A NEW UNIQUE HIGH-PRESSURE PUMP SYSTEM

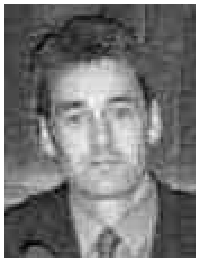
by
Thomas L. Angle
Director, Engineering and R&D
James G. Shaw
Manager R&D Engineering
Weir Specialty Pumps
Salt Lake City, Utah
Steve Cummins
Principal Development Engineer
and
Mike Turner
Engineering Manager
Switched Reluctance Drives Ltd.
Harrogate, United Kingdom

Thomas L. Angle is the Director of Engineering and R&D for Weir Specialty Pumps, in Salt Lake City, Utah. During his 30 years with the company he has held a number of positions in Engineering. He is involved in resolving mechanical and hydraulic issues for end users all over the US and the world. Mr. Angle serves on a number of committees in the Hydraulic Institute, and he has coauthored several published articles on pumps. He is a member of the International Pump Standards Committee test group working to harmonize the Hydraulic Institute and EUROPUMP test requirements. Mr. Angle is certified by the US Department of Energy as a Qualified Pump System Specialist and as a Qualified PSAT (Pumping System Assessment Tool) Instructor.

Mr. Angle received his B.S. and M.S. degrees from the University of California at Davis. He is a Registered Professional Engineer (Mechanical) in the State of California.

James G. Shaw is the Manager of R&D Engineering for Weir Specialty Pumps, in Salt Lake City, Utah. During his 21 years with the company, he has been involved in the research and development of electric submersible motors, sealing systems for down hole oil well equipment, chopper pumps, the development of the improved Pitot tube pump, and the VSR pump system. Mr. Shaw has been granted two patents with several pending. As a Product Engineer at Sta-Rite Industries, in Delavan, Wisconsin, he had design and support responsibility for the multistage submersible pump product line.

Mr. Shaw received a B.S. degree (Mechanical Engineering, 1977) from the University of Cincinnati.



Steve Cummins is Principal Development Engineer with Switched Reluctance Drives Ltd., in Harrogate, United Kingdom. He is involved with the development of drives and motors for industrial applications, most recently within the pumping industry. From 1994 to 2001, he was with the Technology Partnership in Cambridge, UK. During this time he was involved in the development of a variety of electronics products for the commercial and light industrial sector, including: radio transceivers, gas detection equipment, and low-cost printing solutions. From 1991 to 1994 he was with the British Antarctic Survey in Antarctica where he was involved in a combined role involving the installation and maintenance of scientific equipment as well as year-round meteorological observations.

Mr. Cummins has a BEng degree in Electrical and Electronics Engineering from Brunel University in the United Kingdom.

ABSTRACT

The combination of a 16 inch Pitot tube pump with a switched reluctance motor represents a significant development in the field of high-pressure pumping. A field proven Pitot tube pump design has been mechanically integrated with a high performance switched reluctance motor. The resulting system is approximately 40 percent of the size of the standard unit it replaces. The close-coupled pump eliminates the need for a gearbox, two couplings, and field alignment. The unit is able to utilize software within the controller to monitor loading on the pump. The first unit to be installed has been in continuous service at a Yorkshire, United Kingdom, power station for over one year.

INTRODUCTION

Several years ago it became apparent that the marketplace was beginning to develop a requirement for a compact, energy efficient, high-pressure pump with greater operational flexibility. This would be difficult to meet with a conventional rotating case Pitot tube pump unit. By its very nature a rotating case Pitot tube pump assembly tends to be quite long. This is because the typical operating speeds of this type of pump are in general higher than the synchronous speed of a two-pole induction motor operating at either 50 or 60 Hz. This in turn leads to the requirement of using a speed-increasing gearbox, resulting in a very lengthy assembly.

In addition to the three major mechanical components (pump, gearbox, and motor) present, two couplings and coupling guards are needed. In addition, this unit requires field alignment for each coupling as well as requiring a substantial and expensive base. Another disadvantage of using a gearbox as a speed increaser is that it increases the pump inertia reflected back to the motor by the square of the gear ratio. This increases the apparent torque requirement that the motor sees during startup, which lengthens the time it takes for the pump to ramp up to full speed.

After a considerable amount of study it was determined that a direct drive design that eliminated the speed increaser would provide significant benefits by significantly reducing the mechanical components. Furthermore it was realized that a close-coupled design would provide very significant benefits over simply using a high-speed motor coupled to a conventional pump.

A switched reluctance motor was chosen as the drive for this system for its design flexibility and its ability to vary its operating speed up to 5400 rpm. The advantages to using switched reluctance motors include high motor-drive efficiency and reliability, low overall system cost, and increased performance. These motors have control characteristics similar to electronically commutated direct current (DC) motors and operate in a variety of applications, specifically where horsepower to weight ratios, size, and overall ruggedness are critical. Unlike DC motors switched reluctance motors use rotors made entirely of laminated iron, allowing the high speeds required with relatively low motor rotor stresses. Electromotive force, which is produced by sequencing the phase windings with electronically controlled magnetic stator fields, propels the rotor. These motors are characterized by high starting torque and better acceleration rates than comparably sized alternating current (AC) motors. High starting torque is particularly important to a Pitot tube pump because the rotational inertia of this type of pump is quite large in relation to the power employed.

One of the most important factors in choosing this technology is that switched reluctance motors can be specially built in any housing and utilize any required shaft and bearing arrangement. This allowed the housing and shaft to be designed for the required dynamic characteristics and the bearings to be selected to handle the loads that will be imposed by the pump. This would not be possible with standard off the shelf AC motors.

A pump hydraulics expert was called in to review the present design of the Pitot tube and the fluid passageways in the rotating case in an effort to improve the overall efficiency of the Pitot tube pump. After the review, changes were made to the passageways in both the Pitot tubes and in the rotating case. The outside surface of the Pitot tube was also changed. These changes resulted in an increased pump efficiency gain of up to eight efficiency points. Approximately 60 percent of the efficiency increase was due to reducing friction in the Pitot tube interior passage. Another 30 to 35 percent was due to optimizing the impeller (rotating case) design. The remainder was due to changes in the exterior surface of the Pitot tube.

The decision to move to a close-coupled pump design with a high-speed motor required that the rotating case be capable of operating the entire speed range of the motor. Several computer simulations of the rotating case under varied operating conditions were performed. These simulations were used to redesign both components of the rotating case to allow increased operating speeds up to 5400 rpm with standard casing material of ductile iron and 316 stainless steel.

To understand this unique pump, it is first necessary to understand the technology of the rotating case Pitot tube pump and that of switched reluctance systems.

PITOT TUBE PUMP TECHNOLOGY

Description

The Pitot pump is a variation of the centrifugal pump design. It uses a closed casing that is attached to and rotates with the impeller while a stationary Pitot tube captures the discharge flow (Figure 1). The inlet of the Pitot tube is positioned near the maximum inner diameter of the casing as shown in Figure 1. The fluid enters the rotating casing along the axis of rotation and picks up momentum as it passes through the radial vanes of the impeller and into the casing. The liquid maintains its velocity at nearly the rotational speed of the casing. It then impacts the inlet orifice of the Pitot tube near the periphery of the rotating casing. (This is where the pressure and rotational velocity of the fluid mass are greatest.)

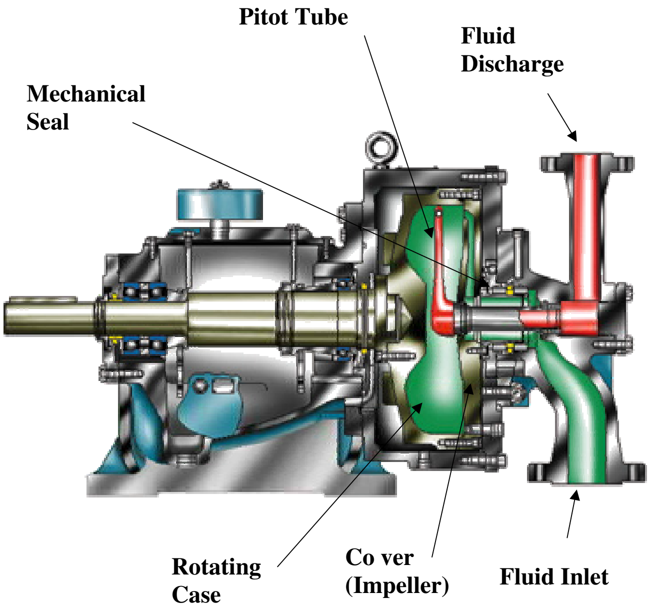


Figure 1. Rotating Case Pitot Tube Pump.

The fluid is then discharged through the internal passageway of the Pitot tube and out of the pump. The total head developed by this type of pump is the sum of both the static pressure head created by the centrifugal force and the velocity head. This sum is equal to approximately 1.6 times the head produced by a conventional centrifugal pump of the same size and speed. Figure 2 shows the overall view of the pump.

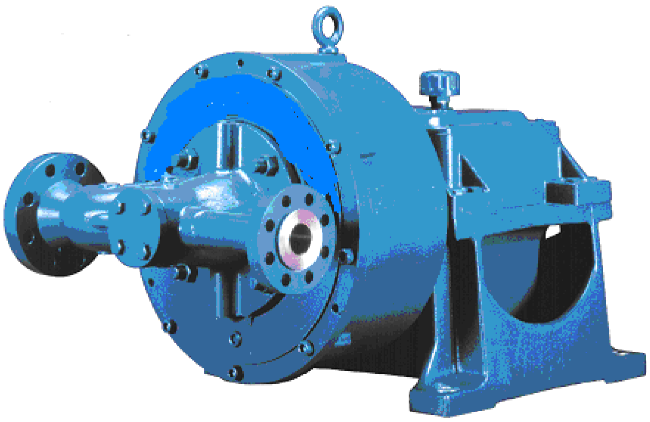


Figure 2. Overall View of Pitot Tube Pump.

There is a significant difference between a rotating casing Pitot pump and a conventional centrifugal pump regarding internal friction.

A centrifugal pump that has an impeller size in the same range as a Pitot pump will be limited in its practical rotation speed due to the effects of disc friction. The amount of energy lost to overcome the disc friction between the rotating impeller shroud and the walls of the stationary casing grows at approximately the fifth power of the impeller diameter. This is why centrifugal pumps designed for the same flow and head as Pitot pumps typically have very small impellers and operate at very high speeds, often above 25,000 rpm.

In the Pitot pump the fluid is rotating at nearly the same speed as the rotating casing, thus the disc friction losses are low. The only hydraulic frictional effects that take place inside the rotor at the full fluid velocity are those between the fluid and the relatively small outside surface of the Pitot tube assembly.

It is the combination of a more effective conversion of velocity head into pressure and minimal friction loss that allows the Pitot pump to develop high heads at moderately high speeds with good efficiencies.

Typical Performance

There are two methods of changing the performance characteristics of the pump. The first is to change the size of the Pitot tube in the pump. This changes the capacity characteristics of the pump. The second method is to change the speed at which the pump is operated. In order to represent both of these methods, a typical performance curve is generated for each size of Pitot tube with a series of head and horsepower curves for each of the common operating speeds. A typical performance curve for a single size Pitot tube is shown in Figure 3.

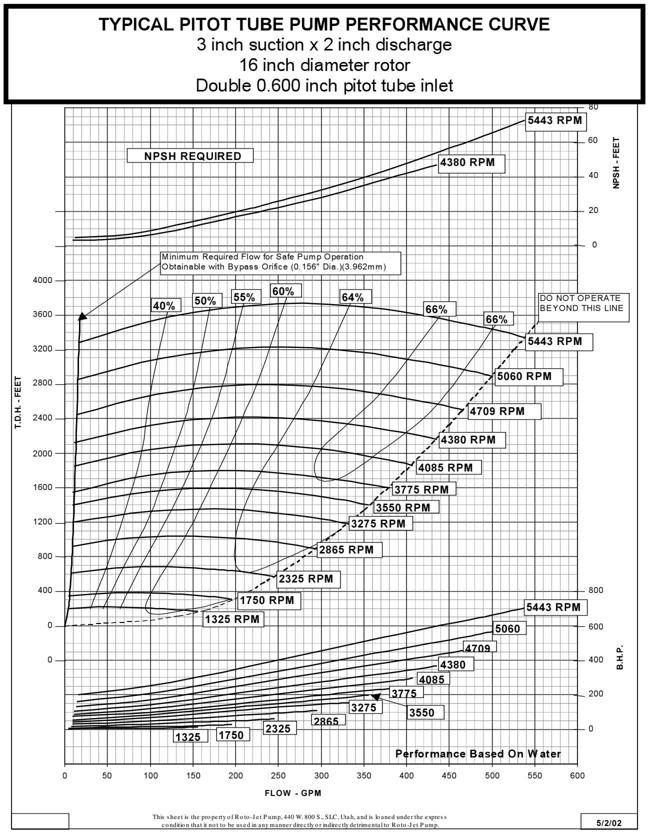


Figure 3. Performance Curve.

KEY FEATURES OF THE PITOT PUMP

Wide Operating Range

A Pitot pump can be safely operated at any point along its head/capacity curve, from full flow to shutoff. The pump can be operated at minimum flow indefinitely, with no wear or damage to the pump.

Only a small amount of flow is required by this pump to keep the seal faces cool and to keep the fluid in the pump from overheating and vaporizing. The amount needed to do this ranges from 10 percent to 15 percent of the best efficiency point (BEP) flow rate for the pump.

Simple Capacity Change

Changing the Pitot tube can easily modify the head capacity characteristic of the pump. This feature maximizes the standardization of pumps. Pitot tubes are available in several sizes and with either one or two inlets.

High Head at Low Speeds

The unique hydraulics of a Pitot pump allows it to produce very high heads at moderately high operating speeds. It can develop approximately 1.6 times the head of a conventional centrifugal pump having the same impeller diameter operating at the same speed.

Low and Stable Hydraulic Loads

The axial load on a Pitot pump is primarily related to the suction pressure and is relatively low and not significantly affected by changes in pump discharge pressure, flow rate, or speed. The radial load is also relatively low, independent of flow rate, and is primarily a function of pump speed and Pitot tube size. These load characteristics allow pump operation anywhere on the head/capacity curve without detrimental effects to bearing life.

Dry Run

A Pitot pump may incur only minor damage if run dry due to loss of suction. For example, a single seal pump will have damage to the seal faces caused by excessive heat. A double seal pump may not have any seal damage at all. The Pitot pump does not rely on the fluid being pumped for lubrication, except for the seal faces of a single seal.

Mechanical Seal Life

The mechanical seal is located on the suction side of the pump, which means it operates on relatively low pressure fluid (refer to Figure 1).

SWITCHED RELUCTANCE TECHNOLOGY

History

The switched reluctance motor operates on the principle that a magnetically salient rotor develops torque so as to move toward a position of minimum opposition to the flow of flux in a magnetic circuit. The phenomenon has been known ever since the first experiments on electromagnetism. In the first half of the 19th century, scientists all over the world were experimenting with this effect to produce continuous electrical motion. In 1838, W. H. Taylor obtained a patent for an electromagnetic motor in the United States and subsequently on 2nd May 1840 he was granted a patent (Taylor, 1840) in England for the same motor. The motor was composed of a wooden wheel on the surface of which were mounted seven pieces of soft iron equally spaced around the periphery. The wheel rotated freely in a framework in which four electromagnets were mounted. The electromagnets were connected to a battery through a mechanical switching arrangement on the shaft of the wheel such that excitation of an electromagnet would attract the nearest piece of soft iron, turning the wheel and energizing the next electromagnet in the sequence to continue the motion. However this motor and other subsequent similar inventions all suffered from problems of mechanically switching the inductive circuits of the electromagnets, and were soon superseded by the invention of the DC machine and the AC induction machine.

Over 140 years after these early experiments, the advent of suitable power electronic switches has meant that an electronic switch can replace the mechanical commutator of the early reluctance motors. Improved magnetic materials and advances in machine design have brought the switched reluctance motor into the variable speed drive market (Lawrenson, et al., 1980; Miller, 1988). The simple brushless construction of the motor offers low-cost construction and reliable operation. The unipolar current requirement of the phase windings results in a simple and very reliable power converter circuit.

Basic Principle of the Switched Reluctance Motor

Like the stepper motor, the switched reluctance motor (SRM) produces torque through the magnetic attraction that occurs between stator electromagnets (formed by winding coils on salient poles) and a corresponding set of salient poles formed on a simple rotor made only of electrical steel (or other ferromagnetic material). The stepper and switched reluctance motor share the same basic principle of energy conversion, and both are members of the family of "variable reluctance" motors.

The intuitively straightforward principle of torque production is easily visualized in the very simple reluctance motor illustrated, in cross-section, in Figure 4.

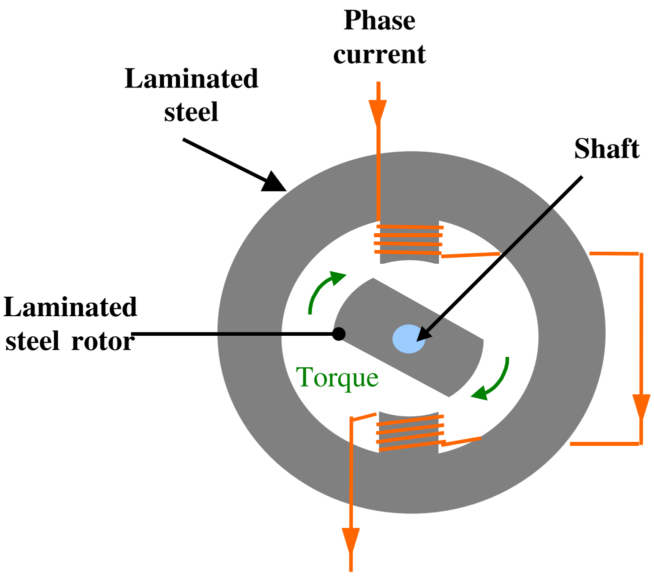


Figure 4. Simple "2/2" Reluctance Motor.

The motor sketched in Figure 4 would commonly be referred to as having a "2/2" pole structure, the two numbers referring to the number of stator and rotor poles, respectively. Intuitively, it will be seen that if current is passed through the stator windings, with the rotor position as shown above, then the rotor will experience a clockwise torque—as indicated by the arrows. Note that, since no permanent magnets are involved, the polarity of the phase current is immaterial.

If the rotor (and any associated mechanical load) is free to move, this torque will cause the rotor to accelerate clockwise. Torque will continue to be produced in a clockwise sense until the rotor reaches the fully aligned position shown in Figure 5. The fully aligned rotor position is sometimes referred to as "top dead center" by analogy with the internal combustion engine.

At top dead center (TDC), the magnetic circuit—completed by the rotor—offers minimal opposition to magnetic flux. This "opposition" is known as the magnetic circuit's *reluctance*, and is analogous to resistance in an electrical circuit. Hence at TDC, the phase reluctance is at a minimum. This means that, for a given value of phase current, the magnetic flux linked by the windings is maximized, and therefore the phase's electrical inductance—defined as flux linkage per unit current—is at its maximum value.

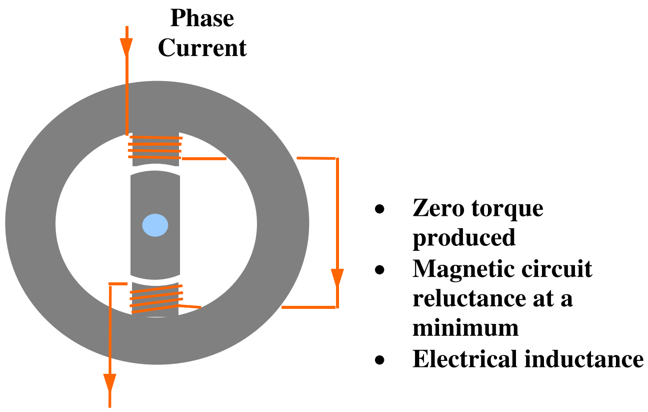


Figure 5. Rotor at Top Dead Center.

Assuming mechanical self-inertia carries the rotor past TDC, it can be seen that the polarity of torque produced by the motor will reverse if the phase windings continue to be energized beyond the fully aligned position (Figure 6).

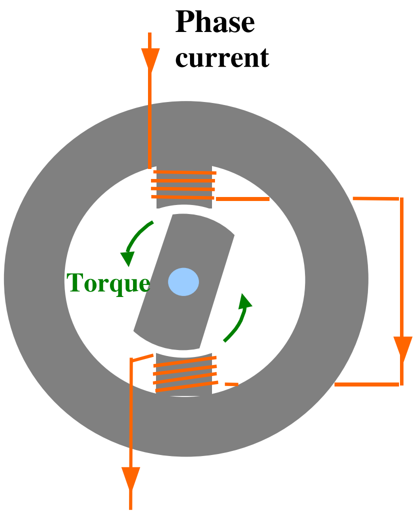
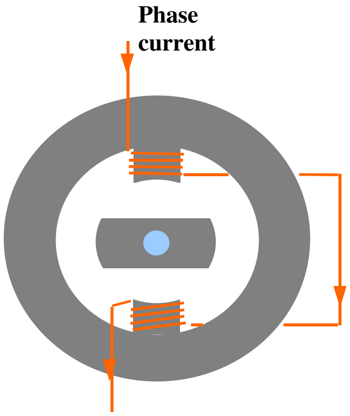


Figure 6. Torque Reversal Beyond TDC.

Although the rotor is still turning clockwise under its angular momentum, the torque is now applied in a counterclockwise sense, and will first reduce the rotor's clockwise angular velocity, and eventually may—depending on the initial rotor speed and the total moment of inertia—cause it to reverse.

Thus the polarity of torque can be reversed, and braking (i.e., generating) can be accomplished without reversing the phase current, and in spite of the fact that the machine has no magnets or windings on its rotor. When braking or generating, mechanical work performed on the rotor is converted into energy in the magnetic circuit, which can then be recovered as electrical energy to the power supply by means of the phase winding.

If the rotor turns still further clockwise, it will eventually reach a second position of zero torque, this time when its poles are fully unaligned with respect to the stator poles. Qualitatively, it may be said the clockwise and counterclockwise forces now balance each other out, and the net torque is zero. The fully unaligned position is commonly referred to as "bottom dead center" (or BDC), as illustrated in Figure 7. In contrast with Figure 5, the magnetic circuit's reluctance is now clearly at its maximum possible value, while the electrical inductance of the phase is correspondingly at a minimum.



- **Zero torque produced**
- **Magnetic circuit reluctance at a maximum**
- **Electrical inductance at a minimum.**

Figure 7. Rotor at Bottom Dead Center.

Operation as a Motor

Motoring operation of the SRM requires that the torque generated by the machine acts in the same sense as the *actual* direction of rotation. In other words, the torque should be of a polarity, i.e., direction, such that it enforces the present direction of rotation.

Through study of Figures 4 to 7, it can be seen that, to operate the machine as a motor, the winding of the machine only should be energized while the rotor and stator poles are approaching each other. In other words, ideally, current will be present in a motor phase only while the magnetic circuit reluctance of that phase is decreasing—or equivalently, while the phase's electrical inductance is increasing—with respect to time.

By way of illustration, let us assume rotation in a clockwise direction is required, starting with the rotor positioned as shown in Figure 4. Then, the phase winding should be energized until the rotor reaches TDC (Figure 5) when the phase current must be switched off. The rotor will then coast beyond TDC under its own self-inertia (Figure 6), until it reaches BDC (Figure 7). The phase can then be switched on again and the whole cycle repeated. If the phase current—or to be strictly correct, the magnetic flux associated with it—is allowed to persist to some extent beyond TDC, anticlockwise torque will be produced while the flux is present and while the reluctance is increasing. This will reduce the average motoring torque produced by the machine over a cycle of operation.

Note that this simple machine will operate equally well as a motor in either direction of rotation, simply by ensuring the phase current is present over the appropriate range of angular rotor position.

Polyphase SR Machines

The simple single-phase machine discussed so far is capable of producing torque over only half of its electrical cycle (which, for the 2/2 pole structure, repeats twice per revolution). Motoring—or, for that matter braking—torque from such a machine will necessarily be discontinuous, and hence starting in the desired direction is not possible from all rotor positions. Single-phase motor starting can be ensured by, e.g., including a small "parking magnet" within the machine, positioned such that the rotor always comes to rest in a torque-productive position. These limitations are acceptable for some applications, and the single-phase SR motor is especially useful for low-cost high-speed applications such as vacuum cleaner fans.

More demanding applications use higher rotor and stator pole counts, with the stator poles wound and connected into two or more identical phases. Figure 8 illustrates, for example, the cross-section of a three-phase "6/4" machine. Here, diametrically opposed coils are connected together to form three phase circuits, here denoted as phases A, B, and C.

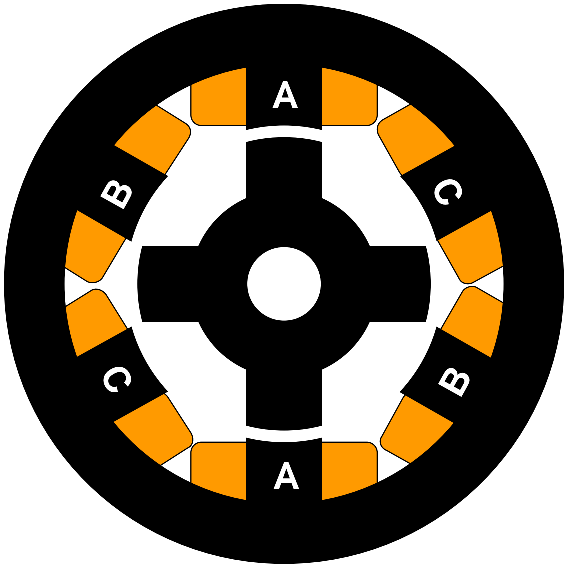


Figure 8. Cross-Section of Three Phase 6/4 SRM.

The excitation of the phases (here three in number) is interleaved equally throughout the electrical period of the machine. (In other words, the phases are spaced at ($360/n_{ph}$) electrical degrees, where n_{ph} is the total number of phases, and 360 electrical degrees is defined as the mechanical period of the phase inductance. For example, in the case of the four-pole rotor shown in Figure 8, 360 electrical degrees correspond to 90 mechanical degrees.) This means that torque of the desired polarity can be produced continuously, thus greatly reducing the instantaneous variation in output torque with respect to rotor angle (the "torque ripple"). Furthermore, machines with more than two phases are able to start in either direction without special measures. The number of phases can in theory be increased without limit, but phase counts from one to four inclusive are the most common for commercial and industrial applications.

Increasing the phase number brings the advantages of smoother torque and, for three phases or more, self-starting in either direction. It also increases the complexity of the motor, the associated power electronics, and signal level control circuits.

Many different combinations of pole count are possible. It is often beneficial to use more than one stator pole pair per phase, so that, for example, the 12:8 pole structure is commonly used for three-phase applications. Each phase circuit of this motor comprises four stator coils connected and energized together.

In the switched reluctance machine, the motor phase currents are always switched on and off taking into account the actual rotor position, i.e., it is a "self-synchronous" machine. This is what really distinguishes it from the stepper motor, and gives the machine its name—it is a (variable) reluctance motor whose phases are commutated, or "switched," in synchronism with the rotor position. The stepper motor, by contrast, relies on a magnetic field rotating at a predetermined speed, regardless of the rotor position, and the phase flux must always be high enough to ensure the rotor follows the field pattern. If the torque is too high to permit this, the rotor loses synchronism with the field and the machine will rapidly stall.

Two-Phase SR Motors for Centrifugal Pumps

Centrifugal pumps require operation in one direction of rotation only, and furthermore, do not require large starting torque. These characteristics permit the use of a particularly economical and simple SR drive based upon a two-phase motor.

Figure 9 shows the pole structure of a simple two-phase SRM with 8/4 geometry. It will be evident that angular symmetry dictates that whenever one phase is at TDC, the other is at BDC. This means that at these positions, neither phase can produce any torque, and therefore starting from the rotor position illustrated is not possible.

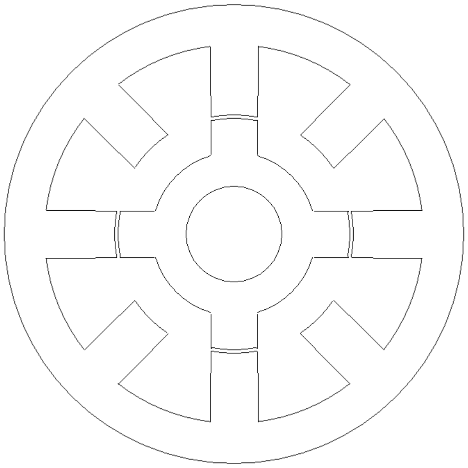


Figure 9. Pole Structure of Simple Two-Phase 8/4 SRM.

However, in the centrifugal pump application, reversibility is not required (nor is it even desirable), and this fact can be used to advantage so as to guarantee starting in a given direction. Figure 10 illustrates the pole structure of an improved two-phase SR motor, in which the rotor pole arc is increased beyond the 22.5 degrees of Figure 9. The additional rotor pole arc is introduced at a smaller diameter, giving rise to a "stepped air gap." This means that (in the case of Figure 10), counterclockwise rotation will result in increasing electrical inductance (i.e., falling reluctance) for *more than half an electrical cycle*, and therefore when the torque contributions from the two phases are summed, there is no rotor position at which the total torque is zero. Provided the load torque at starting—in the case of the centrifugal pump, just the static friction—is less than the minimum motor torque available at any rotor position, starting is guaranteed. Once the machine is rotating at modest speed, the total torque will be averaged by the rotor and load inertia, and the fluctuation in total "air gap torque" is unimportant.

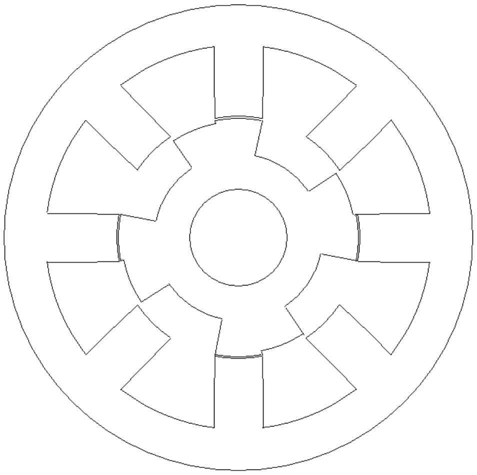


Figure 10. Pole Structure of Two-Phase SRM with Stepped Air Gap.

The two-phase motor described above has a number of advantages. It has a very simple stator requiring only four electrical connections (compared with six for a three-phase SRM or a star-delta AC motor), and needs only four power switches in its associated electronic power converter. Because the two phases are operating electrically *alternately*, a single rotor position sensor (here a simple Hall-effect switch) may be used to determine the switch-on and switch-off points for both phases. For the same reason, a single current transformer or transducer may be used to monitor and control the current in both phases. Furthermore, the low number of rotor poles and phases combine to make the frequencies "seen" in the motor's steel components relatively low, thus reducing the so-called "iron losses" (due to eddy currents and hysteresis). This in turn reduces the cooling burden and increases efficiency.

ADVANTAGES OF THE SWITCHED RELUCTANCE DRIVE

Rotor Construction

Because the rotor carries no windings, magnets, or conductors of any kind, the switched reluctance motor is well suited to high-speed operation, and is a good choice for use in harsh environments and/or at high temperatures. Heating of the rotor is confined to eddy current and hysteresis losses in the steel, and as a result, the rotor runs relatively cool in the majority of applications, enhancing bearing life.

Stator Construction

The stator is also very simple and robust, requiring only singly-pitched coils that are placed over the salient stator poles, and which can easily be prewound on a former or bobbin. The stator windings—unlike those of an induction motor—are not distributed over many slots, and the phases do not cross each other in the end-winding region. This largely eliminates the risk of a phase-to-phase insulation failure. The simplicity of the coils allows the end windings to be much shorter than those typically found in induction motors, and the losses associated with the end windings (which do not contribute to the output of the motor) are reduced. This improves efficiency and allows, if desired, the construction of relatively flat (*pancake*) motors with minimal penalty on specific output. The winding construction tends to yield a lower capacitance to the frame than a conventional AC motor, typically 20 to 30 percent less. This improves electromagnetic compatibility and reduces radio-frequency interference, because coupling of high frequency currents to the stator is somewhat reduced.

As mentioned above, with the possible exception of machines operating at very high speed and at high power, the machine losses are concentrated in the stator, which is relatively easily cooled. Thermal management of the machine is therefore relatively simple. Furthermore, the fact that the rotor heating is minimal, especially during motor stall, means that the stall endurance of the motor is limited by the thermal time constants associated with the *stator*. These are generally long, due to the large stator mass, and the SRM performs very well under conditions of prolonged stall.

By way of a summary, some of these key machine-related advantages are illustrated in Figure 11.

ELECTRONICS AND SYSTEM-LEVEL BENEFITS

The SRM requires the use of power electronic controls for commutation and control, in many ways similar to the inverter used to vary the speed of an induction motor.

However, in contrast to the AC drive, the motor does not require sinusoidal supplies in order to operate efficiently. As a result, the power converter used with the SRM need not switch at high frequencies. This reduces switching losses in the power semiconductors at low motor speeds, and is especially useful in medium and high power (e.g., 10 kW+) drives where switching losses can otherwise be significant. To avoid tonal components in the drive's acoustic noise, it is common to use current control schemes with randomized or "spread-spectrum" switching frequencies.

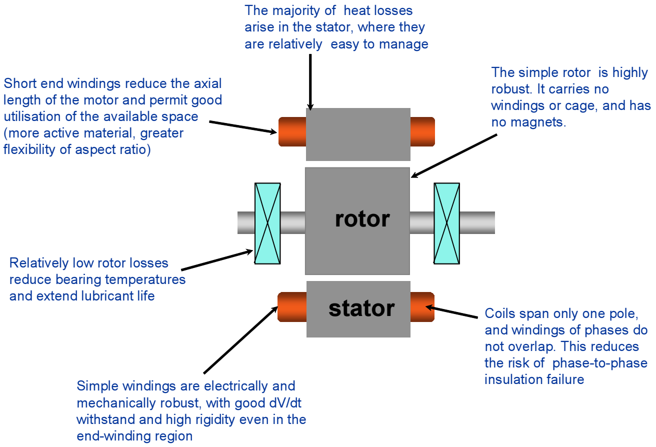


Figure 11. Key Advantages of the Switched Reluctance Machine.

At higher speeds, the power semiconductors switch on and off only *once* per electrical cycle of the machine. The switch turn-on occurs at zero current (which implies zero switching loss), while turn-off may occur at a current less than the peak phase current due to natural "rollover" of the current. The switching losses at high speeds are therefore negligible.

The relatively low electronics switching losses, combined with high torque per amp of phase current, mean that the power semiconductor ratings in the switched reluctance drive can be somewhat lower than conventional systems, with attendant cost savings.

The phases of the switched reluctance drive operate independently of each other, and in the event of a fault developing in one phase, the others are able to continue to produce torque as normal. This gives the machine a unique fault tolerance and the ability to "limp home" in the event of a partial failure. The absence of the "shoot-through" fault condition can ease protection and enhance reliability.

The switched reluctance motor is capable of yielding very high overload torque; its ability to do so is primarily limited by the thermal time constants associated with the stator windings. This high peak torque capability combined with relatively low rotor mechanical inertia (due to material being removed at the outer diameter to form the salient poles), means that very high rates of angular acceleration are possible.

Once the control parameters for a given machine have been determined, the setting up of the drive is extremely simple, and users need concern themselves only with tuning of basic speed control parameters, plus any other features incorporated by desire rather than necessity. These might include speed limits, torque limits, acceleration rates, etc. Here the switched reluctance drive is again similar to the traditional DC drive.

The torque control stability and dynamics do not depend on detailed parameters of the motor, and a good, rapid dynamic response is inherently obtained. The electrical time constants associated with the windings are generally short, and there is no need (unlike the vector-controlled induction motor) to keep the machine fully or partially fluxed when it is lightly loaded, in order to secure rapid response times. This can bring efficiency and thermal benefits, especially in applications such as servo drives that may spend much of their time lightly loaded, and operate only at full torque to skip quickly from one speed or position to another (Institution of Electrical Engineers, 2001).

DISADVANTAGES OF THE SWITCHED RELUCTANCE DRIVE

- The switched reluctance motor is not yet a standard technology; it is less well known and understood by engineers and technicians in industry.
- The motor requires four power cables and not three (though, in fairness, six would be needed for a wye-delta starting of a fixed speed motor).

Availability and Maintenance of Switched Reluctance Technology

Switched reluctance technology has been successfully incorporated by a number of original equipment manufacturers (OEMs), e.g., for air compressors and textile machinery, and as a result many thousands of high power switched reluctance motors are in service today. Lower power motors have been made in the millions, mainly for domestic and commercial washing machines, but also for use as servomotors, actuators for sliding doors, and many other diverse applications. Therefore, while it is not yet widely available for "off the shelf" use as a general purpose industrial drive, it is fair to say that switched reluctance technology already has a proven track record in industrial applications.

Some customers express concerns regarding the repair of a motor other than a standard induction motor or DC machine. These concerns are on the whole unfounded, however, and experience has shown that—because of its inherent simplicity—most rewind facilities have little or no problem in accommodating repair of the switched reluctance motor. The fact that its windings span only one stator pole means that an individual failed coil is relatively easy to remove and replace within the stator. Furthermore, this "singly-pitched" nature permits the supply of a winding repair kit, comprising a preformed coil and all necessary insulation materials. This will allow any reputable motor rewind facility to quickly and economically effect a lasting repair in the unlikely event of a failure. The simplicity of the rotor means that—short of it sustaining severe mechanical damage—it is unlikely to ever require repair.

The electronic controller utilizes a wide range of standard components and assemblies, and particular attention has been paid, in designing both the hardware and software, to facilitate fault diagnosis and service repair on-site by the pump manufacturer's service technicians. Unlike many variable frequency drives (VFDs) the controller has few parameters to set or adjust, and this, combined with attention to clear diagnostic messaging, greatly simplifies both commissioning and repair.

DEVELOPMENT OF THE VARIABLE SPEED PITOT TUBE PUMP

This novel pumping arrangement has been developed over the past three years and combines a proven fluid end design with switched reluctance technology to create a revolutionary high-pressure pump system, replacing the conventional fixed-speed induction motor and step-up gearbox drive. This style of pump has a track record in demanding and difficult high-pressure applications and the challenge was to bring to market a new system that would afford higher levels of reliability with improved efficiency, increased performance, and greater operational flexibility.

This pump combines the technology of a rotating case Pitot tube pump with a switched reluctance drive system. The unique quality of these two technologies results in a high-pressure pump that is compact, rugged, has variable speed capability, and has a wide operating range. The compactness of the design is shown in Figures 12 and 13. The overall length of a conventional Pitot tube system is between 120 inches and 168 inches as compared to 58 inches for a close-coupled system.

Close-Couple Design Alternatives

A close-coupled design was considered by using a conventional National Electrical Manufacturers Association (NEMA) or Institute of Electrical and Electronic Engineers (IEEE) motor and VFD, but this design was rejected for several reasons.

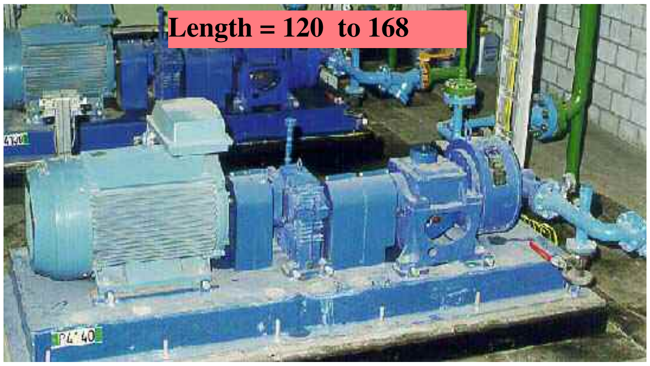


Figure 12. Conventional High Speed Pitot Tube Pump.

Figure 13. Close-Coupled Variable Speed Pitot Tube Pump Design.

- The rotor of a rotating case Pitot tube pump must, for process and efficiency reasons, be quite large. In general the shaft diameter of a conventional AC motor will not be adequate to support the rotating case of the pump.
- The bearings in a conventional AC motor will typically not have adequate thrust capacity.
- Typical operating speeds of above 4500 rpm will be marginal even for AC motors designed for 90 Hz application, due to stresses in the motor rotor.

Advantages of a Switched Reluctance Close-Coupled Design

On the other hand, the use of a switched reluctance motor with the pump in a close-coupled configuration eliminates each of the above problems.

- Because each motor is designed for the particular conditions of speed and power required, an adequate shaft could be sized and then designed into the motor as required.
- Likewise the required bearing arrangement can be specified for the motor.
- The rotor in a switched reluctance motor consists of steel laminations having no additional copper bars. Allowable operating speeds of the motor are significantly above the maximum speed of the pump.

Furthermore, a number of other advantages come with the use of a close-coupled design.

- The length of the pump assembly becomes much less as shown in Figure 13. Compare the 58 inch length of the variable speed Pitot tube pump shown in Figure 13 with a length of 120 to 168 inches for a standard Pitot tube pump assembly as shown in Figure 12. This provides a footprint comparable to that of a high speed centrifugal pump. Prior to this, a Pitot tube pump could not match a high-speed centrifugal pump from the point of view of installation space required.
- The close-coupled design eliminates the requirement of coupling guards and also eliminates two expensive and time consuming field alignment operations.
- The close-coupled design eliminates the need for a very rigid, large, and expensive base that must be grouted in place.
- There is a significant reduction in mechanical components as follows:
  - Three shafts to one.
  - Nine bearings to three.
  - Two gears to zero.
  - Two couplings to zero.
  - Four keys to one.
  - Twelve anchor bolts to four.

The switched reluctance drive system comes with inherent variable speed capability. From a life cycle cost consideration, the ability to vary the speed to meet various load conditions without using a control valve is often the single most important factor in minimizing operating expense.

Disadvantages of a Switched Reluctance Close-Coupled Design

- The switched reluctance motor is not as yet a standard technology; most motor shops are not prepared for this type of motor repair.
- This pump system is not cost competitive for applications that require heads of less than 500 psi.
- This pump system is not cost competitive for applications that do not need variable speed, unless a smaller footprint is required.
- The Pitot tube type pump has limited solids handling capability. Pump balance is a potential problem when pumping solids. If the solids come out of suspension and adhere to the walls of the pump an out-of-balance condition can occur. Abrasion is another potential problem area in a Pitot tube pump. The maximum velocity of the fluid at the inlet of the Pitot tube can be as high as 380 ft/sec. In general, when solids are present, a 100-mesh screen on the suction line of the pump is recommended when practical for the application. A number of materials have been used in various components that can reduce the abrasive wear to acceptable levels. However, given the high velocities present, the Pitot tube pump must be applied with a great deal of caution when solids are present.
- Pumping light hydrocarbons with a high vapor pressure increase with temperature change is another area where care must be used in applying a Pitot tube pump. The geometry of the pump requires the fluid to pass through the mechanical seal and along the Pitot tube extension before it gets to the eye of the impeller. This allows the fluid to absorb heat prior to entering the impeller with a corresponding increase in vapor pressure. This must not exceed the net positive suction head actual (NPSHA).
- In general a Pitot tube pump will have a relatively high net positive suction head required (NPSHR). The primary reason is that both the flows to and from the pump are in collinear tubes that must pass inside the diameter of a mechanical seal. (While other configurations are possible they have proven to be too complex mechanically for practical use.) From both seal pressure rating and economic standpoints, it is advantageous to use the smallest possible seal. Likewise the Pitot tube extension that supports the tube and through which the discharge flow must pass needs to be large enough to support the Pitot tube. These issues tend to require, for economic reasons, suction velocities (and losses) that result in higher NPSHR than a conventional centrifugal pump.

Some Design Issues

The design of the combined unit posed a number of issues and challenges from a mechanical standpoint.

- The maximum operating speed will be 5400 rpm.
- Bearings will be grease lubricated.
- Minimum bearing B10 life must be greater than 25,000 hours.

A conventional Pitot tube pump will usually have a 100 mm 15 or 25 degree spindle bearing closest to the rotating case and a pair of 40 degree angular contact bearings in a back-to-back configuration on the drive side to handle the thrust load. Generally at speeds above 4400 rpm the bearings will be oil lubricated.

Oil lubrication was ruled out to avoid viscous losses, which might otherwise arise due to the presence of oil in the motor airgap region. After considerable analysis of alternatives it was decided to use a pair of 15 degree (80 mm) spindle bearings in tandem on the drive side coupled with a single 15 degree (140 mm) spindle bearing on the rotor side. This decision was based on consultation with the bearing supplier, extensive testing, and the authors' experience with 40 degree (60 mm) angular contact grease lubricated bearings at speeds above 4500 rpm. To allow for axial expansion of the rotor, particular care was needed in designing the bearing system, and in managing heat transfer, in order to ensure the internal bearing clearances are maintained at all times. (In general the design of this close-coupled unit required much more careful attention to heat transfer and cooling than with a conventional Pitot tube pump.)

Another issue from a mechanical standpoint relates to structural natural frequencies in the machine. Typically pumps will operate at certain discrete speeds based on motor and typical drive selections. That is, a choice of speeds may be available such as 3600 rpm, 3900 rpm, 4200 rpm, etc. There can be a structural frequency between these speeds that will not be actuated that may be undetected for years. For a pump that is designed for variable speed operation this is not acceptable. All structural frequencies below about 7000 rpm had to be designed out of the unit in order to allow operation at any speed from minimum up to 5400 rpm. This analysis was performed by modeling the entire assembly using a solid modeling software program. A series of dynamic analyses using a computer software program was performed that allowed the development of a structure having the required natural frequency characteristics.

A separate program was initiated to improve the hydraulic efficiency of the Pitot tube pump. The first step was to call in a pump hydraulics expert to review the pump design. The flow passages in the Pitot tube and rotating case were then modeled using a solid modeling program. This allowed a detailed examination of the velocity profile as the fluid flows through the passageways by utilizing computational fluid dynamics (CFD) analysis. The passageways were redesigned to minimize velocity profile problems and to regulate the change in the velocity of the fluid as it passes through the passageway. The external shape of the Pitot tube was also changed to reduce the friction losses between it and the fluid in the case. These changes resulted in an increased pump efficiency gain of up to eight efficiency points. Approximately 60 percent of the efficiency increase was due to reducing friction in the Pitot tube interior passage. Another 30 to 35 percent was due to optimizing the impeller (rotating case) design. The remainder was due to changes in the exterior surface of the Pitot tube.

In conjunction with the other design projects, the structural integrity of the rotating case was put under close scrutiny. The requirement to increase the operating speed of the ductile iron and 316 stainless steel rotating case from 4400 to 5400 rpm was not taken lightly. The first step was to make a solid model of the existing rotating case. The model was transferred to a finite element analysis (FEA) program where the pump operating conditions could be simulated and the stresses in the rotating case evaluated. A baseline for the maximum allowable stress was established by simulating the maximum operating conditions at 4400 rpm. This was chosen as a conservative approach as the authors' have 20 plus years of experience operating the pumps under these conditions. The rotating case redesign was then a series of iterative steps based on the original model and simulating the maximum operating conditions at 5400 rpm. The stresses in the case were calculated by the FEA program, areas of higher than allowed stress in the case were redesigned, and the model reevaluated by the FEA program. This process was repeated until the maximum stress in the new rotating case at 5400 rpm was equal to or less than the maximum stress in the present case when maximum operating conditions were simulated at 4400 rpm.

The final design is illustrated in Figures 14 and 15. Some design analysis and verification testing data are shown in APPENDIX B.

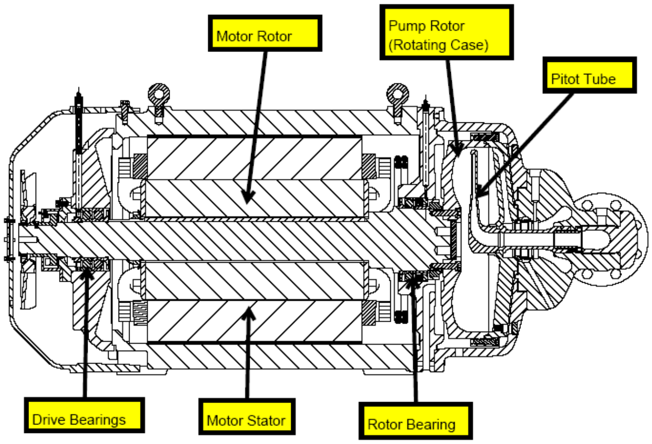


Figure 14. Variable Speed Pitot Tube Pump Cross Section.

Figure 15. Variable Speed Pitot Tube Pump Overview.

First Field-Test Unit

The first field test unit (Figure 16) was commissioned in March 2003 in a Yorkshire, United Kingdom, power station flue gas desulfurization (FGD) plant. The pump replaced a triplex piston pump, which was costing approximately $60,000 per year to maintain. Assuming a two-year seal life, annual maintenance costs for the variable speed Pitot tube pump are expected to be under $4000. The efficiency of the triplex pump is not known but a positive displacement pump will always be hydraulically more efficient than a centrifugal pump in this flow range. The cost of the new pump was on the order of $70,000.

The unit was originally specified for 31 gpm at 3684 ft, pumping potable water at 68°F. However the target flow given initially was incorrect, and the pump is now actually providing 44 gpm at 3684 ft, operating at a speed of around 5450 rpm. The pump is a 3 inch × 2 inch configuration with a 16 inch diameter rotating case.

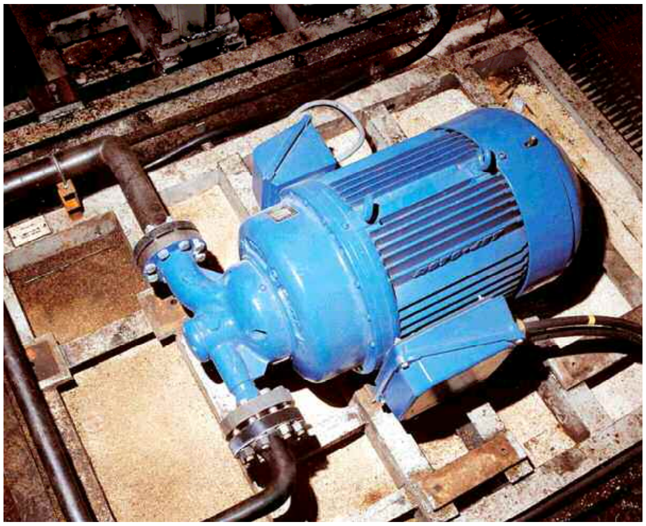


Figure 16. Variable Speed Pitot Tube Pump in Place at a Yorkshire, United Kingdom, Power Station.

The FGD process basically takes hot gas from the boiler that contains sulphur dioxide (SO_2) and drives it through the "gas/gas heater" (a heat exchanger) to lose the heat. The process creates a by-product of gypsum, particles of which attach themselves to the gas/gas heater and, after a period of time, reduce the efficiency of the process. A cleaning cycle is then run for about 12 hours per heater, without stopping the process. A total of six heaters is employed, each of which is cleaned as and when the process requires.

The cleaning is done using two hydraulically actuated lances. Each heater is 50 ft in diameter. The lances are traversed across the heater, cleaning the plates as they move.

Of particular interest in Figure 16 is the obvious compactness of the variable speed Pitot tube pump as compared to the triplex pump it replaced. The variable speed Pitot tube pump is shown mounted on the base of the triplex pump assembly.

CONCLUSIONS

The combination of a rotating case Pitot tube pump with a switched reluctance motor provides a pump that is compact, rugged, has variable speed capability, and can be operated anywhere on its curve. In many applications this pump offers a number of improvements over existing high-pressure pump technology.

Compared to other rotating case Pitot tube pumps the variable speed Pitot tube pump:

- Eliminates the requirement for a separate gearbox speed increaser.
- Eliminates two sets of couplings and their associated hardware and guards.
- Eliminates the need to field align the pump assembly.
- Eliminates the need for a rigid and expensive baseplate.
- Reduces the overall pump assembly length by over 50 percent.

From operating cost standpoint the variable speed Pitot tube pump offers a number of advantages:

- The pump comes with variable speed capability already built in.
- The electronics allow feedback control for pressure, load, or flow control.
- The controls allow for warning and/or shutdown to be implemented when parameters such as head, flow, vibration, or load deviate from allowable ranges.

APPENDIX A—
HYDRAULIC THEORY OF THE PITOT TUBE PUMP

Theory

The Pitot pump develops its head in two mechanisms, by means of both a centrifugal (static) and velocity head. The combination of these two produces the total head developed by this pump.

Centrifugal Head

If the rotating casing is considered as a cylinder filled with liquid, as it rotates there will be an internal pressure developed by the centrifugal force field according to the equation that in terms of head (feet) of liquid can be expressed as follows:

$$Hc = \frac{U^2}{2g} \qquad \text{(A-1)}$$

where:
Hc = Head (ft)
U = Rotor peripheral velocity (ft/sec) at the radius of the Pitot tube inlet
g = 32.2 ft/sec^2

Velocity Head

The maximum velocity head, Hv, developed can be calculated by the expression:

$$Hv = \frac{v^2}{2g} \qquad \text{(A-2)}$$

where:
Hv = Maximum velocity head (ft)
V = Liquid velocity (ft/sec) at the radius of the Pitot tube inlet
g = 32.2 ft/sec^2
V = U for ideal conditions (no slippage)

Theoretical Head

The theoretical (assuming no hydraulic losses) maximum head, Ht, developed by a Pitot pump is approximated by the following equation:

$$Ht = Hv + Hc \qquad \text{(A-3)}$$

where:
Ht = Total head (ft)

The equations above are not significantly different from the expressions for the theoretical (virtual) head a conventional centrifugal pump generates when operating close to zero flow and in the absence of slip and losses. However, the conversion of velocity to pressure head by the Pitot tube is much more efficient than in a conventional centrifugal pump. A centrifugal pump of similar specific speed may in practice produce an actual total head in the range of 70 to 80 percent of the virtual head. The Pitot pump can produce an actual maximum head as high as 97 percent of the virtual head.

There are some additional observations to note regarding the development of head by a Pitot pump.

- The theoretical centrifugal and velocity heads are practically equal.
- The value of Ht is determined according to equation using the rotating casing speed N to calculate the fluid velocity. In reality, there is always some slippage and the fluid will rotate at an angular velocity lower than the casing speed. The amount of slippage that takes place is a function of hydraulic friction and turbulent exchange within the rotating casing, affected by the Pitot tube drag (Spassky, 1986; Spassky and Schaumyan, 1973).

- Regarding internal friction, there is a significant difference between a rotating casing Pitot pump and a conventional centrifugal pump. A centrifugal pump that has an impeller size in the same range as a Pitot pump will be limited in its practical rotation speed due to the effects of disc friction. The amount of energy lost to overcome the disc friction between the rotating impeller shroud and the walls of the stationary casing grows at approximately the fifth power of the impeller diameter. This is why centrifugal pumps designed for the same flow and head as Pitot pumps must have very small impellers and operate at very high speeds, often above 25,000 rpm.
- In the Pitot pump the fluid is rotating at nearly the same speed as the rotating casing, thus the disc friction losses are low. The only disc frictional effects that take place at the full fluid velocity are those between the fluid and the relatively small surface of the Pitot tube.
- It is the combination of a more effective conversion of velocity head into pressure and minimal friction loss that allows the Pitot pump to develop high heads at moderate speeds with good efficiencies.

APPENDIX B—
TESTING AND ANALYSIS

Test Data

Figure B-1 is typical of the daily temperature data that were taken during several hundred hours of high speed endurance testing in the laboratory to prove out the bearing design prior to placing the first prototype in the field. Bearing temperatures were taken with a thermocouple on the bearing outer race. The rest of the data were taken with an infrared temperature sensor. The primary concern from a design standpoint was that the temperatures would be acceptable for the grease selected and that the operating temperatures would stabilize.

Table B-1 illustrates vibration data taken over a several month period under various speeds and operating conditions to prove the validity of the structural and dynamic analysis.

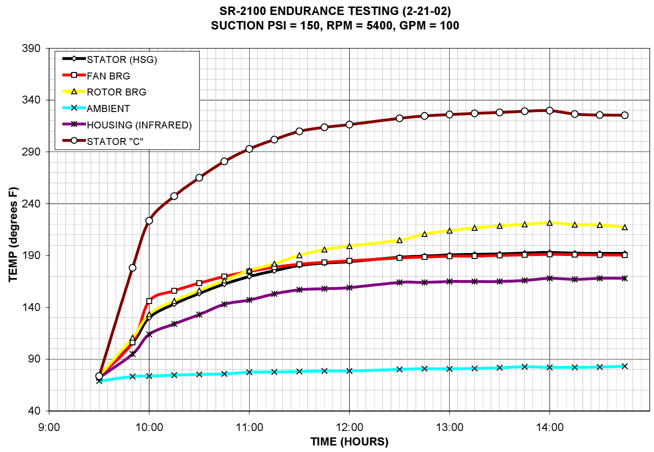


Figure B-1. Daily Log of Typical Endurance Test Run.

Table B-1. Vibration Data under Various Flow Conditions.

				Overall Vibration: in/sec peak velocity				
Date	RPM	Flow (gpm)	Suction Pressure (psi)	Fan Vertical	Fan Horizontal	Rotor Vertical	Rotor Horizontal	Axial
13-Feb	3550	70	-----	0.053	0.064	0.031	0.037	0.034
12-Feb	3550	95	-----	0.055	0.045	0.035	0.033	0.03
14-Feb	4380	90	-----	0.054	0.071	0.04	0.053	0.038
12-Feb	4380	100	-----	0.079	0.068	0.041	0.042	0.039
12-Feb	5400	70	-----	0.094	0.122	0.059	0.086	0.069
12-Feb	5400	100	-----	0.113	0.098	0.061	0.056	0.079
15-Feb	5400	100	-----	0.076	0.104	0.066	0.065	0.061
20-Feb	5400	100	100	0.072	0.138	0.036	0.121	0.081
20-Feb	5400	100	150	0.079	0.145	0.085	0.124	0.101
27-Feb	5400	10	-8	0.082	0.186	0.074	0.164	0.089

Analysis

Figure B-2 illustrates the results of the dynamic analysis that was performed on a slightly simplified model of the pump assembly. The configuration of the feet required a number of iterations to give adequate stiffness while still allowing adequate airflow over the surface for cooling purposes.

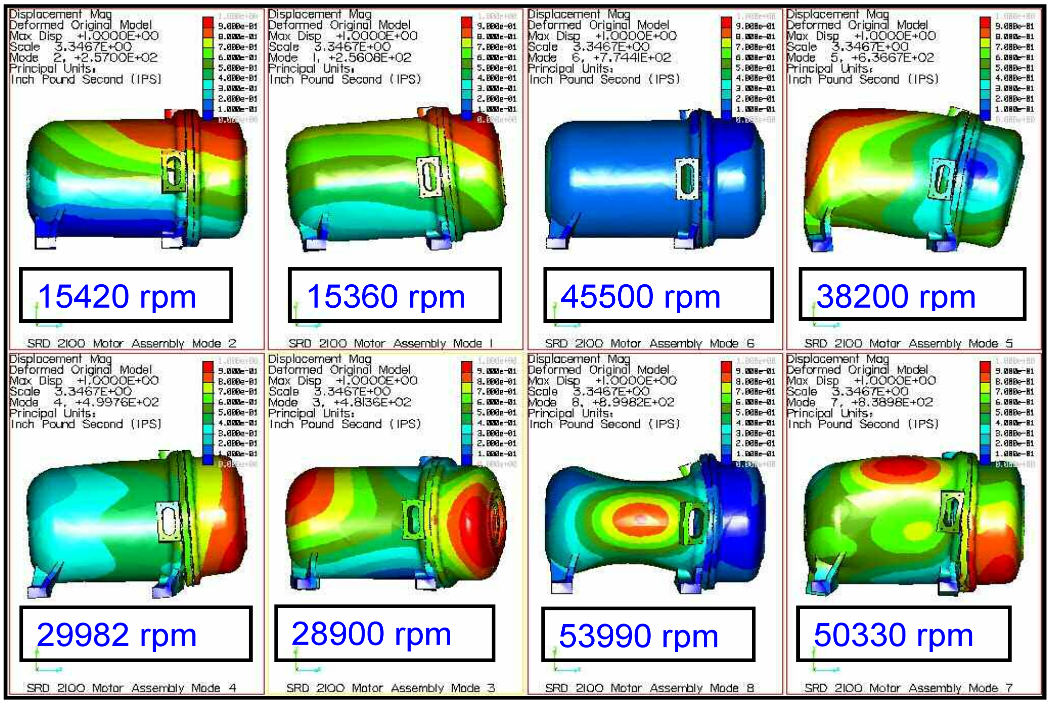


Figure B-2. Housing Dynamic Analysis Showing Deflected Mode Shapes.

Figure B-3 shows the stress in the rotor assembly under combined suction pressure, developed hydraulic pressure, and centrifugal loading.

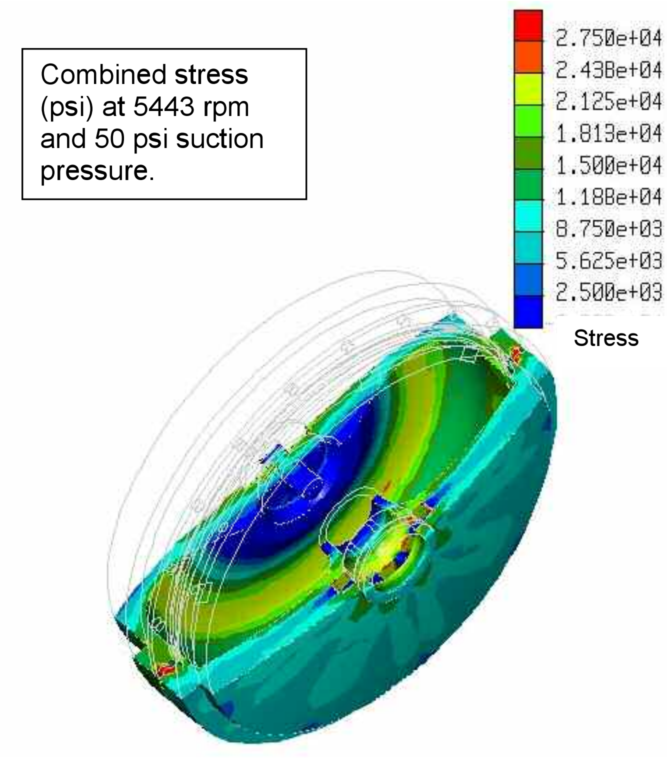


Figure B-3. Pump Rotor Stress Analyses Including Centrifugal and Pressure Loading.

Figure B-4 shows the calculated first four modes of vibration in the shaft and rotor assembly.

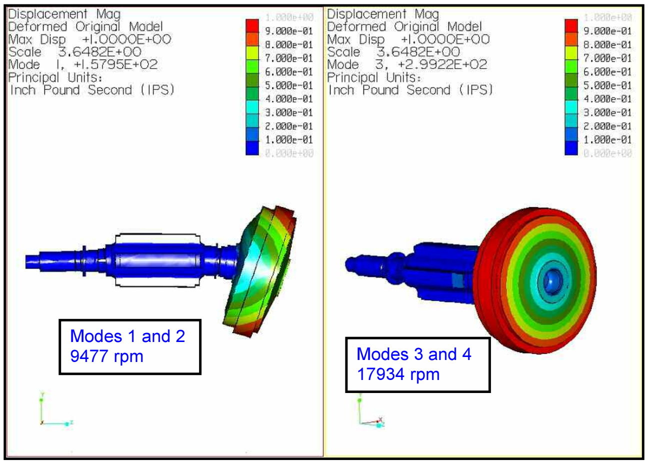


Figure B-4. Rotor and Shaft Dynamic Analysis Showing Deflected Mode Shapes.

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