted' yoke achieved simply by adjusting travel stops
Captured springs

Alternative design - by QTRCO - clearly superior.

QTRCO has designed a new scotch yoke actuator that is so unique that we named it Flat Yoke ™.

The Flat Yoke actuator employs a scotch yoke mechanism but shares little else with the traditional scotch yoke design. As a result, the Flat Yoke accomplishes:



- Weight balance (and lighter weight)
- Internal force balance
- Zero shaft bushing loading (no frictional losses, no wear)
- Elimination of rod bushings while applying zero side loading to the rods
- Elimination of rod seals
- Elimination of 'canted' yokes while retaining canted capabilities
- No rod support carriers required, no sliding friction
- No sliders in contact with the lever
- No spring rotational forces acting upon lever interface
- Captured, yet accessible springs

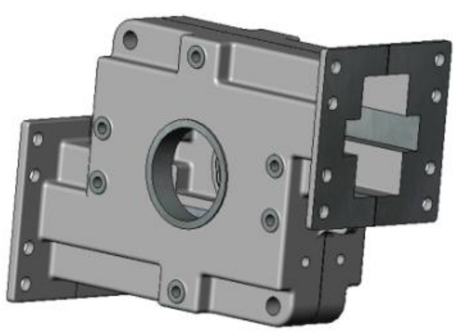
- Rapid (if ever) on-site (on valve) seal replacement
- Turn top side down action reversal (no actuator disassembly, no special training, no special tools)
- Standard, optional mounting geometries to suit user needs
- TRUE MODULAR design
- Modules require no internal attachment (Fasten to body, period!)
- Interchangeable modules (spring, air, hydraulic, jackscrew, high speed, high temperature)
- Ductile and also stainless steel constructions
- Body module consists of only three main parts, two shaft bushings and two fasteners
- Spring module uses a springpaq, cylinder, end cap and tie rods (external)
- Fully adjustable end cap and body located travel stops that stop the pistons

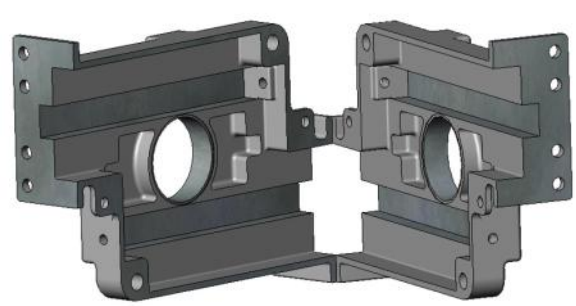
The QTRCO Flat Yoke TM design:

The basic design begins with how we support the rod. Actually, not a rod, but a clevis that straddles the dual arm yoke for enhanced force distribution.

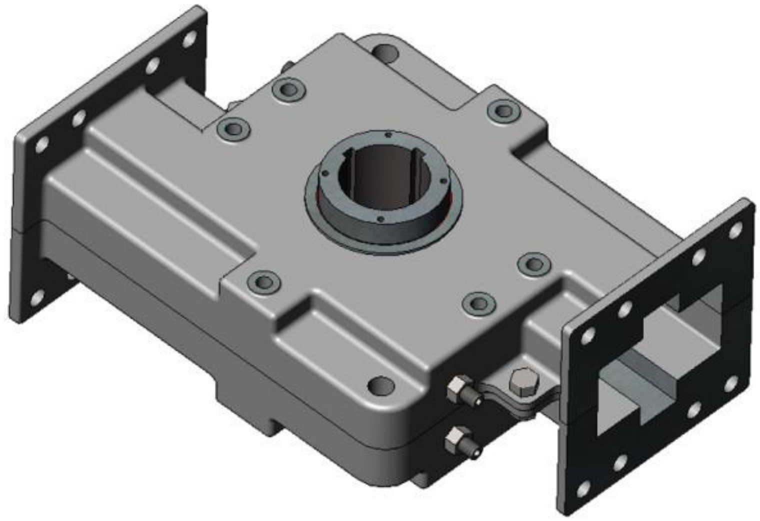
On one end the clevis threads onto the force module rod (when the force module is standing alone; no cross threading risk). The other end contains a roller and pin assembly where the center roller engages the lever slot and the outer rollers engage with slots in the body. The clevis straddles the yoke arm for enhanced force balance, rather than the yoke straddling the rod as with other designs.

The side loading forces from the yoke slot transfer to the center roller, then to the pin, then to the outer rollers, then to the body slots. Absolutely no side loading is applied to the clevis nor the piston.



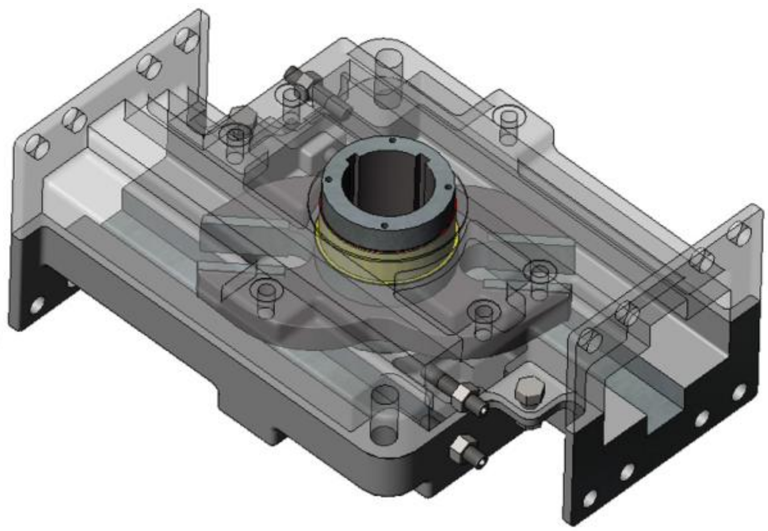


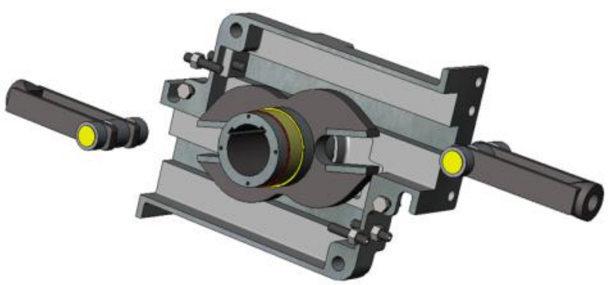
Images:
- Body halves
- Shown mated and also open to display patent pending slots
- Clevis, pin and roller assembly as assembled and cut-a-way to display components
- Unique dual lever 'flat yoke'

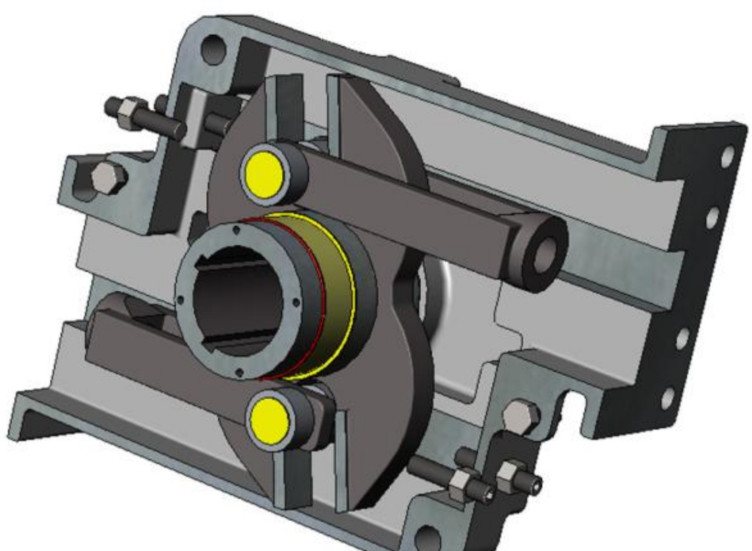


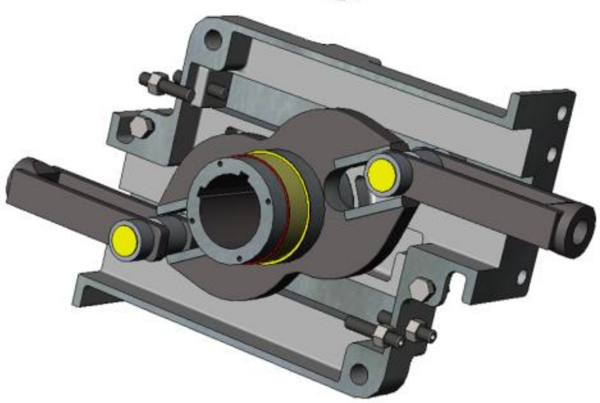
Here we see a Flat Yoke body assembly. It consists of two body halves, a yoke, two shaft bushings, two o-rings and four fasteners. Without a doubt, the Flat Yoke body assembly contains the fewest number of parts and is the least complex of all designs.

The clevis and pin assembly is part of the force module but we show the clevis being inserted into the body only to show how absolutely simple it is to engage the clevis and the yoke. Other than fastening the force module to the body, there are NO parts to thread together and no chance of cross threading (see other manufacturer's warnings in their massive instruction manual).







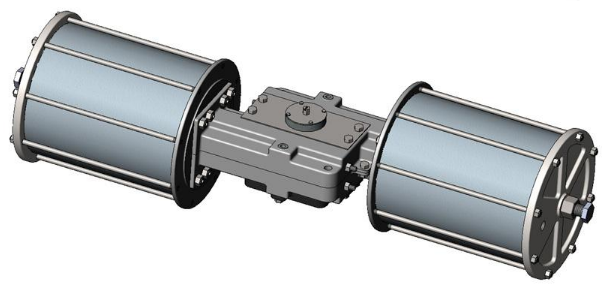


Now we show the clevis insertion as part of the force module. Insert the two force modules simultaneously, install nuts onto the force module studs, tighten and you are done. Can you imagine how easy this is as compared to competitive scotch yoke actuators?

Action reversal:

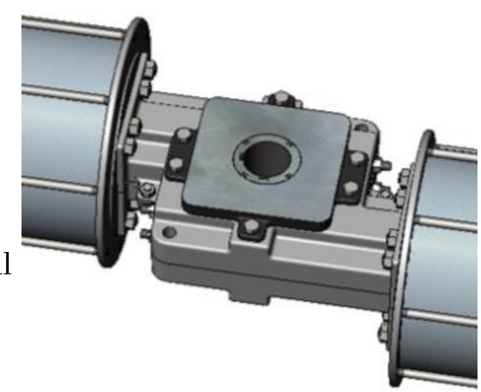
To reverse the action (say from fail closed to fail open) competitors explain how, with well trained and well equipped personnel, you are to relocate the spring module from one end and exchange it with the air module from the other end. They also warn that the modules are heavy and that you should assure having the proper equipment available.

By comparison, it would be easy to reverse the Flat Yoke force modules as there is not the myriad of steps required to remove and replace them. Yes, it would be easier, BUT, it is not even necessary. Because we make both sides of the Flat Yoke actuator identical, you can drive the valve with either side. Therefore TO REVERSE ACTION WITH A FLAT YOKE ACTUATOR, SIMPLY TURN IT TOP SIDE DOWN!



Oh, since we do convert the top side to drive NAMUR accessories and the bottom side has a Universal Mounting Plate (UMP), you do have to spend 5 minutes moving these form one side to the other.

The image shows an undrilled UMP because we do not drill them until we learn your BCD and thread size requirements.



Maintenance:

If any one of the numerous proprietary seals fail in a competitor’s scotch yoke actuator, you will need to remove the actuator from the valve (hopefully it removes without being stuck to the valve shaft and without causing damage to the valve internals). Also, hopefully you have on-site lifting equipment so as not to have to rent this costly equipment. Once removed from the valve, you will transport the actuator to maintenance (or ship to an outside repair facility) where the actuator will be almost completely disassembled to access the failed seal. This seal may have originally cost only a few dollars, but being proprietary and it making little sense to replace only this one failed seal, you will need to purchase an entire seal kit. At this point you will learn that the manufacturer, who may have met competitive pricing at the time of purchase, is now going to make up for any lost initial revenue. From experience, products that may earn 25% profit margins will see 70 and 80% margins for their repair parts.

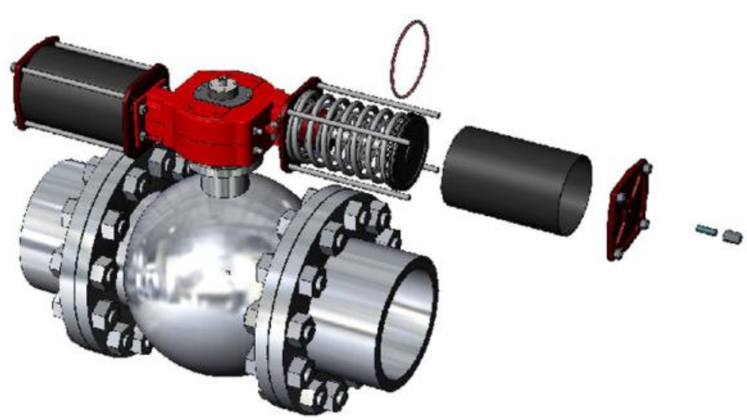
QTRCO has a philosophy that we will design our products for infinite life but if repairs should be required, the replacement seals will be readily available from local sources and we will advise the common part number description to enable user choice as to seal source. We will readily sell them at inflated prices, nicely packaged with part numbers and descriptive information but the user is also welcome to source them locally for relative pennies. All Flat Yoke seals are industry standard components.

<u>One more important feature that demonstrates our confidence in the Flat Yoke actuator is that , for three years from the date of shipment from QTRCO, we will provide free replacement repair seals and other parts and will repair the actuator for free if you cover the cost to ship it to and from the QTRCO factory in Tomball, TX.</u>

While discussing seals, maybe our emphasis on low cost replacements is overdone since the only dynamic seals are those on the piston. There are no rod seals and no seals internal to the pistons. Therefore the only seals that can fail are the piston seals. Because the seals experience no side loading and are properly applied, they very seldom fail as demonstrated by our Rack & Gear actuators that have the same seal design concept and have been providing outstanding service now for 11 years. .

Seal access:

The sole dynamic seal and the only wearable seal is replaced by removing the end cap and the cylinder. This completely exposes the piston seal for replacement. This can be accomplished while the actuator remains mounted on the valve (requires sufficient space available). After cleaning the pistons and the cylinder and replacing the seal, should the cylinder have been scratched by foreign contaminants, it can be turned end for end and re-used. The entire length is bored suitable for use and the inner half is not touched by the piston, so it is available as a spare cylinder (one on each end of course). Another way QTRCO fails to earn big profit from selling replacement parts! Are we just no very smart or does our commitment to saving our customers money mean more base sales in the future?



Speaking of user costs, when an actuator fails there is the obvious cost of repair parts + labor + equipment (perhaps rented) + the lost product revenue. If the actuator does not fail, that is certainly the best option, if something does fail however, we think the ability rapidly repair the actuator with minimal cost will mean a great deal in the user's decision as to whose actuators to select in the future. Then we'll earn our meager profit.

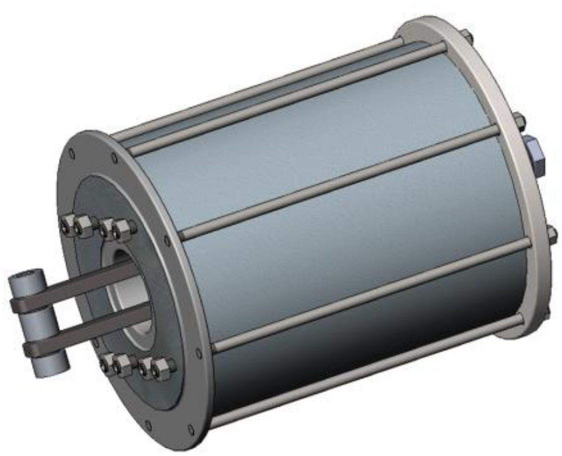
Safety:

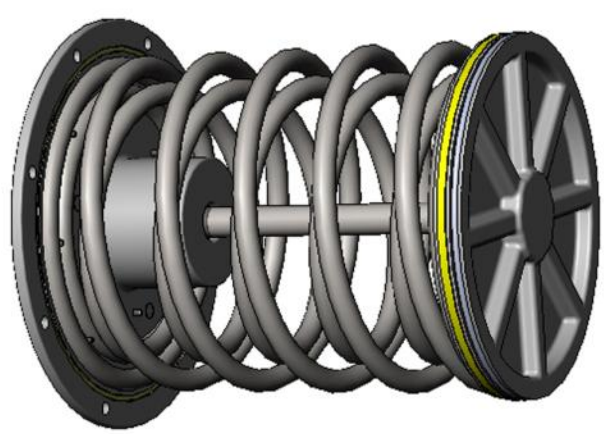
Our (separate) instruction manual is rather brief compared to our competitors' because the Flat Yoke actuators are so easy to assemble and disassemble. Also we have captured the springs so that they do not extend as the end caps are removed. Some manufacturers say it is a safety feature to have the spring extend as the end cap is removed. We respectfully disagree as there is too much of a chance that the fasteners will not be removed in the proper procedure allowing the springs to become wedged between the end cap and the end of the cylinder.

We do not weld our springs into an inaccessible cylinder where one cannot tell if there is a problem with breakages etc. As such our springs are fully accessible BUT NOT REPLACEABLE except as a complete springpaq.

As seen on the previous page, the end cap and cylinder may be removed without concern that the spring will expand. This is because we capture the spring between the piston and the base plate (spring retainer) via the piston rod and an inaccessible (without having compressed the spring in a press) safety collar.

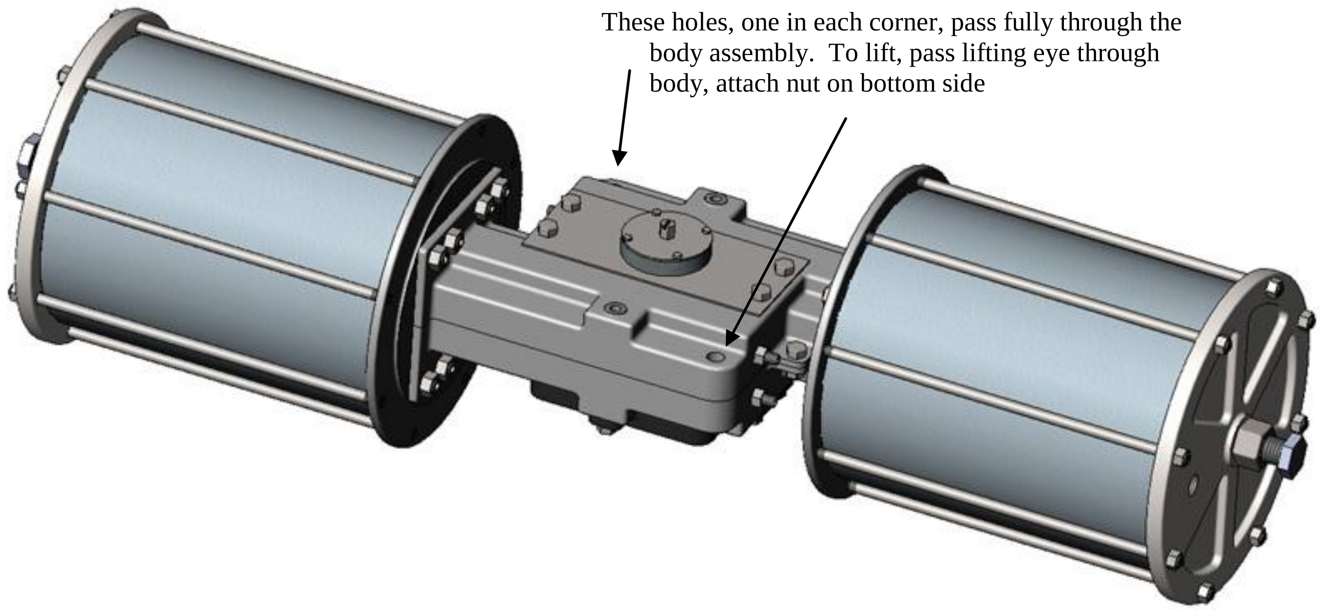
Note that the clevis also serves to secure the captured spring, but it is not a required component. Also the portion of the piston bolt that threads to the clevis is stronger than need be, but is smaller than the oversized main portion of the bolt (to which the safety collar threads) because while neither will fail in service, we design so that the main bolt portion will withstand greater forces than the clevis attachment.





Installation:

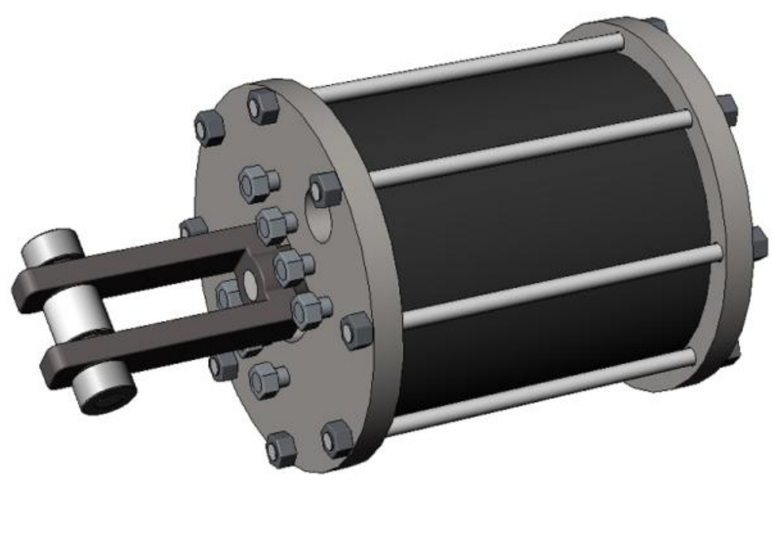
Installation is made easier by the balanced weight. Also, sizes F375 and larger have provisions for lifting eyes to pass fully through the body (eliminates threaded hole tensile loads for enhanced safety).



Also, should you ever need to remove the actuator, being able to lift directly upward alleviates binding between the valve and actuator shafts from a weight tilted actuator.

Double acting version:

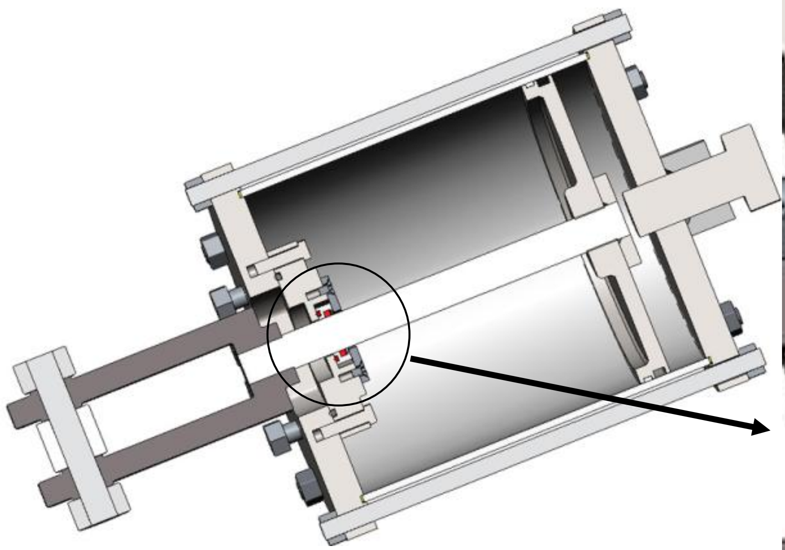
Recall that force modules are totally interchangeable on Flat Yoke actuators - enabling conversion from SR to DA and from large cylinders to small by simply removing a few fastener nuts. The same body assembly is used for DA and SR versions)

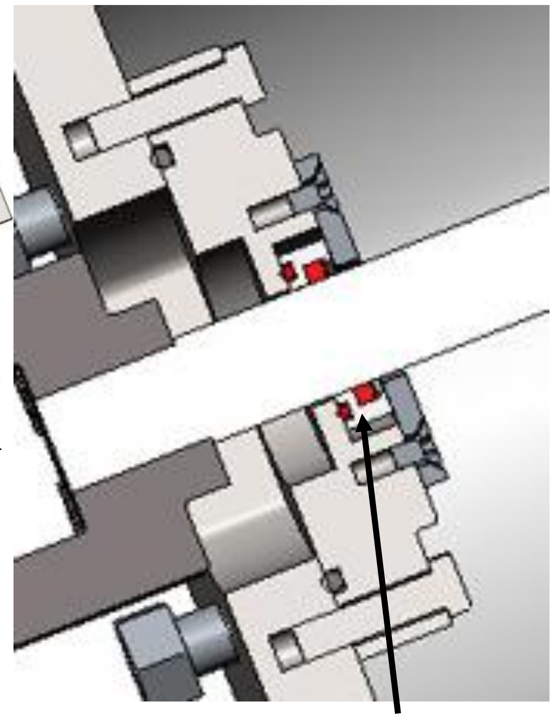


Double acting actuators require pressure to be applied alternately to each face of the pistons. The Flat Yoke employs a force module located rod seal that is able to move side to side should the rod axis move sideways as the actuator strokes. Note that the rod axis will not move sideways, but we included the moveable seal 'just in case'.

The next image shows a cut-a-way of the

DA module. Pressure is introduced to the lower plate to push the piston outward and to the end cap to push inward.





The rod seal retainer is able to move from side to side to accommodate any lateral movement of the piston rod thereby assuring proper engagement of the rod and seal.

Available options:

- Jackscrew override
- Hydraulic override
- Tag Out Lockout, mechanical lock to prevent actuator rotation
- Partial stroke testing device (by far, the best available - see XRCISER ^{TM} literature)
- Dribble control two firm positions of stroke for topping off operations
- SafeStart - partial opening to eliminate water hammer (and bypass valves) on line fill operations
- High temperatures (to 600F)
- High speed (as fast as 0.2 seconds for each direction of travel
    - Third party or integral shock absorbers
- Zero plastic and/or ALL METAL construction

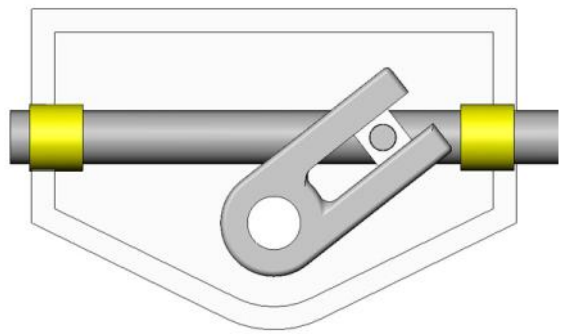
Competitors:

We are not about to tell you that out major competitors make poor products. This would fly in the face of your experiences. We will however mention their designs and allow you to make a decision as to which might be superior for you applications. As Fox news says 'we report, you decide'.

For comparison we use Morin, Bettis G series and the 'new' Flowserve RG. For copyright purposes, rather than our copying and pasting their product images, we ask that you refer to their respective literature or web sites to view their designs and claims. We will feel free to use images created in house.

Caution - information is as provided in each manufacturer's literature. We take no responsibility for design changes that may cause the following information to be erroneous.

- Morin
  - Single arm yoke lever pinned to thru shaft (high shaft bushing loading)
  - Yoke arms straddle a central rod
  - Round rod extends through actuator body connecting air end with spring end
  - Rod engages yoke arm via pin and rollers similar to cam followers which extend from each side of the rod



  - Rod is supported only be bushings on each end of the body (friction point)
  - Rod rotation resisted only by engagement of rollers and yoke slot
  - Springs are located on the opposite side of the body from the air end
  - Air is applied to the outer face of the air piston pushing the rod inward and compressing the spring outwardly.
  - Springs are compressed as the end cap fasteners are tightened and loosened and extend from the cylinder as the end cap is backed away from the cylinder
  - Tie rods are external to the cylinders
  - Center of gravity is never on the shaft axis and is offset considerably when springs are installed
  - Shaft drive is square male on 45 degree angle to actuator axis. Top side is shorter than bottom so as to conform to NAMUR. It is not obvious as to how reversed action is achieved.
  - Mounting pattern is specific to Morin

- Bettis G series
  - Single arm integrally cast with the actuator shafts (high shaft bushing loading)
  - Yoke arms straddle a guide component that both supports and aligns piston rods
  - Round rods from air end and spring end thread into a center guide
  - Rods pass through bushings but are primarily supported by a second rod via a 'guide block' (friction)
  - Rod rotation is permitted on larger sizes as a 'PwerSwivl ™' is employed to prevent harm from such rotation
  - Yoke slot is engaged by a rectangular component that slides along the slot as the piston strokes (friction)
  - A rod seal is employed on the air end as pressure is applied on the inward side of the piston making it necessary to seal the rod (wear and failure possible)
  - Tie rods on the air side are located within the cylinder and pass through the piston adding at least two more important seals (wear and failure point)
  - Springs are captured in a welded housing and located on the opposite end of the body from the air module
  - Said to be 'modular' but design challenges one's ability to exchange one module for another
  - Center of gravity is located well away from the shaft axis and moves as the actuator is stroked
  - Shaft drive is keyed female
  - Travel stops stop the lever (high stresses)
  - Maintenance requires removal from the valve
  - "Easily" (according to the literature) reversible by removing and reinstalling the spring and air modules. No, turning the actuator top side down will not result in reversal of action.
- Flowserve RG series
  - A newly introduced design meant to replace the R series. Looks more like a Bettis G series now except the air end tie rods are external to the cylinder.
  - All other comments are as per the above Bettis information
- Flat Yoke by QTRCO
  - Dual lever arm cast integrally with shaft (zero shaft bushing loading)
  - Clevis' straddle the flat yoke arms

- Rods are replaced by clevis' that require no bushing support as both side loading and rotation are prevented by engagement of rollers in body slots
- Yoke engagement is via rollers for low friction
- Engagement of force modules to the yoke arms happens automatically when modules are fastened to body making this an truly easy task and the actuator truly modular
- Springs are captured as part of the piston assembly allowing safe maintenance while yet mounted on the valve
- Center of gravity is exactly centered on the shaft axis and remains there throughout the full actuator rotation
- Air is applied to the outer face of the piston, thus rod seals are not required nor present
- Shaft drive is keyed female (unless user desires an alternative
- Top and bottom geometry are identical making action reversal as simple as turning the actuator top side down
- Bottom mounting is via a Universal Mounting Plate that is drilled as tapped according to the user's desired BCD and threads
- Travel stops stop the pistons to minimize stress on the yoke arms and to increase useable life