COMPENSATING ECCENTRIC MOTION IN PROGRESSING CAVITY PUMPS

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Background

The progressing cavity pump developed by Dr. Rene Moineau in France over 60 years ago has proven to be one of the most enduring and innovative mechanical inventions in history. The interaction of a single helical rotor rolling eccentrically within a double-threaded internal helical gear of double the rotor pitch length produces a series of cavities progressing from inlet to outlet that totally supplement each other and produce a pulsationless positive displacement flow without the need for valves (Figure 1).

Figure 1. Dr. Moineau’s Invention Circa 1930

A second patent of Dr. Moineau’s utilized an elastomeric outer gear (stator) to achieve a compression fit between the two gears (rotor and stator), eliminating any clearance requirements. The effect of rotor and stator clearance elimination is high volumetric efficiencies at both high and low fluid viscosities, as well as abrasion resistance superior to all other positive displacement pumps.

The displacement per revolution of the progressing cavity pump is a function of three design constants: the cross-sectional diameter of the rotor (D), its eccentricity (e) from the rotor center and the stator pitch (Ps). The selected ratios of these three design constants to each other determines operating efficiencies, entrained solids size, internal fluid velocities and other aspects of pump performance to meet specific application requirements (Figure 2).

The pump’s pressure capabilities are determined by the number of rotor/stator seal lines. By repeating the identical single helical configurations, the length of the rotor and stator is increased to handle higher pressures (Figure 3).

Figure 3. Rotor/Stator Configuration

Forces on the Drive Mechanism

The torque required to drive the rotor is defined by the displacement per revolution (Disp/rev = 4e D Ps) times the differential pressure (∆P) plus the relatively constant frictional torque (Tf)

\[ T = \frac{\text{Disp/rev} \cdot \Delta P}{0.326} + T_f \]

The thrust on the drive mechanism is the differential pressure times the area of the rotor envelope (D+2e) or

\[ F = \frac{(D + 2e)^2}{4} \cdot \Delta P \]

In a progressing cavity pump, the rotor rolls in an eccentric path opposite to the direction of rotation. The forces inherent in the progressing cavity pump must be transmitted through universal joints, flexible shafting or flexible stator mounts. Compensatory challenges arise between the eccentrically rotating rotor and the concentrically rotating drive shaft. Improper compensation methods can result in operative inefficiencies, seal leakage, increased stator wear and short operating life. Following are some vital points to discuss that are applicable to all methods of drive.
First, the vertical or radial components of the thrust force increases with a decrease in the length of the connecting rod. A comparatively shorter connecting rod results in an increased angle for a given eccentricity (Figure 4).

**Figure 4. Vertical/Radial Components of Thrust Force**

Secondly, this vertical component serves as a moment on the cantilevered drive shaft as well as a radial force on the stator. Therefore, it is wise to (1) keep the angle of transmission ($\angle$) as small as practical, and (2) position the universal joint as close to the bearings as practical to minimize radial bearing load and shaft deflection. This important factor resulted in the hollow drive shaft design (Figure 5). It not only brings this vertical or radial component close to the bearings greatly reducing the radial force on the bearings, but eliminates shaft deflection in the stuffing box area.

**Figure 5. Hollow Shaft Design**

The hollow shaft design does increase the surface velocity in the packing area due to the larger shaft diameter, but since progressing cavity pumps are essentially low speed pumps, this factor is relatively negligible compared to the previously mentioned advantages.

Having briefly discussed the forces involved in driving a progressing cavity pump, it will be helpful to review the various methods currently utilized.

**Ball and Pin-Type Universal Joint**

Used by Dr. Moineau in his earliest design of the progressing cavity pump, variations of this design are still heavily used by the original licensees, (e.g., Robbins & Myers, Inc.), and many of the more recent manufacturers of the pump.

Note that the hole in the ball of the connecting rod is not machined angularly in all directions like an hourglass, but only along the axial plane of the rod (Figure 6). This allows the necessary rocking of the ball on the pin while the remainder of the universal action is affected by the pivot of the ball on the pin axis.

**Figure 6. Earliest Design of Progressing Cavity Pump**

Torque and the axial components of thrust are transmitted through line contact from the ball to the pin while the radial component of the thrust is transmitted again through line contact to the rotor or shaft connection by the outer surface of the ball. The only area where these forces are transmitted through a surface is the interface between the pin and the shaft or rotor head. It is significant that finite forces transmitted through line contact, without deformation or wear of the surfaces, produce infinite stress.

Given these extreme pressures at the point of contact, lubricants do little other than prohibit abrasion. With due respect to a design that has remained a major player as a method of driving progressing cavity elements for over 60 years, it is a free, low-friction universal joint that can run without lubricant, is simple and easy to maintain, and is one of the least expensive drive methods. The ball and pin joint, however, must be considered lighter duty than some of the more rugged alternatives available. Some manufacturers today offer bushings for their connecting rods and rotor/shaft connections, but after a thorough evaluation of such devices, the cognoscenti would best equate it to putting earrings on a sow.

Adding a bushing to what would normally be a hardened, precision-integral piece has several disadvantages:

1. It necessitates opening clearances since the accumulation of tolerances for multiple parts necessitates compensation. This degrades contact points.

2. The hole in the connecting rod bushing is hourglass-shaped rather than the angularly elongated slot to eliminate the necessity of indexing the bushing to the rod axis. This further degrades contact points.

3. The load bearing outer surface of the ball is no longer a hardened surface.

4. The cost of the universal joint assembly goes up as do the maintenance efforts to replace parts.

With the extreme pressures effected by the line contacts of the ball and pin-type universal joint, lubrication is of less benefit than for those devices that distribute the forces over a surface. For obvious reasons, a lubricant must be used that does not degrade to abrasive solids under extreme pressure and localized heat conditions.

Seals are important in ball and pin joints, if not so much to contain the lubricant as to exclude abrasives. The best seal arrangement if pump configuration allows it, is a well-protected bellows seal. Another less positive option is a lip-type seal (Figure 7).

**Figure 7. Bellows Seal and Lip Seal**

The ball and pin-type universal joint has served the progressing cavity pump well for over 60 years and will continue to do so, but heavier, more rugged universal joints are available. The user must be certain to request the type of universal joints that are suitable for their requirements and severity of duty.
Geared-Type Universal Joints

The most rugged, heavy-duty universal joint drive available for progressing cavity pumps was developed by Robbins & Myers, Inc., and entered the market in the 1960s after extensive expenditure of development time and funding. Torque is transmitted through multiple hardened stub tooth 30° pressure angle gears. The inner gear is crowned, as shown in an exaggerated manner in Figure 8, to allow the less than 1-1/2° angle required for the universal motion. This driving mechanism is similar to that used in heavy-duty flexible couplings for decades.

Figure 8. Crowned Gears

The thrust forces are transmitted through the spherical gear ball to matching bearing bronze thrust plates situated on each side of the ball making the universal joint bidirectional (Figure 9). The thrust plates are keyed, as is the hardened outer gear to the rotor head or shaft. The gear ball is driven by the connecting rod through a flat root involute spline and locked into position with a lock nut. The full universal joint is almost totally encapsulated in a heavy metal shell that leaves very little of the elastomeric seal exposed or vulnerable to potential damage caused by fluid flow.

Figure 9. Geared Universal Joint

Although the torque is transmitted by line contact through the hardened crowned gear teeth, it is multiple gear teeth contact as opposed to the single line contact of the ball and pin joint. The thrust is transmitted through the large full area of the thrust plate. Lubrication is very important and seal design is paramount.

Note in Figure 9, the surface backing of the elastomeric seal conforms to the seal’s shape with no sharp edges or pinch points that could be created when a static head forces the seal against the plate. Also note that with the seal positioned close to the fulcrum of the universal joint and the connecting rod going through an angle of movement of less than 1-1/2°, the bellows goes through minimum, almost negligible tension or compression. In a typical design, this movement would be less than 1/16°. Thus, almost negligible movement and the low surface exposure of the bellows are finer points of design responsible for the extremely long operating life of the geared type universal joint. The bellows are held through compression on both the I.D. and O.D. creating the positive long life seal that is needed with the gear-type universal joint since retention of lubrication is imperative with surface area contact. The universal joint is packed with an extreme pressure grease that under proper load need not be replaced for years.

It is quite obvious that this heavy-duty, gear-type universal joint is a more expensive method of driving a progressing cavity pump than the original ball and pin joint. It is also more difficult to assemble or disassemble than the ball and pin joint. Both drive methods are readily available, but they are designed to serve different duty cycles. If the duty is relatively light or intermittent, the ball and pin joint may provide adequate service and satisfactory maintenance expense. The gear joint, on the other hand, is designed to operate without maintenance for much longer periods of time. Experience over the last thirty years has proven that this design advantage is being realized. Continuous duty life without maintenance extending over several years has been well documented at Robbins & Myers.

Flexible Rod Method of Drive

Another method of driving industrial progressing cavity pump elements that has shown some semblance of usage over time is the flexible shaft (Figure 10). To eliminate stress concentrations, the flexible shaft must be extremely uniform in diameter, smooth over its full length and terminate in smoothly radiused rigid joint connections. With the forces imposed by the bending of the rod, any slip fit connection would be subject to fretting and make disassembly impossible. Taper fits that are tightened to eliminate any clearances in the connections are commonly used, but any method that eliminates clearances between the rod head and driver/rotor in operation is acceptable.

Figure 10. Flexible Shaft

Since the drive side of the progressing cavity pump necessitates a drive shaft stuffing box, the discharge is usually the opposite end. The differential then puts the flexible rod normally under compression. The flexible rod design then walks the tightrope between a design stiff enough to resist excessive buckling due to thrust, and flexible enough to bend through the necessary eccentric path without adding undue side forces on the stator and drive shaft.

The forces that exist in a flexible connecting rod are as follows:

(a) Forces due to bending moment (eccentric path)

(b) Forces due to the interaction of torsion and bending
(c) Thrust forces due to compression (or tension)

(d) Centrifugal force

Since the side force due to bending is opposed to the centrifugal force, at a particular speed and pressure these forces will balance. Note, however, that since centrifugal forces are a function of speed squared while bending force is a constant, this situation of balance exists at a single point only which makes it a somewhat insignificant factor.

A flexible rod properly designed must be operated under design or lower-than-design conditions. Under no conditions must the rod be strained beyond its elastic limit. If no instantaneous overload protection is provided, an inadvertently closed valve or plugged discharge will produce a relatively large corkscrew out of the flexible rod, the diameter of which equates to the inside of the suction housing.

The secret to a successful long-life flexible shaft is the consistency of the material and the lack of any stress points such as machining grooves or corrosion pits. Rods should be made of materials resistant to the corrosion of the pumping environment or coated with a corrosion-resistant plastic. The use of a Titanium alloy with lower modulus allows a shorter design with excellent corrosion resistance. This development in the early 1980s was documented with a patent by Baker Hughes for use in their down-hole progressing cavity drill motors. Drill motors operate with the flexible rod in compression similar to the normal industrial pump applications, so results are applicable.

A flexible rod designed to operate under tension only is a less complicated device since buckling is not a consideration. Oilfield down-hole progressing cavity pumps use the flexing of a sucker rod drive to satisfy the eccentric movement necessary. Centralizers are used higher in the drive string to prevent the rod from rubbing against the tubing due to well deviation or centrifugal force. Manually operated down-hole progressing cavity water pumps have also used the drive rod to transmit the torque eccentrically for decades. Given enough drive rod length, obviously there is no need for universal joints.

Therein lies one of the disadvantage of the flexible shaft. It make an already long pump longer. As mentioned previously, the use of special alloys such as Titanium can shorten the length but the flexible shaft design still results in the longest overall pump length of the more popular drives for progressing cavity pumps.

Various Other Methods of Progressing Cavity Pump Drive Configurations

Cardan-Type Universal Joint

Close-coupled joints of this type have been used for smaller, light-duty progressing cavity pumps since the 1950s (Figure 11).

Since forces are transmitted through surfaces rather than the line contact of the original ball and pin joint, lubrication type and amount and the sealing thereof is very important. Little protection of the rubber cover from tramp metal, etc., is afforded the cover as shielding is difficult. For heavier loads, the universal joint becomes relatively bulky and expensive. It is primarily used, therefore, on clear fluids and lighter loads.

Wobble Stators

In the early 1950s, Robbins & Myers patented a device that eliminated the need for universal joints in progressing cavity pumps (Figure 12). By mounting the stator in an integral elastomeric skirt, this design allowed the stator to move through the eccentric motion while directly driving the rotor on center. Design of the skirt — its shape, mounting and housing — evolved from the original Robbins & Myers patent to a design of a progressing cavity pump capable of pressures up to 200 psi. Limited to smaller capacities for the most part, millions of these pumps have been used in a variety of applications.

Rubber Universal Joints

During the critical days of the mid-1950s at the renowned Y12 plant in Oakridge, the ball and pin joints in several hundred large progressing cavity pumps, operating continuously, were replaced by joints that allowed the one degree eccentric action through rubber compression (Figure 13). The classified fluid was one that defied any form of lubrication and embrittled hardened parts. Hence the continuous duty of the conventional ball and pin joints begged for a more dependable solution and the rubber joints served the purpose for this application.
Oldham Coupling

The Oldham or sliding block coupling (modified to take thrust in either direction) seems at first glance to be an ideal drive for progressing cavity pumps (Figure 14). Since its motion allows it to take the place of two universal joints, it would shorten considerably the overall length of an inherently long pump. Thrust and torque loads are transmitted through surfaces as opposed to the line contact of ball and pin joints. However, these two advantages add up to a huge disadvantage. The fact that the coupling goes through the full eccentricity in a very short length means that the sealing device goes through extreme flexing. The fact that the loads are transmitted through surfaces, as previously mentioned, means that proper lubrication and the sealing thereof is paramount. The irregularity of the sliding block surfaces and its constant movement negates the potential of physical backing of the elastomeric seal. Unless the modified Oldham is used on a pump for lubricating oil where a seal is not needed, no practical solution to seal design limits the value of this device.

Figure 14. Modified Oldham Coupling

Lobe-Type Universal Joint

In the mid-1950s, a well driller from Indiana (Wallace Clark) patented the use of progressing cavity elements as a drilling mud-driven hydraulic motor to power the drill bits down hole (as opposed to turning the drill bit through the drill stem with a rotary table on the surface). Today, with the dominance of directional and horizontal drilling, this device is heavily used worldwide. The first mud motor prototypes were made by Robbins & Myers utilizing the conventional ball and pin-type universal joints. The heavy thrust loads, the abrasive drilling mud and the very limited space available within the hollow drill stem quickly showed the deficiencies of the ball and pin joint in this application.

In 1967, Robbins & Myers patented an apparatus that cut lobe shapes in tubing somewhat similar in configuration to the spinal column that was capable of taking both the thrust and the torque and would do so within the limited inner diameters of the drill stem. Later, a thrust ball was added internally for additional thrust capacity. Although some mud motor manufacturers presently are using other methods of universal drive, the lobe-type universal joint (Figure 15) was the dominant method of drive for mud motors for the first three decades of heavy market penetration and growth.

Figure 15. Lobe-Type Universal Joint

Flexible Shafting

Progressing cavity pump elements have also been driven eccentrically by various other methods of flexible shafting other than the solid bar. Rubber covered flexible wire cable has been used, as well as both fabric and wire-reinforced rubber hose for lighter-duty, unidirectional applications. The cables or hose are usually in tension and the lay of the cable has to be such that it is tightened rather than unwound by the direction of rotation.

Summary

Substantial development effort and funding have been spent worldwide on improvements to one of the greatest inventions in the positive displacement pump field — the progressing cavity pump developed by Dr. Rene Moineau over 60 years ago. Although elastomeric development for the progressing cavity pump stator and improved abrasion-resistant rotor materials have received a fair share of this effort, the method of eccentrically driving the progressing cavity elements has dominated improvement efforts at Robbins & Myers and will continue to do so.

Due to its ease of assembly and lower cost, the ball and pin-type universal joint first utilized by Dr. Moineau is still the most widely used method of drive. Bushing these universal joints not only adds to the cost, but detracts from performance. Drilling the connecting rods or bushing holes in an hourglass shape as opposed to the original angular slotting also detracts from performance.

The geared type universal joint is by far the most rugged device presently on the market and offers long service life with minimal maintenance. This advantage is partially offset by the more complex assembly and higher cost, but with several years of maintenance-free, continuous-duty operation documented, the total cost of ownership remains very low.

Other methods of eccentrically driving progressing cavity elements may prove superior on a specific application, but are more limited than the universally applied light-duty ball and pin joint and the heavy-duty gear-type universal joint. Careful consideration should be given to selecting the best type of drive for the application. Consider only those manufacturers offering a full range of drive configurations with the application experience necessary to select the proper drive for your application.

About the Author:

J. David Bourke is a retired vice president and general manager of Moyno Oilfield Products, and technical director of Moyno, Inc., both units of Robbins & Myers, Inc. He began his career at Robbins & Myers in 1949 and served the company for 45 years before his retirement in 1994. Mr. Bourke is a graduate of the University of Dayton with a bachelor’s degree in Electrical Engineering.