EXPERIMENTAL METHODS

SYSTEM DRIVES

ELECTRIC MOTORS

PREAMBLE

No attempt is made to give detailed mathematical analysis of any motor. That is beyond the scope of this note. The focus is on types of motors and how they work.

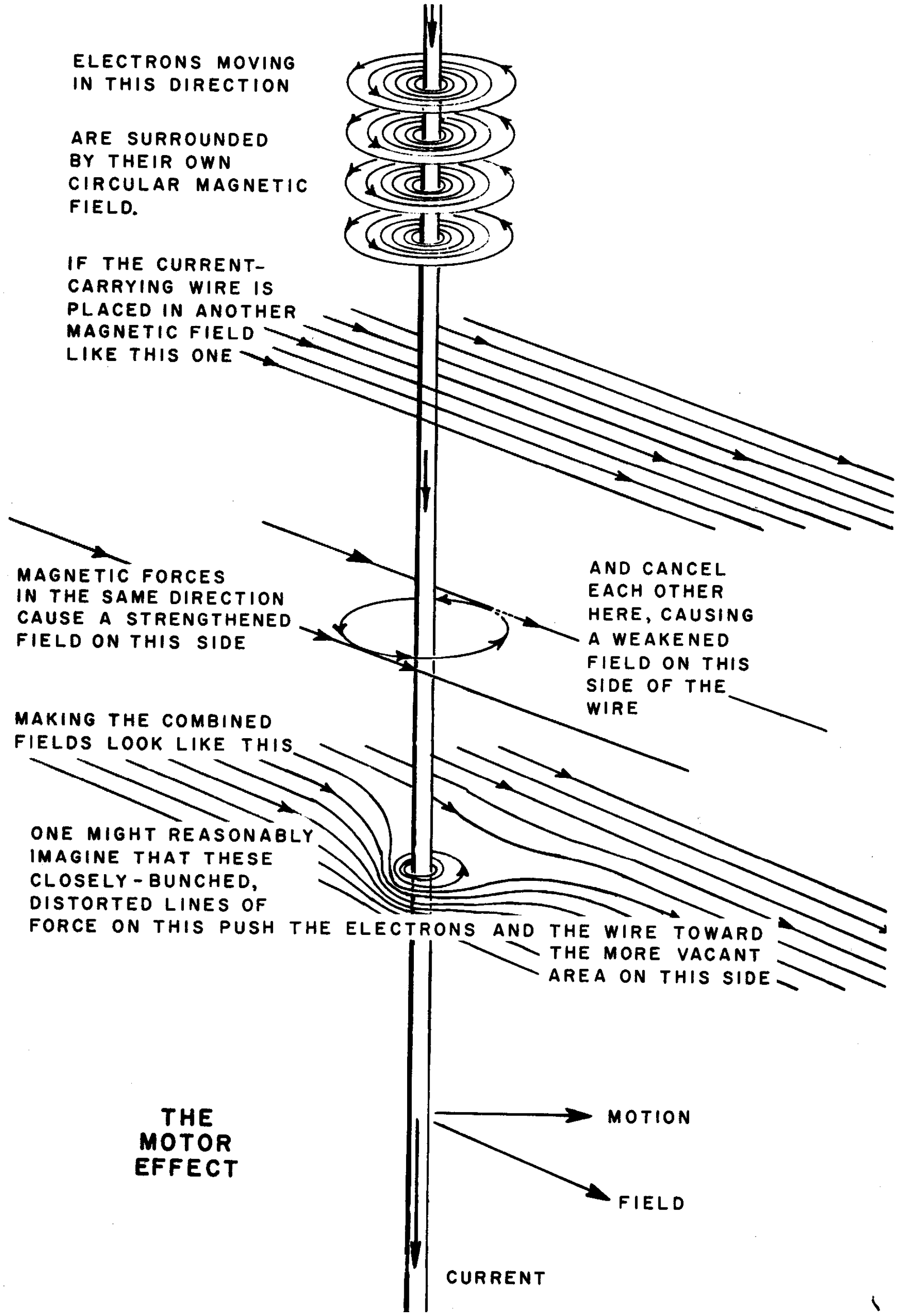
MAGNETS AND MAGNETISM

What exactly is a magnet? Is it a source of energy like a battery? At the microscopic level, each electron spins around an internal axis, and each has a north and south pole, much like the Earth. In a magnet, all of these microscopic magnets are aligned. In a permanent magnet, a very strong imposed magnetic field and heat is needed to force the alignment. The alignment remains after the magnetic field and heat is removed. So, in this sense, a magnet is something like a battery. In an electromagnet, the alignment is temporary. The alignment of microscopic magnets is possible only in certain materials. The rare earth material neodynium makes very strong permanent magnets: soft iron makes very good electromagnets.

FUNDAMENTAL MECHANISM

Basically, theory suggests that, when current or charge flows through a wire that is in a magnetic field that has flux lines which are perpendicular to the direction of the wire, the wire experiences a force that is perpendicular to the flux lines and the wire direction. This force is known as the Lorenz force. When wire is coiled around a rotor, the Lorenz force causes it to rotate. The magnetic field can be created by permanent magnets or electromagnets. To keep the rotor turning, it turns out that the current in the coils must be periodically switched. Usually, the rotor has a soft iron core. This helps the imposed magnetic field make better contact with the coils.

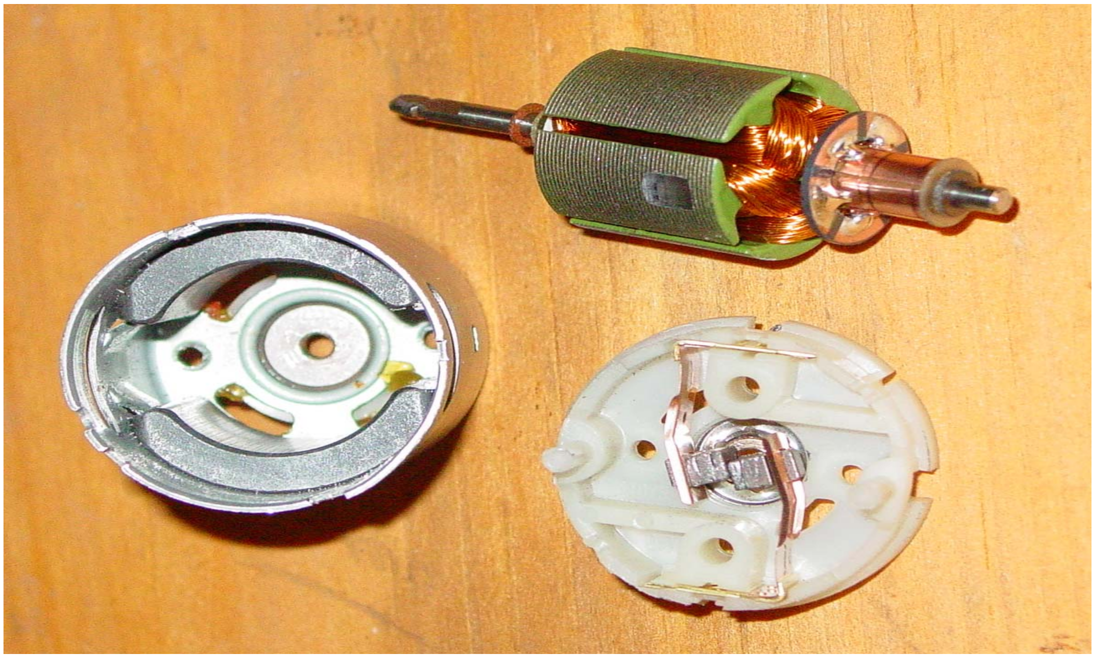
How the Lorenz force is created is not fully understood. Current theory suggests that the magnetic fields cause a flow of subatomic particles known as bosons. Some researchers suggest that the Lorenz force is something like the Coriolis force which acts on flow down a straight pipe that is rotating. The Coriolis force keeps changing the direction of the flow so that it is aligned with the direction of the pipe. Other researchers suggest that the Lorenz force is something like the Magnus force which causes spinning baseballs to move laterally. The current in the wire generates a circular magnetic field around the wire. This magnetic field adds to the imposed magnetic field on one side of the wire and subtracts from it on the other side. So, there is a stronger magnetic field on one side relative to the other. This pulls the wire laterally. A spinning motion of a baseball adds to the flow over the ball due to its motion on one side of the ball and subtracts from it on the other side. The Bernoulli principle shows that this causes low pressure on the high flow side of the ball and high pressure on the low flow side. This pressure difference gives the Magnus force.

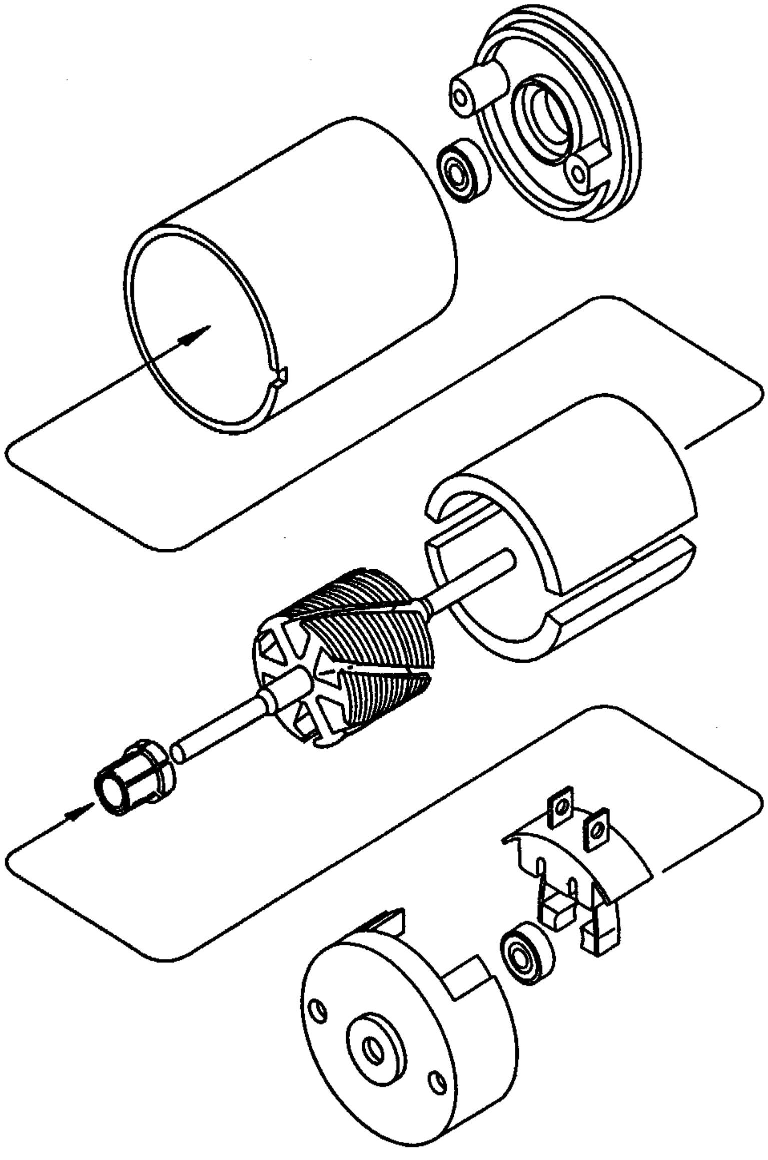


THE MOTOR EFFECT

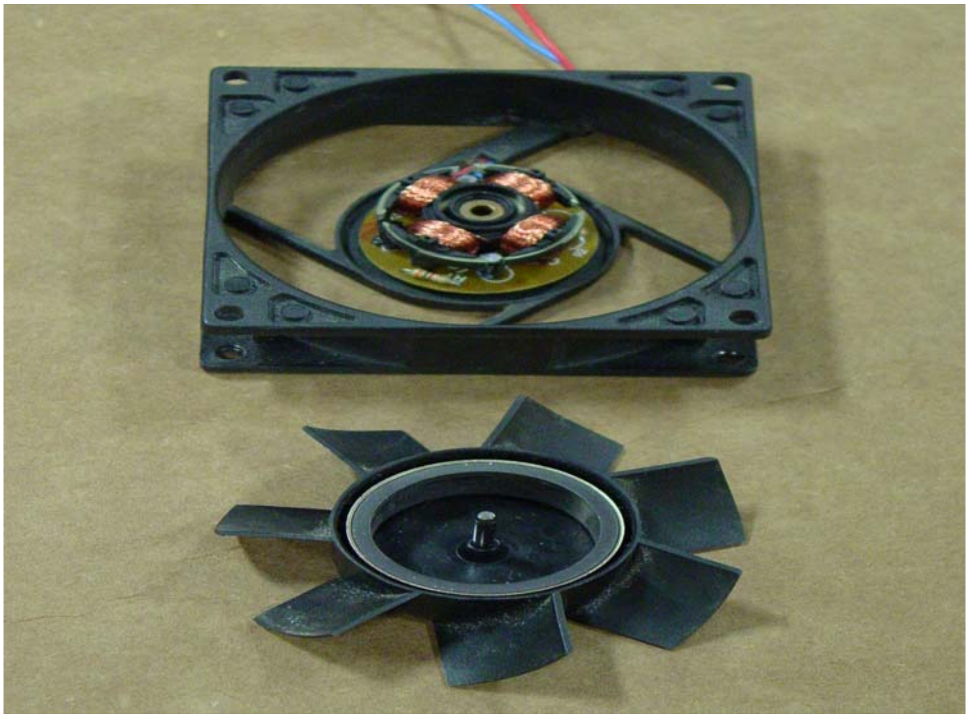
DIRECT CURRENT OR DC MOTORS

In brush DC motors, magnets are located on an outer fixed stator and the coils are located on an inner rotor. Sliding contact brushes are used to switch the current in the coils. A brush DC motor is shown in the photo below. The stator with its two permanent magnets, one north and the other south, is shown on the left. The rotor, with its coils of wire and split ring commutator, is shown in the upper right corner. The brushes can be seen in the lower right corner. On the rotor, the wires are coiled around an iron core. This is not solid but is instead made from thin sheets or laminates. This helps suppress eddy currents, which generate magnetic forces which oppose motion.

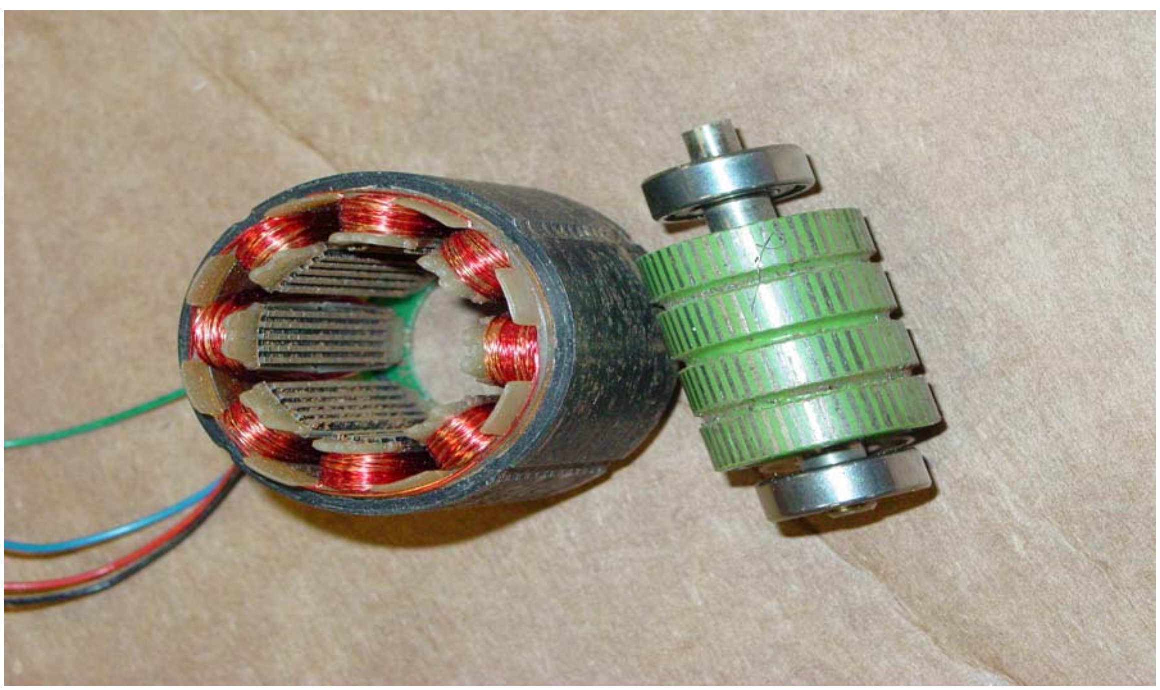




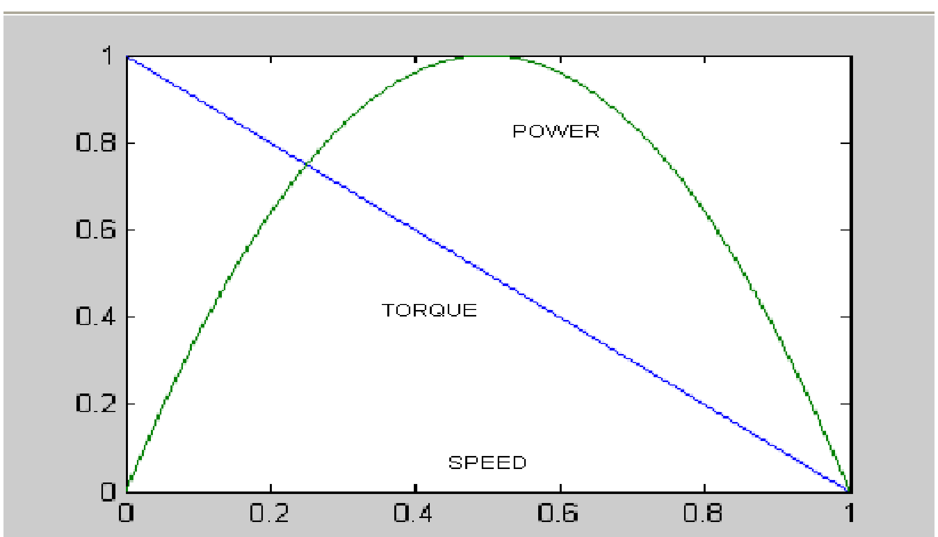
In brushless DC motors, the magnets are located on an outer rotor and the coils are located on an inner fixed stator. Sensors on the stator, which detect the magnets on the rotor, are used to switch the current in the coils. A brushless DC motor, from a cooling fan, is shown in the photo below. A ring magnet, which has alternating north and south poles along its perimeter, is attached to the fan. There are 4 coils of wire on the stator: each is coiled around an iron core. When energized, these coils make the cores north or south poles. These attract or repel the permanent magnet north and south poles. So, this motor does not make use of the Lorenz force directly.



Stepper motors are DC motors which have an axial magnet on an inner rotor and coils of wire on an outer stator. Pole pieces are used to convert the magnet into many north and south poles. When current flows through the coils, many north south poles are generated, which attract or repel the magnet north south poles. Because of how the motor is constructed, this generates a small rotation. When the current in the coils is reversed, another bit of rotation in the same direction is generated. Switching the current back and forth gives a rotary motion. Notice the teeth on the rotor and the stator. The magnetic interaction between the rotor and the stator is strongest at these teeth. The teeth create many north and south poles.



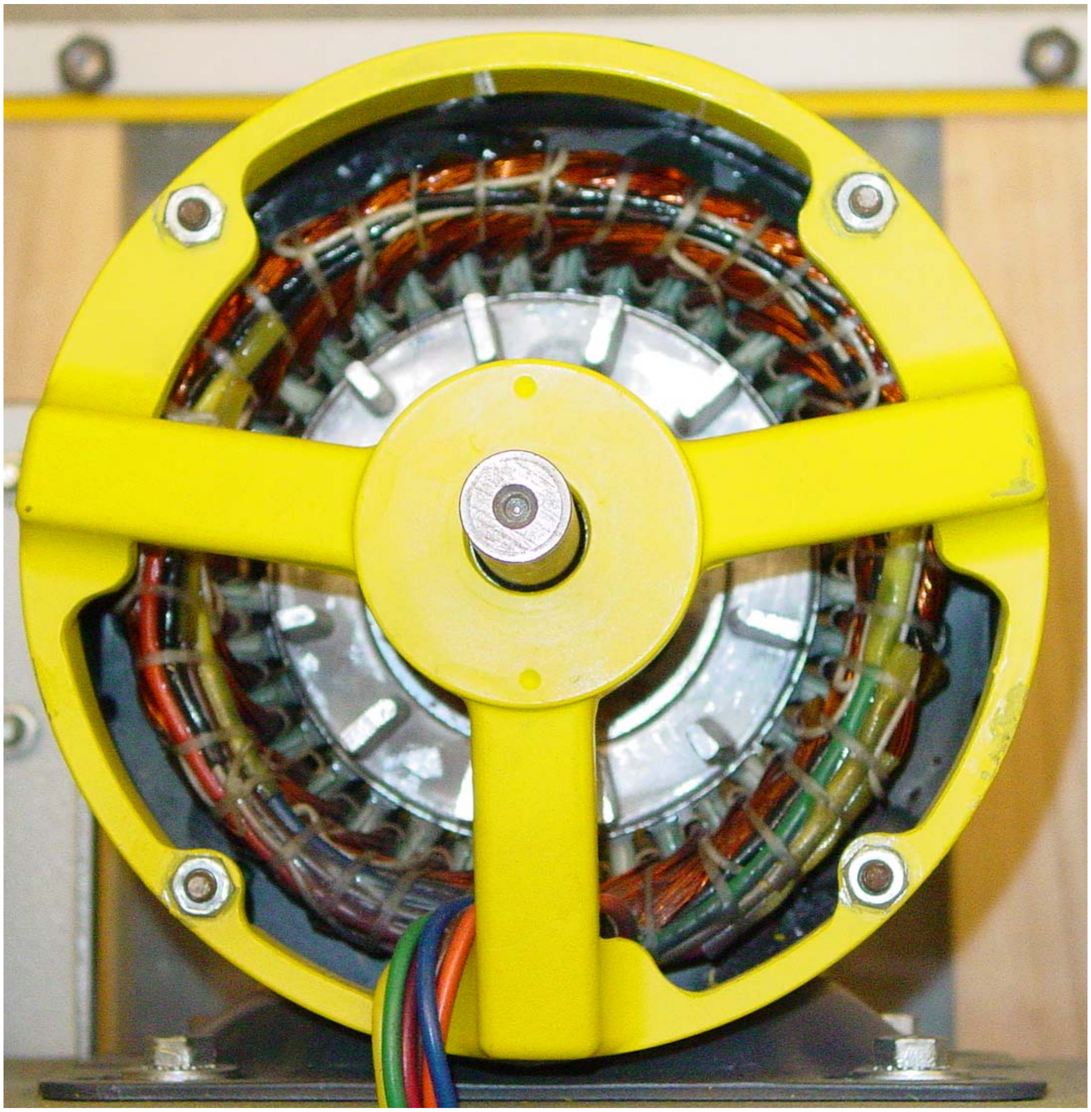
The most important thing one wants to know about a motor is its torque versus speed characteristic. The power output of the motor is torque times speed. The power input is voltage times current. The characteristic of a motor depends on many factors. A typical torque versus speed characteristic of a permanent magnet DC motor is shown in the sketch below. Also shown is its power versus speed curve. This is for a constant applied voltage. Note that the torque drops almost linearly with speed. This is because, as the rotor turns in a magnetic field, its wires act like a generator. An emf is built up in the wires which opposes the applied voltage. When the emf cancels the applied voltage, there is no current and thus no torque. From an efficiency point of view, one should operate a motor where its power peaks. This means there is a best efficiency point (BEP) or best operating point (BOP) on the torque versus speed curve.



ALTERNATING CURRENT OR AC MOTORS

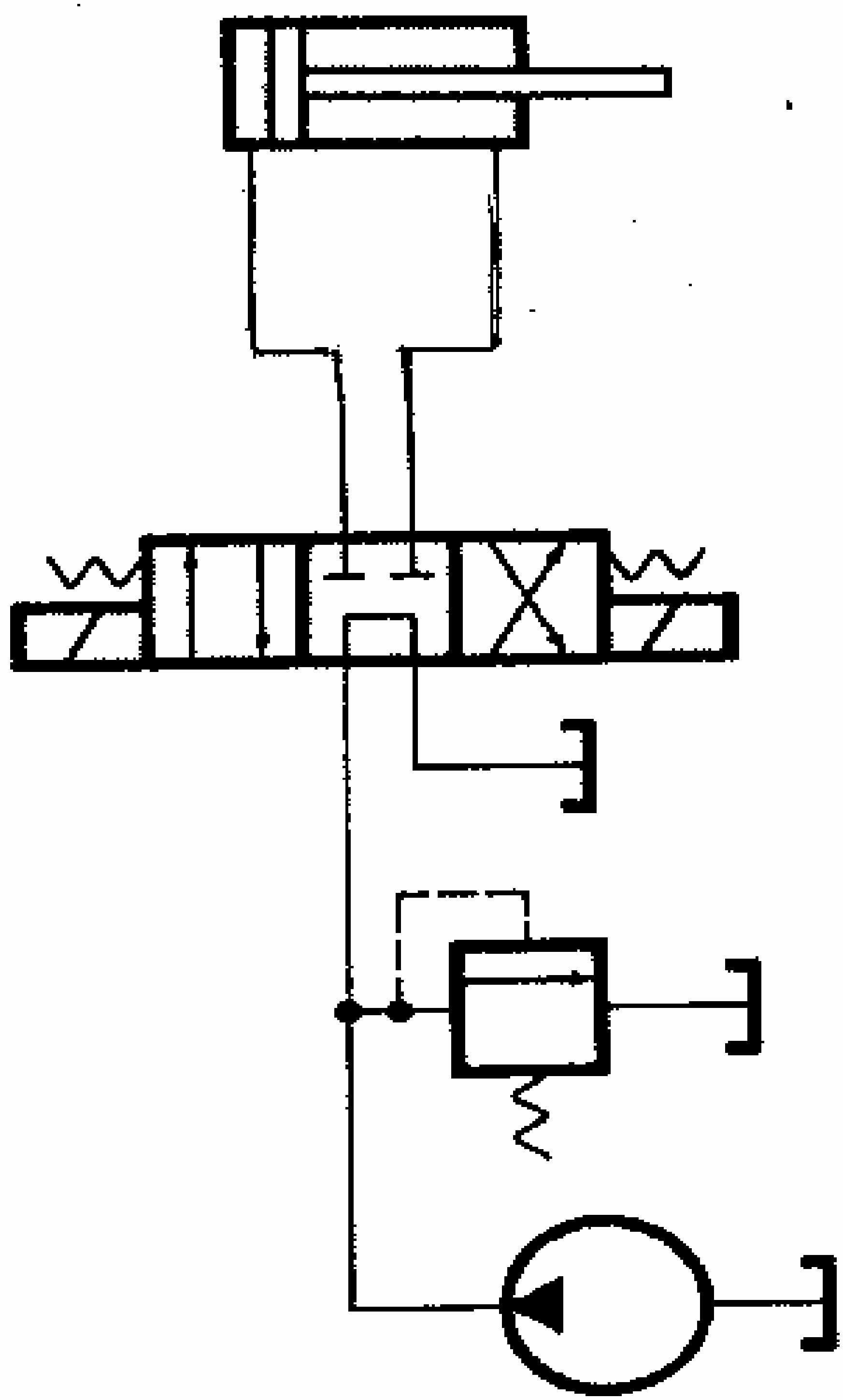
AC motors use alternating current to create magnetic fields. A good example of an AC motor is the Squirrel Cage Induction Motor. A photo of such a motor is shown on the next page. It has coils of wires on an outer fixed stator and iron bars running axially along an inner rotor. Current is applied to the coils in such a way that a magnetic field moves around the stator. This induces currents in the iron bars which magnetizes them and makes them follow the rotating magnetic field in the stator. There are no electrical connections between the rotor and the stator, and so this motor does not need brushes. It has a simple robust design and is used extensively in industry.

Most AC motors use grid power, which has a frequency of 60Hz. It turns out that this makes their speed constant. For many industrial applications, this is not a problem because, in many cases, constant speed is desirable. So it appears that, if variable speed is needed, one must use DC motors. However, recently it has become possible to take 60Hz power and convert it to other frequencies. These variable frequency drives can change the motor speed.

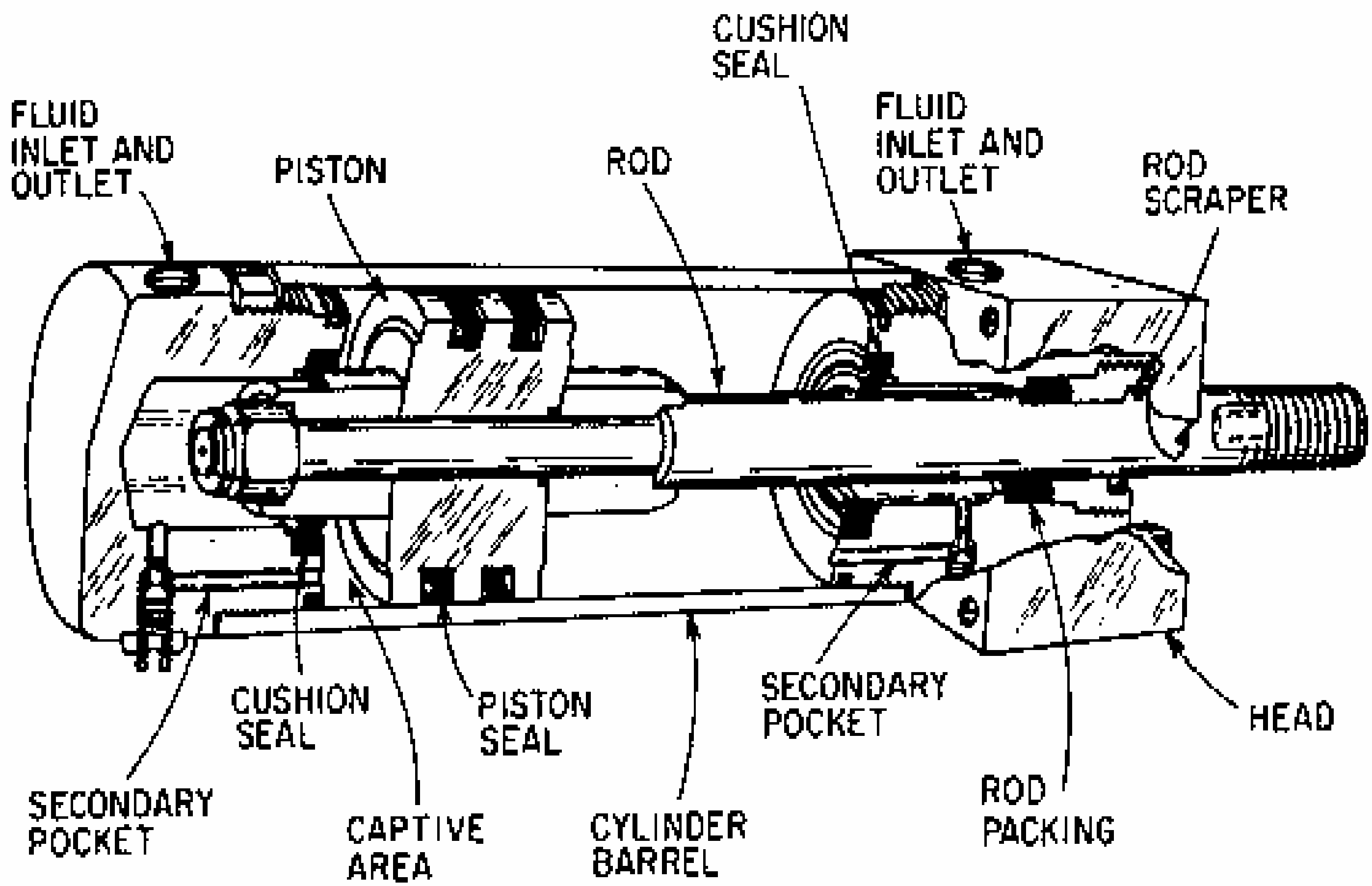


HYDRAULIC AND PNEUMATIC SYSTEMS

A simple hydraulic system is shown on the next page. A pump is used to supply high pressure hydraulic oil to a flow control valve which in turn sends the oil either to an actuator or to a sump. The circle represents the pump. A pneumatic supply looks similar except the arrow inside the circle is not shaded. In this case the circle represents a compressor or an air storage tank. The large rectangle made of squares represents the control valve: the cylinder with piston represents the actuator: the square is a pressure relief valve. The slash in the small rectangle at each end of the valve indicates that it is solenoid operated. The zig-zag line immediately next to each small rectangle means that springs are used to return the valve to its neutral position when both solenoids are deactivated. In this case, the oil from the pump goes directly back to the sump. When the bottom solenoid is deactivated and the top one is activated, the two arrows in the top block move down into the center block and create flow paths from the pump to the top of the actuator and from the bottom of the actuator to the sump. The flow of oil moves the piston rod assembly downwards. When the top solenoid is deactivated and the bottom one is activated, the flow of oil moves the piston rod assembly upwards.

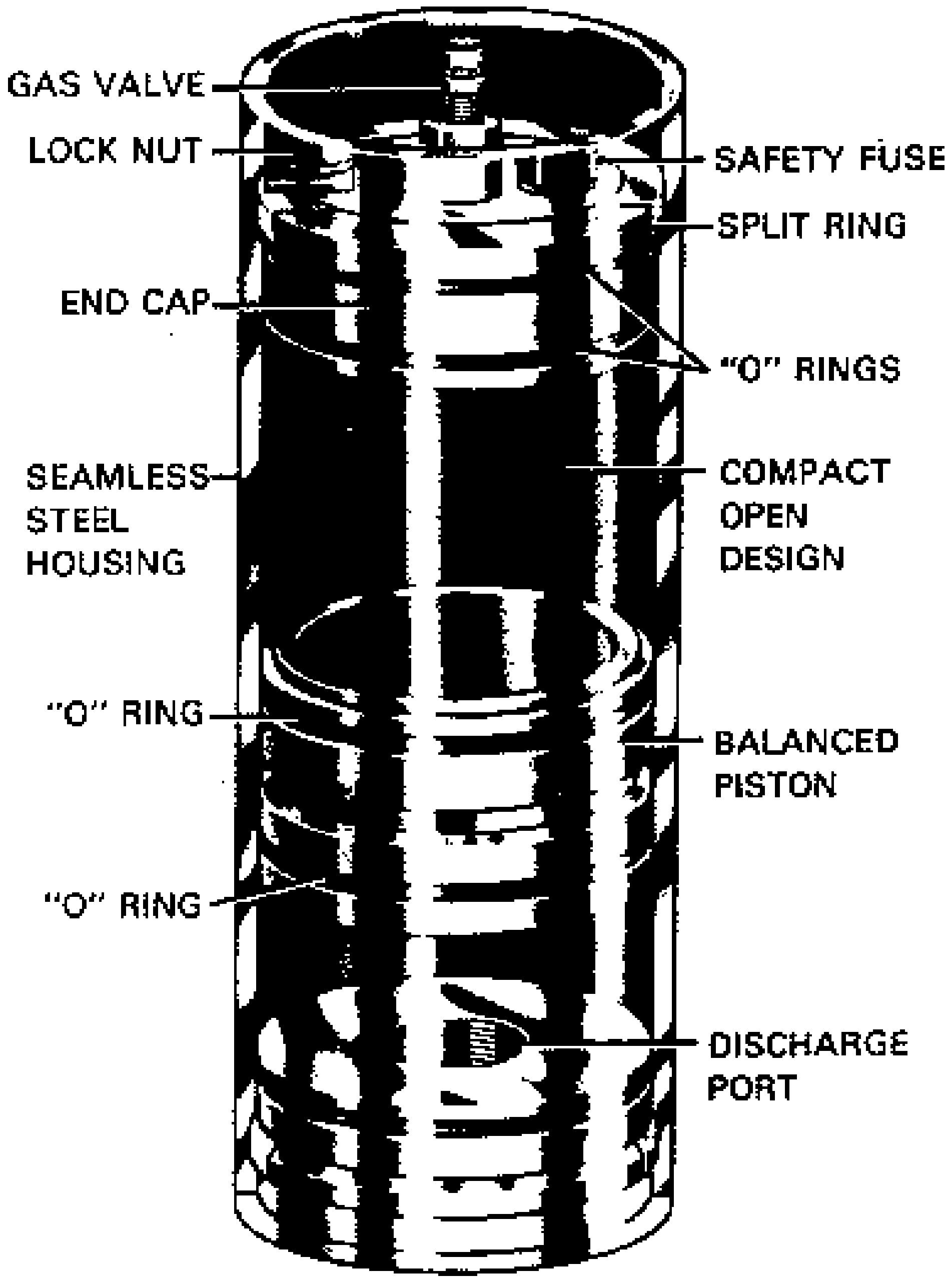


A schematic of a typical hydraulic actuator is shown on the next page. Pneumatic actuators look roughly the same. As can be seen, the actuator consists of a piston in a cylinder: a rod attached to one side of the piston passes through one end of the cylinder. When a rod is pushing against a stationary load, the pressure across the piston is around 20 MPa or 3000 psi. Special seals are needed to keep leakage of oil along the sides of the piston and the rod tolerable. The main ones are cup gaskets and piston and wiper rings. High pressure can cause regular o-rings to jam into the space between the piston and the cylinder walls. Pistons generally move very fast and they can slam into the ends of a cylinder. Special devices are needed to lessen impact loads. When they are constructed from flexible materials, they are known as cushions. The actuator shown in the schematic has a plug attached to each side the piston: as the piston nears an end a plug blocks oil passageways and this causes pressure to increase which in turn provides a cushioning effect. The plugs are shown in the actuator schematic.


FLUID
INLET AND
OUTLET
PISTON
ROD
CUSHION
SEAL
FLUID
INLET AND
OUTLET
ROD
SCRAPER
SECONDARY
POCKET
CUSHION
SEAL
CAPTIVE
AREA
PISTON
SEAL
CYLINDER
BARREL
SECONDARY
POCKET
ROD
PACKING
HEAD

Conservation of mass considerations allow us to calculate the speed of an actuator rod. This gives Q=S*A where Q is the volumetric flow rate, S is the speed of the rod and A is the cross sectional area of the piston. Manipulation gives: S=Q/A. A simple static force balance gives the stalled load of an actuator. One gets F=P*A where F is the load and P is the pressure acting on the piston.

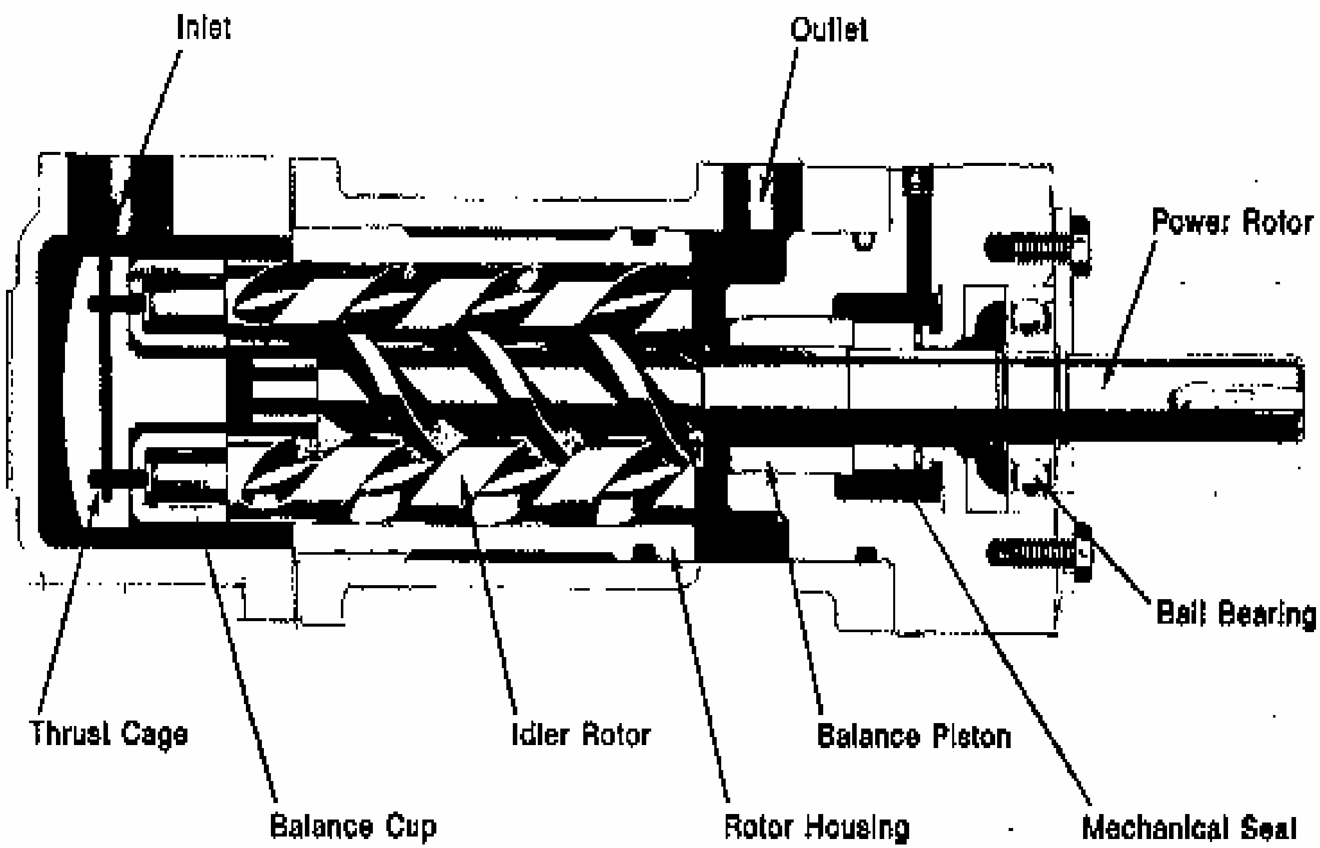
Hydraulic oil is basically incompressible. When load suddenly stops an actuator or there is a sudden valve closure, very high pressures can be generated in oil lines. Accumulators are used to counteract this. The sketch on the next page shows a typical accumulator. It consists of a tube with a piston. The part of the tube below the piston is open to the oil line: the part above contains nitrogen gas. During normal operating conditions, the gas pressure is approximately the same as that in the oil line. When pressure in the line suddenly goes up, flow of oil into the tube pushes the piston upwards and compresses the gas. This increases the gas pressure. However, this increase is limited, and the pressure in the line gradually settles down to a normal level.



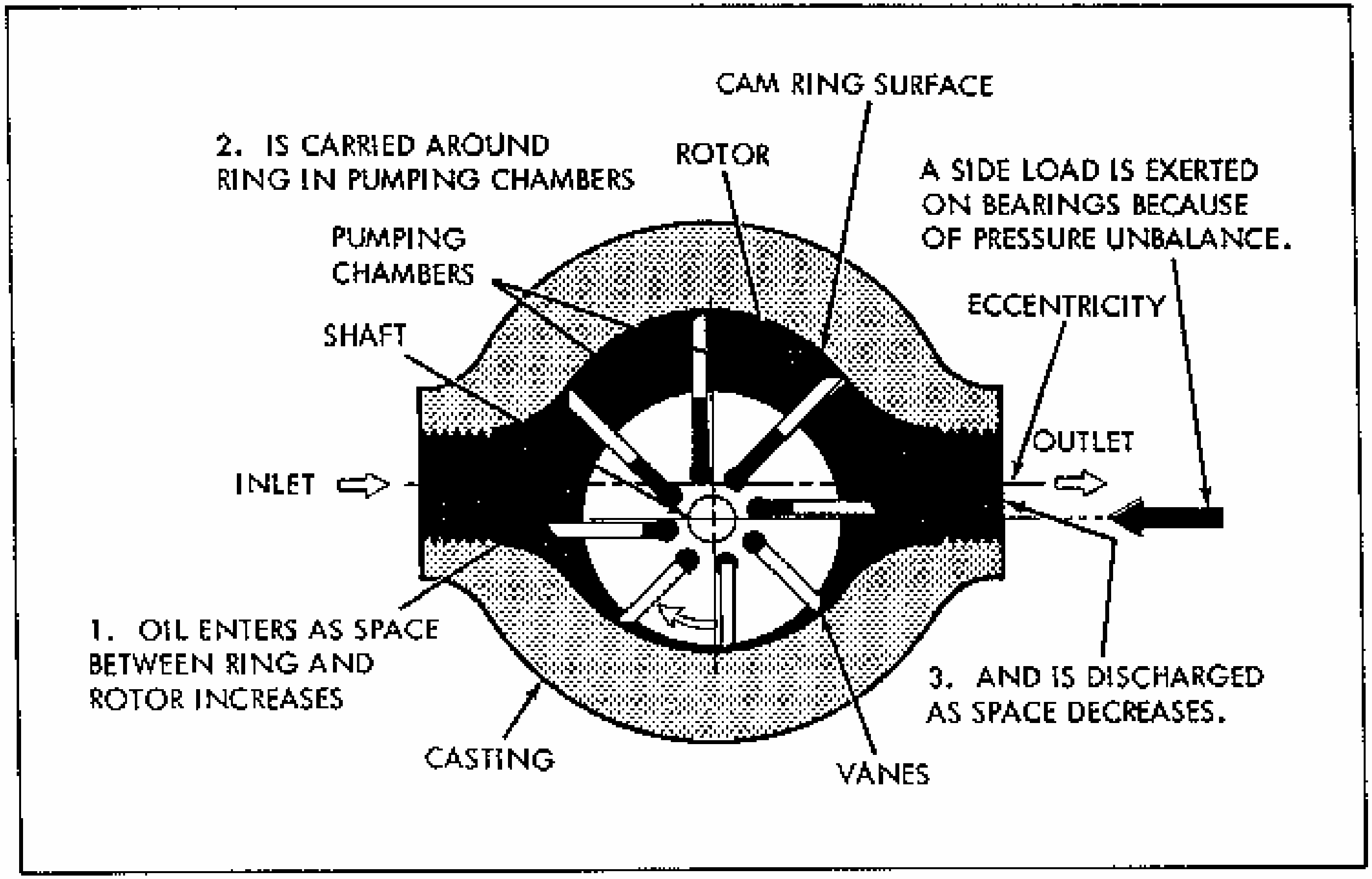
GAS VALVE
LOCK NUT
SAFETY FUSE
SPLIT RING
END CAP
"O" RINGS
SEAMLESS STEEL HOUSING
COMPACT OPEN DESIGN
"O" RING
BALANCED PISTON
"O" RING
DISCHARGE PORT

Conservation of momentum considerations show that for a wave in a pipe the pressure change ΔP across it is equal to $\rho a \Delta U$ where ΔU is the speed change across it, ρ is the density of the fluid and a is the wave speed for the pipe. One can show that the wave speed is $a=\sqrt{[\mathbf{K}/\rho]}$ where **K** is the effective bulk modulus of the pipe. This is $\mathbf{K}=K/[1+[DK]/[Ee]]$ where D is the diameter of the pipe, K is the bulk modulus of the fluid, E is the Elastic Modulus of the pipe wall material and e is the wall thickness. One can estimate the wave speed of a pipe by sending a pulse up the pipe and measuring the wave period T. Theory shows that the wave period T is 4 times the transit time $\mathcal{T}$ for the pipe, which is length of the pipe L divided by wave speed a. Manipulation gives $T=4\mathcal{T}=4L/a$ or $a=4L/T$.

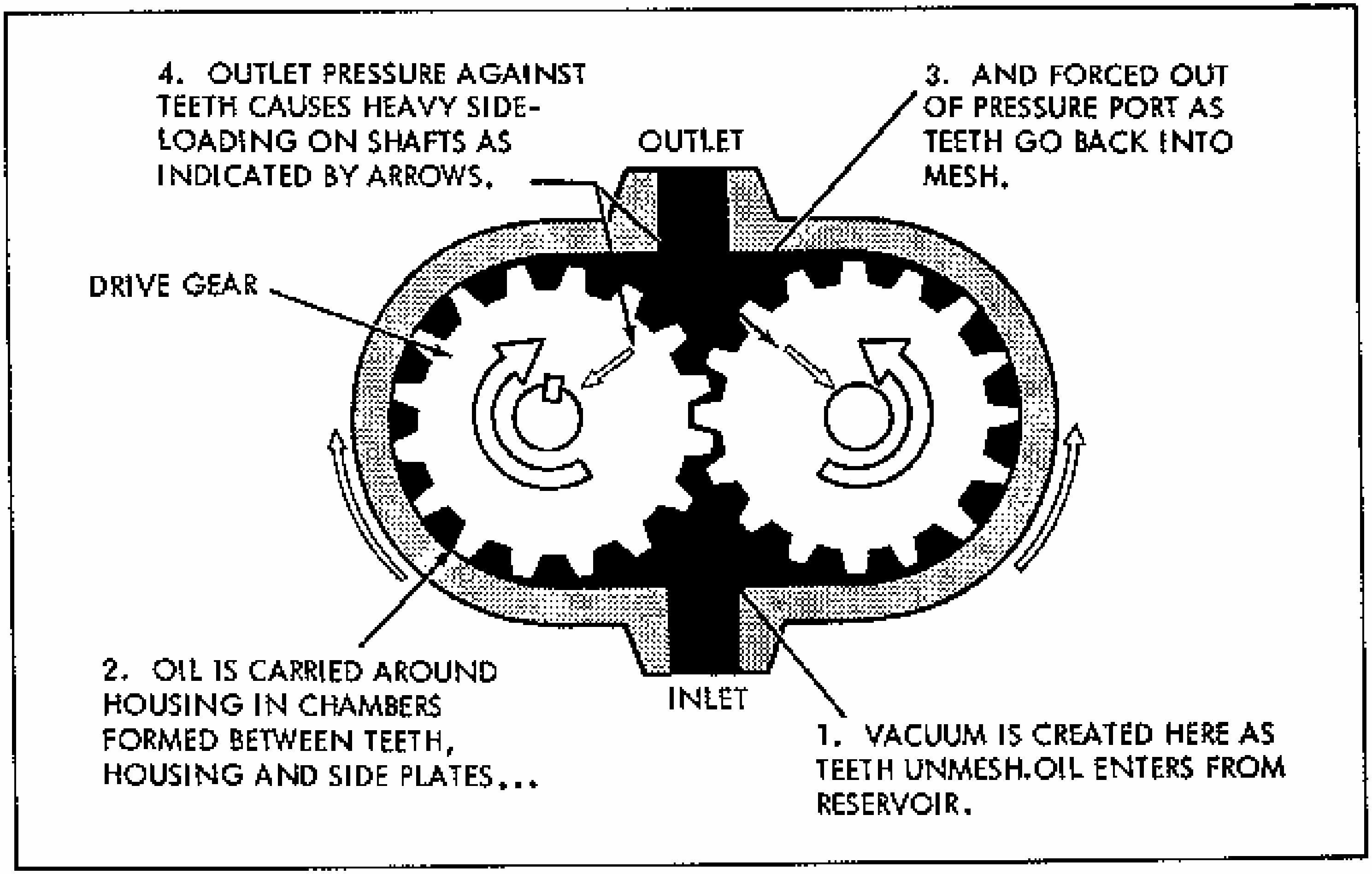
Some schematics of pumps used in hydraulic systems are given below. All are positive displacement devices. This means that, when they are stopped, oil does not back flow through them. Note that some pumps are pressure compensated. This means that, as pressure builds up downstream, components within them move in such a way to limit pressure build up. Usually, when pumps are non compensated, relief valves are used to limit pressure. When pressure reaches a certain level, it forces a spool to move in such a way that a flow path to the sump is created and build up in pressure is stopped. Such a valve is shown in the system sketch. A spring loaded check valve can also be used for this purpose.


Inlet
Outlet
Power Rotor
Ball Bearing
Thrust Cage
Idler Rotor
Balance Piston
Balance Cup
Rotor Housing
Mechanical Seal

SCREW PUMP

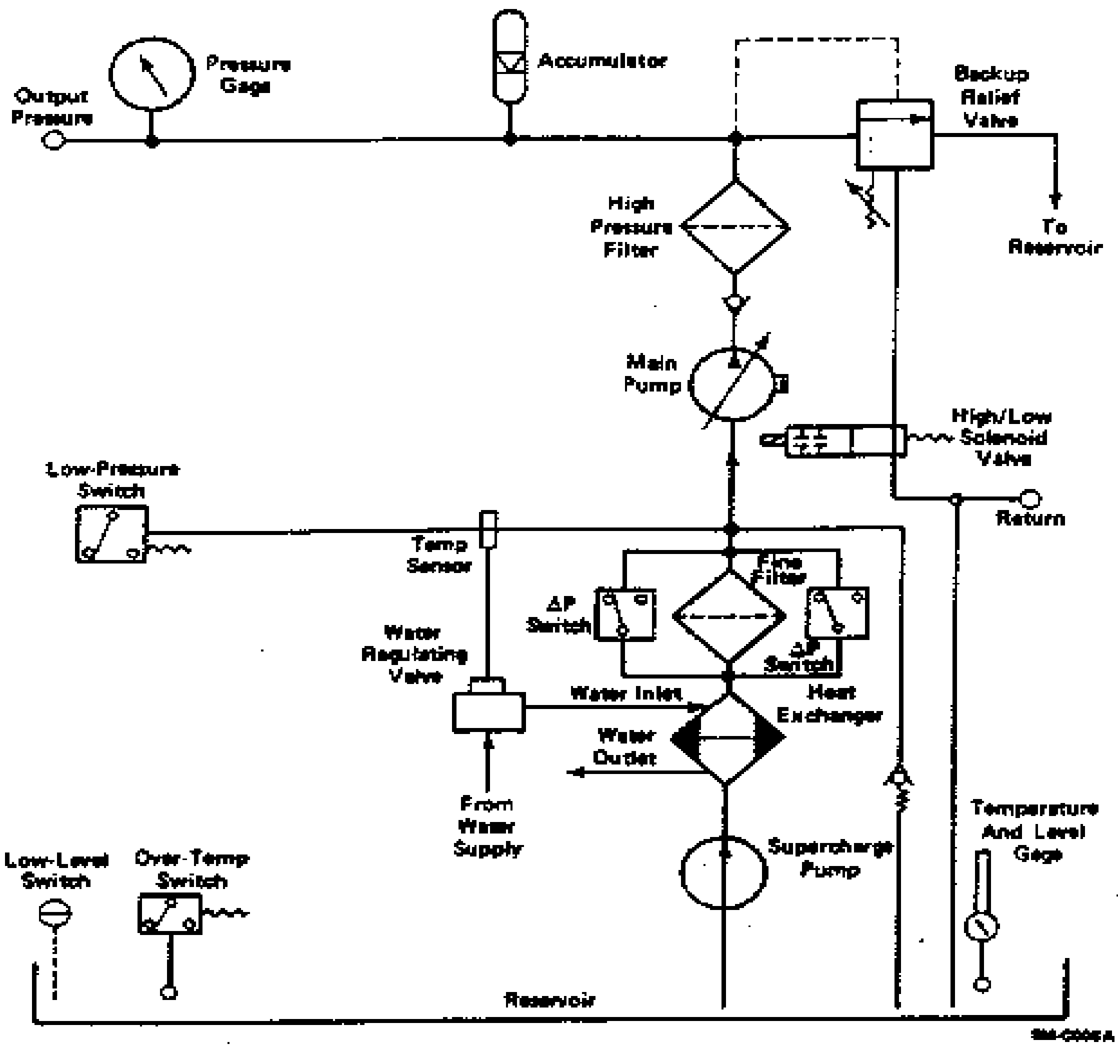

CAM RING SURFACE
2. IS CARRIED AROUND RING IN PUMPING CHAMBERS
ROTOR
A SIDE LOAD IS EXERTED ON BEARINGS BECAUSE OF PRESSURE UNBALANCE.
PUMPING CHAMBERS
ECCENTRICITY
SHAFT
OUTLET
INLET
1. OIL ENTERS AS SPACE BETWEEN RING AND ROTOR INCREASES
3. AND IS DISCHARGED AS SPACE DECREASES.
CASTING
VANES

VANE PUMP


4. OUTLET PRESSURE AGAINST TEETH CAUSES HEAVY SIDE-LOADING ON SHAFTS AS INDICATED BY ARROWS.
OUTLET
3. AND FORCED OUT OF PRESSURE PORT AS TEETH GO BACK INTO MESH.
DRIVE GEAR
2. OIL IS CARRIED AROUND HOUSING IN CHAMBERS FORMED BETWEEN TEETH, HOUSING AND SIDE PLATES...
INLET
1. VACUUM IS CREATED HERE AS TEETH UNMESH.OIL ENTERS FROM RESERVOIR.

GEAR PUMP

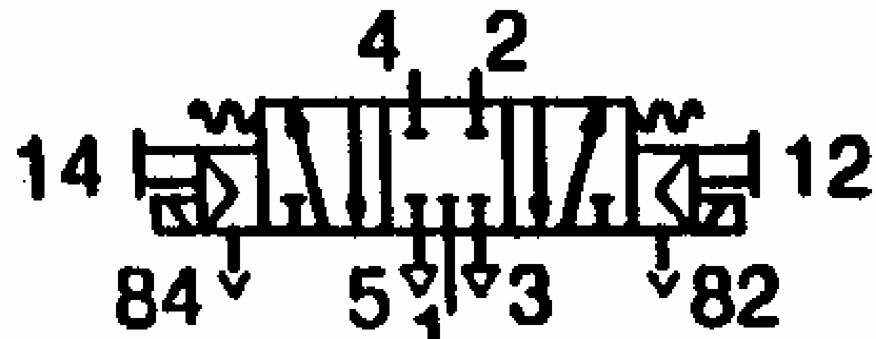
A schematic of the hydraulics setup in the engineering building at MUN is shown below. This supplies high pressure oil to experiments in the structures lab and elsewhere. Note that there are two pumps: one high pressure and one low pressure. Both are screw pumps. Note also the accumulator and filters in the hydraulic lines.



FESTO PNEUMATIC VALVE #1

This valve could be used to port high pressure air to one end of an actuator and exhaust it to atmosphere from the other end. It could be used to move a piston rod back and forth or lock it into position. The slashes in the small rectangles at the ends of the valve indicate that it is solenoid activated. The triangles at the ends indicate that the valve is pilot operated. This means that the solenoids create pathways for pressure that move a small piston or spool and the motion of the spool creates pathways for flow to an actuator or some other device. The zig-zag lines indicate that springs are used to return valve to the center or neutral position when both solenoids are deactivated. When the left solenoid is activated, flow paths in left block slide over to middle block and line up with high and low pressure ports. When the right solenoid is activated, flow paths in right block slide over to middle block and line up with high and low pressure ports. The small rectangles with the overhanging ends means valve can be manually adjusted with setscrew.

MYH-5/3G-M5-L-LED



#1

0997 2....8bar

34311

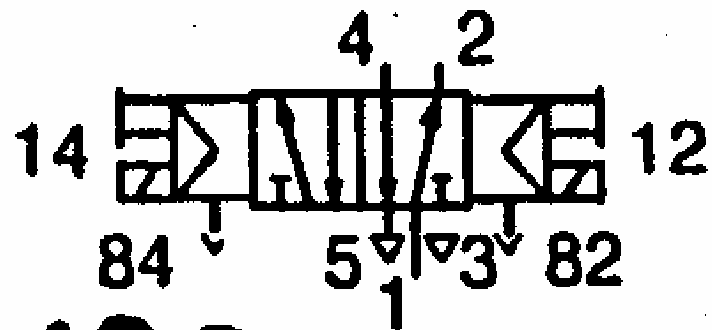
FESTO

FESTO PNEUMATIC VALVE #2

This valve could be used to move a piston rod back and forth but it cannot lock the rod into position. It does not have a neutral position. When the left solenoid is activated while the right solenoid is deactivated, flow paths in left block slide to the right and line up with high and low pressure ports. When the right solenoid is activated while the left solenoid is deactivated, flow paths in right block line up with high and low pressure ports. If only one solenoid was activated and it was then deactivated, flow paths would not change. During solenoid deactivation the solenoid pilot pressure would be vented. This would make the net load on the flow spool due to its two end pressures zero. In this case, flow paths would be held in place by friction.

JMYH-5/2-M5-L-LED

#2



0496

2....8bar

34310

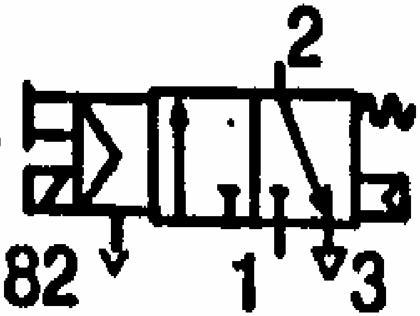
FESTO

FESTO PNEUMATIC VALVE #3

This valve could be used to port high pressure air to the pressure end of an actuator with a spring return. When the solenoid in not activated, flow path is as shown in sketch: the pressure end of the actuator is connected to atmosphere. When the solenoid is activated, flow path on left slides to the right and connects the pressure end of the actuator to high pressure. This pushes back or compresses the spring and extends the piston rod. When the solenoid is deactivated, the valve spring causes flow paths on right to slide back into position. This vents the pressure end of the actuator to atmosphere and the spring within the actuator retracts the piston rod.

MYH-3-M5-L-LED

#3



1297 2....8bar

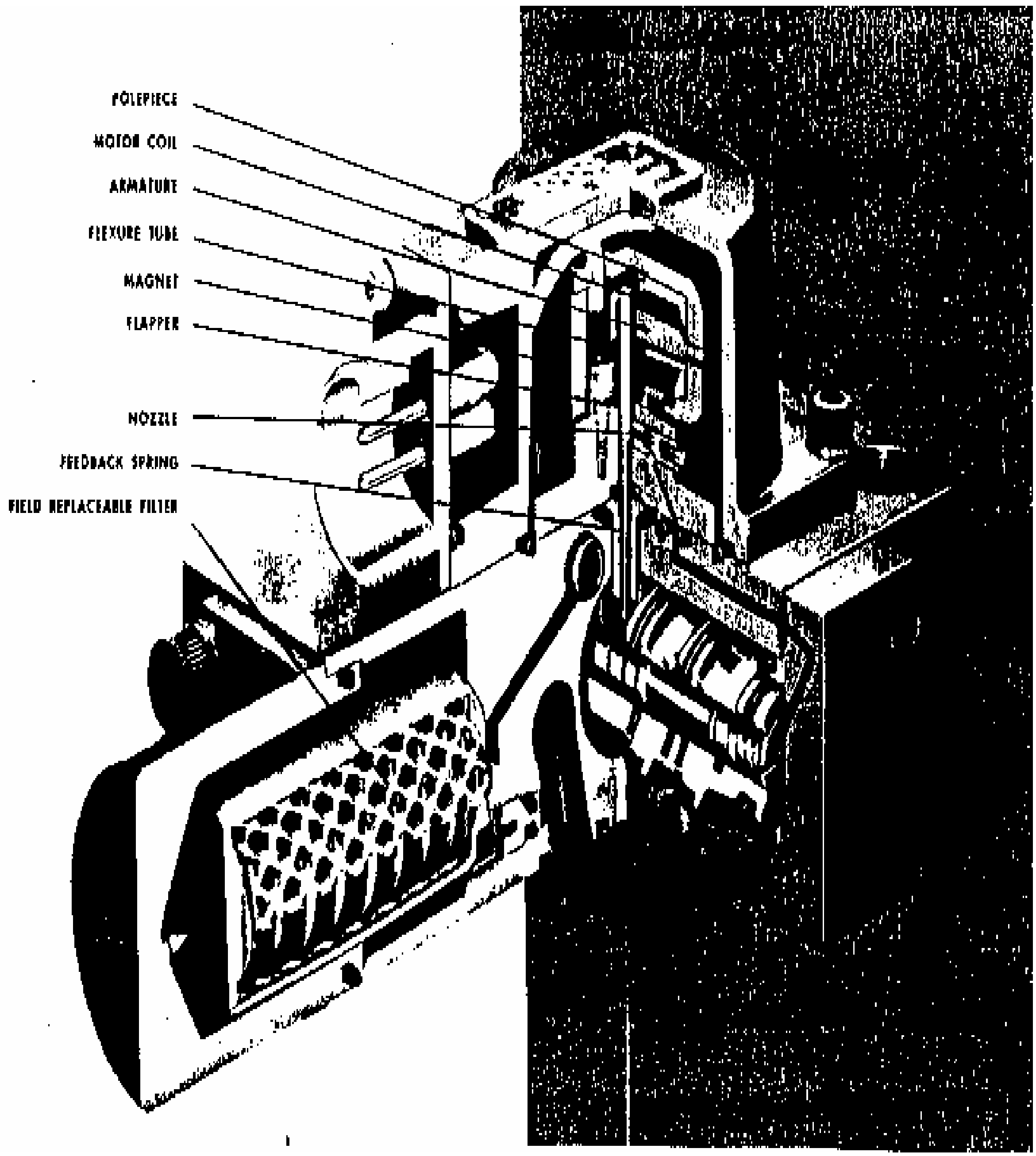
34307

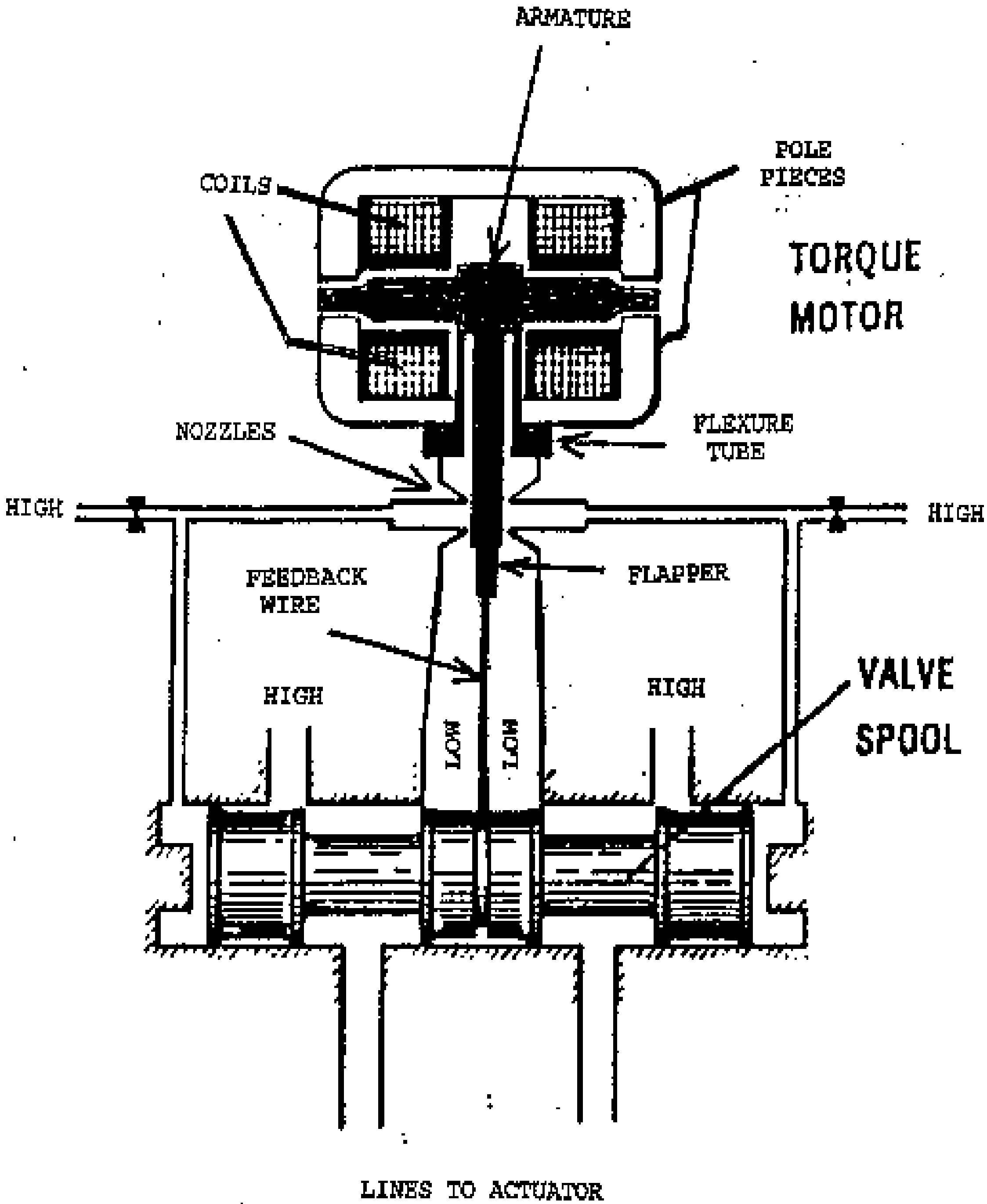
FESTO

MOOG HYDRAULIC SERVOVALVE

A servovalve consists of two main parts: an electrical part and a hydraulic part. The two parts are separated by something called a flexure tube. The hydraulic part is connected to a supply of high pressure oil and to a low pressure sump. The supply and sump pressures are both approximately constant. Two vertical permanent magnets positioned front and back make one pole piece a north pole and another pole piece a south pole. The control signal energizes a set of copper wire coils. The magnetic field set up by the coils is such that it causes one end of an iron armature to become a north pole and the other end to become a south pole. The north end of the armature is attracted to the south pole piece while its south end is attracted to the north pole piece. This generates a torque which causes the armature, which is supported by the flexure tube, to rotate slightly either clockwise or counterclockwise, depending on the polarity of the control signal. The amount of rotation depends on the magnitude of the control signal. As the armature rotates, a flapper attached to it moves laterally and modulates the flow areas of two nozzles, making one larger and the other smaller.

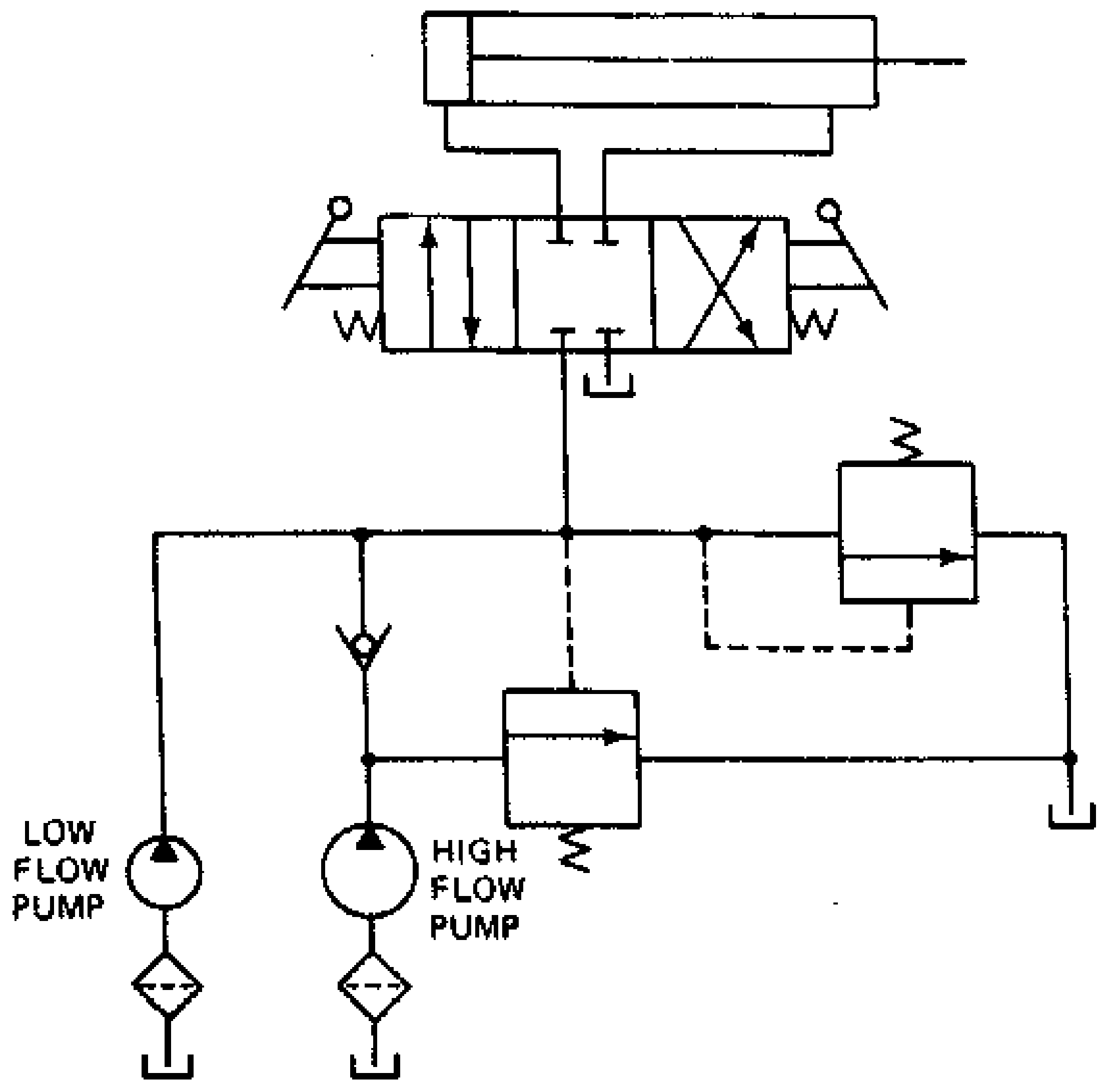
This causes flow through one nozzle to increase and flow through the other nozzle to decrease. As these flows move through fixed hydraulic resistors upstream, one causes pressure to increase on one end of a spool while the other causes pressure to decrease on the other end of the spool. This causes the spool to move. As it moves, a flexible feedback wire exerts an opposing torque on the armature, which tends to recenter the flapper. The spool moves until the flapper is basically recentered, and the pressure difference from one end of the spool to the other is the small amount needed to balance the feedback wire force. So, for any level of control signal, there is a corresponding spool position which is dependent only on the magnitude and the polarity of the signal. The spool connects the actuator lines to the supply of high pressure oil and the low pressure sump. It creates a flow passageway between them. Flow into the actuator is controlled by the size of this passageway. When the control signal is constant, flow is constant and the actuator rod moves at a constant speed. When the control signal is made a function of rod position error, the rod moves towards a target or command position.


POLEPIECE
MOTOR COIL
ARMATURE
FLEXURE TUBE
MAGNET
FLAPPER
NOZZLE
FEEDBACK SPRING
FIELD REPLACEABLE FILTER


ARMATURE
POLE
PIECES
COILS
TORQUE
MOTOR
NOZZLES
FLEXURE
TUBE
HIGH
HIGH
FEEDBACK
WIRE
FLAPPER
HIGH
HIGH
VALVE
SPOOL
LOW
LOW
LINES TO ACTUATOR

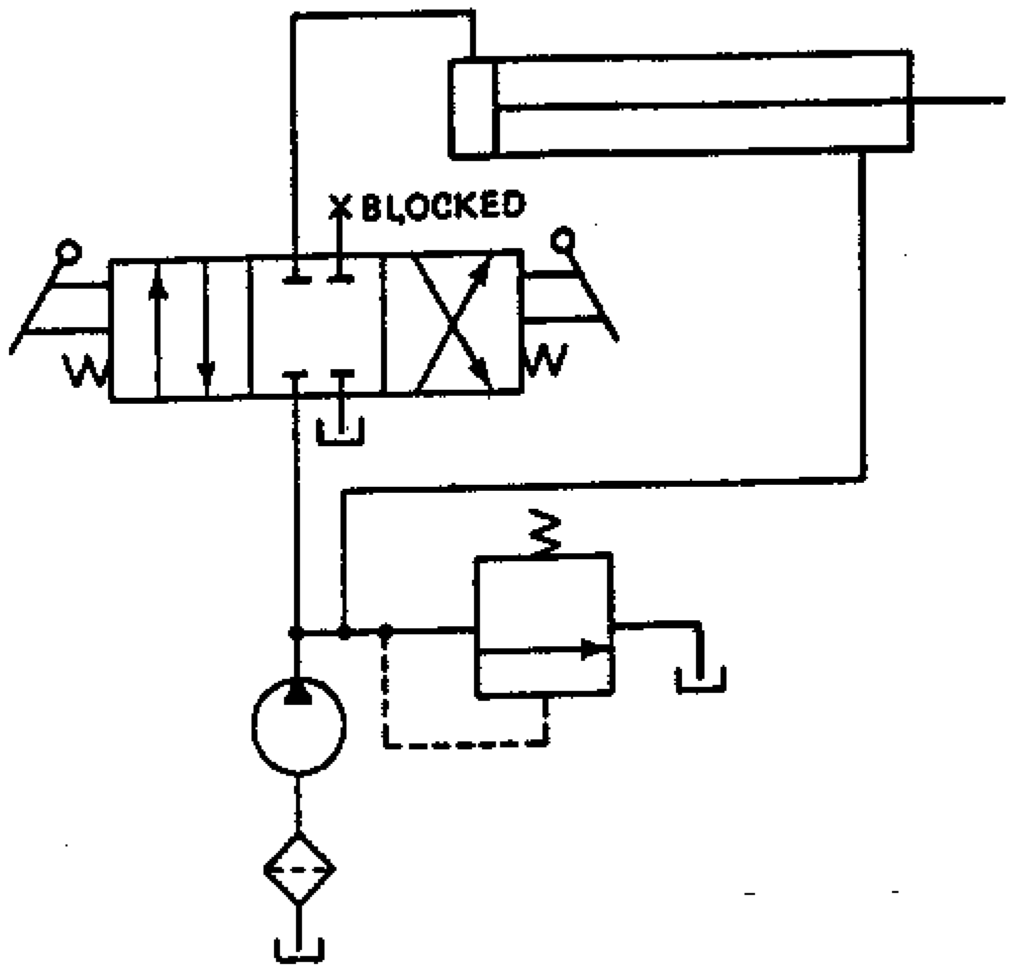
DOUBLE PUMP HYDRAULIC CIRCUIT

In most hydraulic circuits, when the flow requirements are high, the pressure requirements are low, and when the pressure requirements are high, the flow requirements are low. For example, during extension or retraction of an actuator, flow requirements are high but pressure requirements are low. However, when the actuator pushes against something at the end of its stroke, the reverse is true. As shown in the sketch, one could use two pumps to supply hydraulic oil: one pump would deliver high pressure at low flow and the other would deliver high flow at low pressure. This is less expensive than a single high pressure high flow pump. When the actuator is extending or retracting, the high flow pump controls the pressure in the flow lines. When the actuator pushes against something at the end of its stroke, the high pressure pump controls the pressure. This pressure could damage the high flow pump. A one way valve isolates it from the high pressure. Relief valves are used to limit pressure that can be generated by each pump.


LOW
FLOW
PUMP
HIGH
FLOW
PUMP

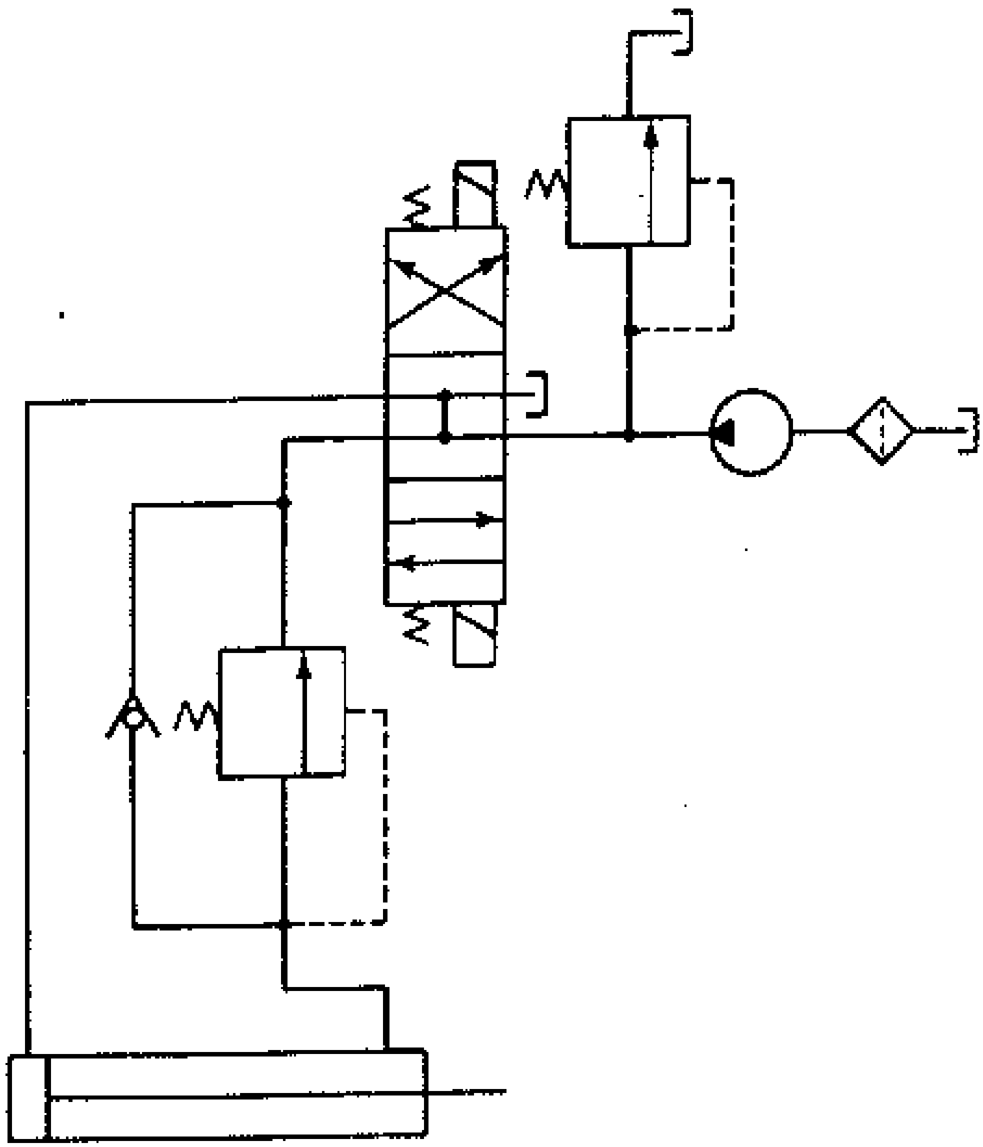
REGENERATIVE HYDRAULIC CIRCUIT

Usually, during extension or retraction of an actuator, high speed is important because a slow actuator wastes time. A regenerative circuit can make an actuator move very fast. When the flow paths on the left are moved to the center, the actuator moves very fast to the right. The pressure is approximately the same on both sides of the piston. Because of the rod on the right, the area over which pressure acts is slightly greater on the left. This is why the actuator moves to the right. The hydraulic oil that is expelled from the right side of the actuator joins with that from the pump and enters the left side of the actuator. Geometry considerations show that the flow that enters the left side can be many times that from the pump. In fact, in the limit as rod diameter goes to zero, flow and speed tend to infinity. However, inertia and friction would counteract this.


X BLOCKED

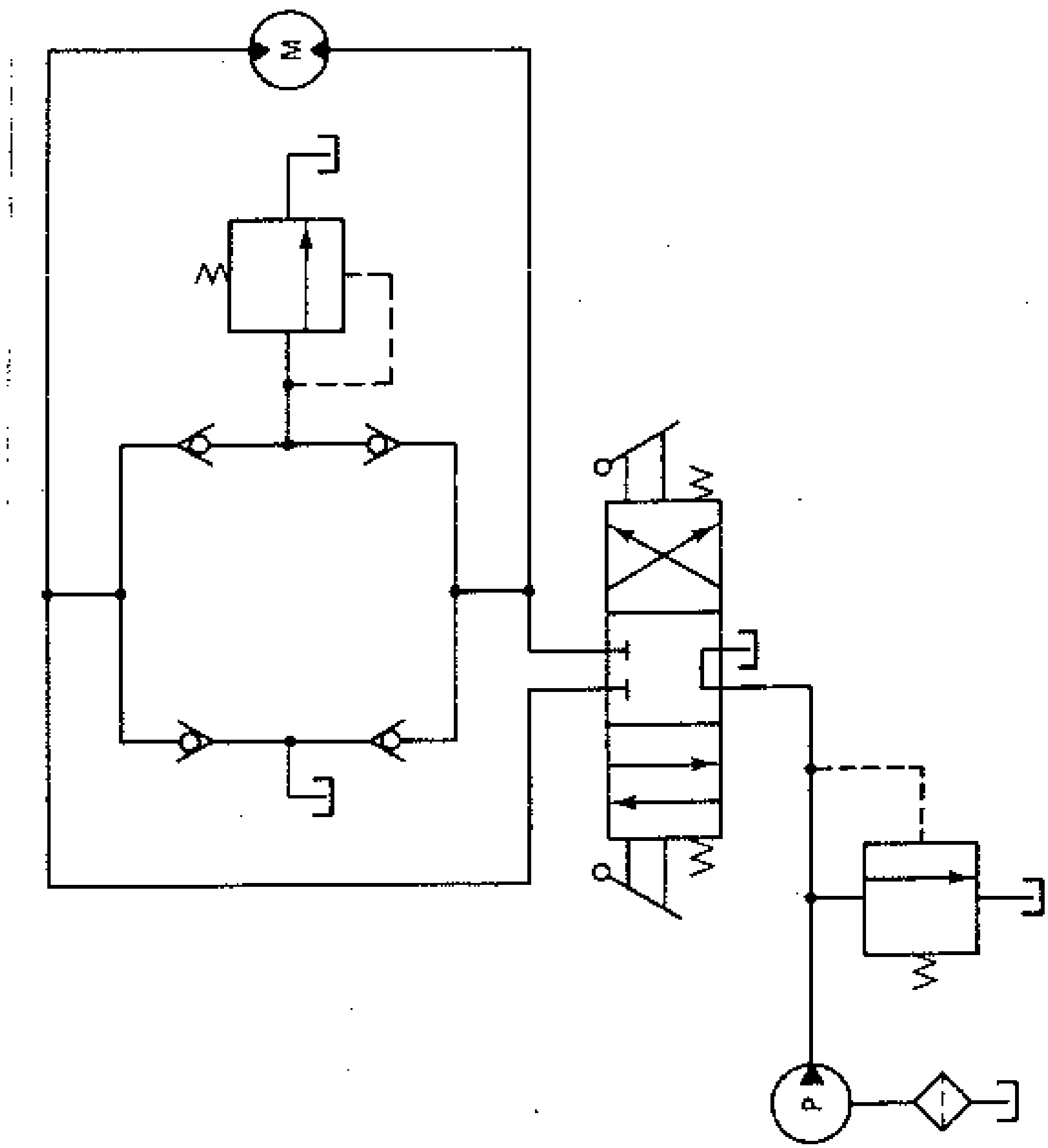
COUNTERBALANCE HYDRAULIC CIRCUIT

Sometimes, power failures can cause hydraulic pistons with heavy loads to become unsupported and fall under gravity. This could cause damage to equipment or people. A counterbalance circuit protects against this. Such a circuit is shown to the right of the actuator. With the flow paths as shown, the pressure relief valve traps the hydraulic oil directly below the piston. Its operating pressure is greater than the pressure required to support the piston load. So, the piston does not fall. When the flow paths on the right are active, the pressure below the piston becomes high and opens the relief valve and the piston moves downward. When the flow paths on the left are active, oil bypasses relief valve through check valve and the piston moves upward.



HYDRAULIC BRAKE CIRCUIT

Sometimes, hydraulic pumps are used to operate hydraulic motors. Imagine that the flow paths on the left were operating but because of a power failure the neutral paths suddenly took over. Because of its inertia, the hydraulic motor could act as a pump and generate high pressure one side of it and low pressure the other side of it. Both could damage the hydraulic lines. The circuit to the left of the motor protects the lines from such pressures. If hydraulic oil was moving down through the motor at the moment of failure, it would generate pressure below that would open the relief valve and allow oil to escape to the sump. It would also suck oil from the sump through the top check valve on the left: this would prevent collapse due to suction. Because the motor is acting as a pump, it would gradually lose its energy to the oil. The oil would act as a brake.


M
P

PRESSURE INTENSIFIER CIRCUIT

Punch presses require high pressure when they are pressing something. One could use a double pump circuit to get such pressures. However, one could also use just a high flow pump and a pressure intensifier. Essentially, a pressure intensifier is a piston that has a larger area on one side than on the other. During a press operation, the larger area side feels low pressure oil from the high flow pump. The other side pressurizes oil in the press actuator. Only a limited amount of oil can be pressurized so the movement of the actuator piston must be small.