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Vacuum Mechatronics Components

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Chapter 4

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4.1 Actuators

In many cases the vacuum environment is utilized effectively only when it is possible to input the power to actuate mechanisms which can do useful work. This can be accomplished by mechanical feedthroughs or by electrical feedthroughs beyond the vacuum boundary. Power can either do the work directly, or can be converted by an actuator into the necessary form, e.g., electrical to mechanical by motor, shape memory alloy, or piezoelectric actuators. During the conversion and transfer, a certain amount of heat is generated and the resulting mechanism is also a potential source of particle contamination. Thus, the transduction mechanisms must be very efficient in order to minimize heat generation and mechanical contact. In this section, various types of actuators for the vacuum environment will be discussed.

Rotary and Linear Feedthroughs

Mechanical feedthroughs are divided into two classes: rotary and linear. For applications at pressures down to 10^{-6} Torr, O-ring seals (e.g., "Viton A" O-rings lubricated with graphite) are often used to seal the transmission of rotational motion. Figure 4.1 shows two typical assemblies of low-speed rotary feedthroughs. Multiple seals are sometimes used to reduce the leakage rate, and pumping of the cavities formed by consecutive seals is even more effective. The seals are not bakeable, however, and thus are not suitable for ultra-high vacuum applications.

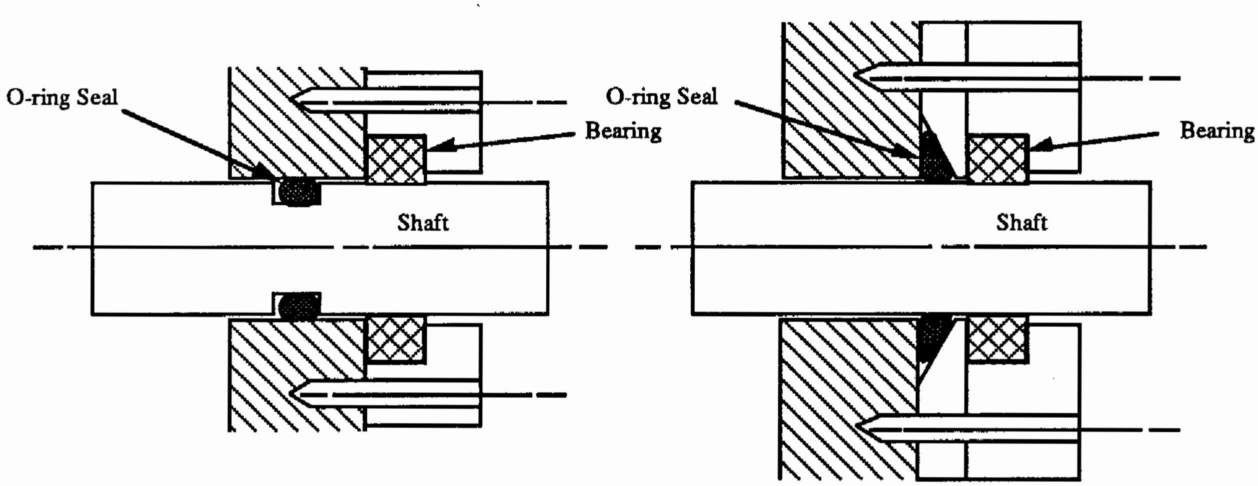


Fig. 4.1 Rotary feedthroughs for low speed.

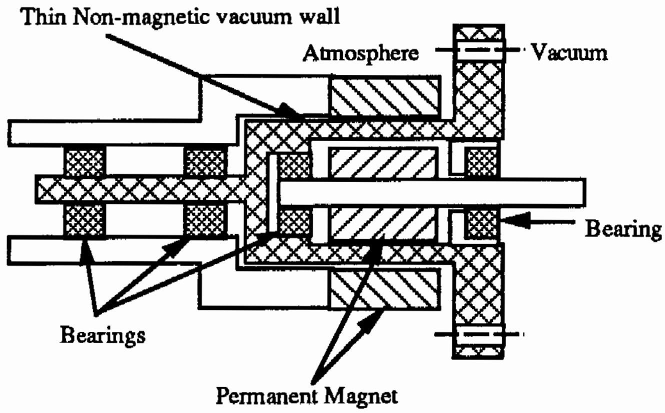


Fig.4.2 Rotary motion feedthrough using magnetic coupling.

A magnetic coupling effect can be used to implement a low-torque feedthrough, as shown in Figure 4.2. Opposite poles of permanent magnets are lined up against each other to produce the magnetic coupling. The rotational movement of permanent magnets on one side forces the shaft on the other side to move in the same direction. The transmitted torque is limited by the strength of the magnetic seal, which is inversely proportional to the distance between the two permanent magnets. There is a one-to-one ratio between the input and output shaft positions when the feedthroughs are operated below the saturation torque.

Sealing of rotary motion can also be achieved using a magnetic liquid suspension as a vacuum seal (Figure 4.3). Multiple seals are formed by a magnetic liquid material and magnetic field which is provided by the permanent magnet in the housing. This feedthrough allows transmission of high torques and high rotational speeds.

O-ring seals have a tendency to roll and twist in the gland under relative linear motion, and so are not suitable for use in linear feedthroughs. Linear motion in a vacuum can be achieved by a rotary feedthrough in concert with a rack-and-pinion at one end. This arrangement requires lubrication of mechanical components with relative motion in vacuum. This mechanical contact will introduce contaminants into the vacuum environment.

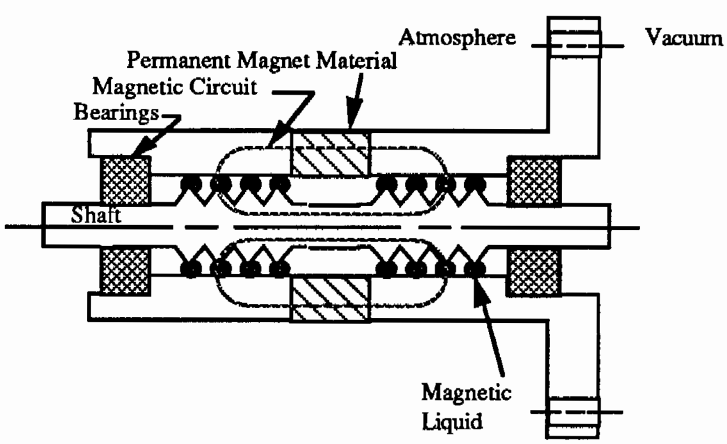


Fig. 4.3 Rotary motion feedthrough with magnetic liquid sealing.

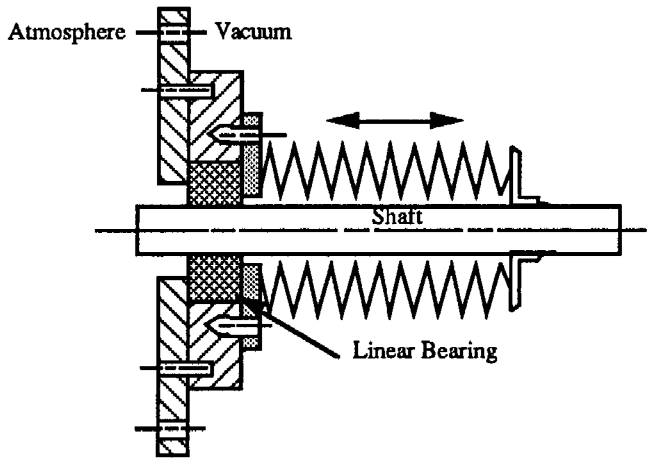


Fig. 4.4 Bellows-sealed linear motion feedthrough

A satisfactory linear motion feedthrough is achieved by using bellows, as shown in Figure 4.4. Two types of bellows are available: hydraulically-formed bellows and edge-welded bellows. The formed bellows are generally less costly, but the welded bellows give a superior performance in terms of flexibility and linear motion along the axis per unit length of bellows. Welded bellows are usually made of 18/8 stainless steel and thus can be baked to 450°C. The bellow system is suitable for low linear speeds and small strokes. Miniature metal bellows with low stiffness have been manufactured by an electro-deposit method. These bellows are made by forming a mandrel to the shape of the inside of the bellows and depositing metal with the desired stiffness on the mandrel. The ends are trimmed and the mandrel is dissolved. These bellows have been made with outside diameters as small as 0.035", and are extremely flexible.

Vacuum Motors

Motion inside a vacuum can also be achieved without a mechanical feedthrough, using motors that are specially designed to operate in a vacuum. The design constraints include: minimum power dissipation, a heat conduction path to the atmosphere, vacuum-compatible lubricants to avoid bearing seizure, and winding insulation with a high temperature rating (>150°C).

Stepper motors are commonly used for vacuum applications. The motor mount is used to conduct heat through the vacuum wall to an external heat sink. For continuous heat dissipation, water cooling may be provided at the heat sink. Temperature sensing is essential and is achieved by attaching a thermistor to the stator or to the housing furthest from the mounting. There is a time-delay on the order of 20 minutes before the casing reaches the same temperature as the inside winding insulation. When operating a motor inside a vacuum, the holding current should be reduced or eliminated when the mechanism is in a holding mode, and the power should be reduced after the motor's initial movement.

Motors operating in vacuum will outgas with rising temperature. For good vacuum performance, the motor temperature must usually be kept below 100°C. Motors can be baked prior to the vacuum application in order to minimize the initial outgassing. Commercially available vacuum-compatible motors and encoders are discussed in chapter 6. Appendix A lists company names.

Piezoelectric Actuators

Certain types of crystals, when mechanically deformed, produce an electric field; conversely, when an electric field is applied the crystals undergo a physical deformation. This phenomenon is the basis of the piezoelectric actuator. Single crystals of many compounds show piezoelectric properties, e.g. quartz, rochelle salt, ammonium dihydrogen phosphate, and tourmaline. Recent advances in ceramic technology have produced ceramic materials, such as barium titanate and lead zirconate titanate, with piezoelectric properties.

The general expression relating the strain vector S produced in the piezoelectric block by the electric field E is:

$$S = d \times E \quad \text{Eq. (4.1)}$$

where d is the piezoelectric strain coefficient. By measuring the strain $\Delta x/x$, for certain applied voltages at a no-load condition, and then adding a load that returns the dimensions to the original length, a stress-strain characteristics diagram can be generated. Repeating the experiment for different voltages produces a family of graphs, as shown in Figure 4.5.

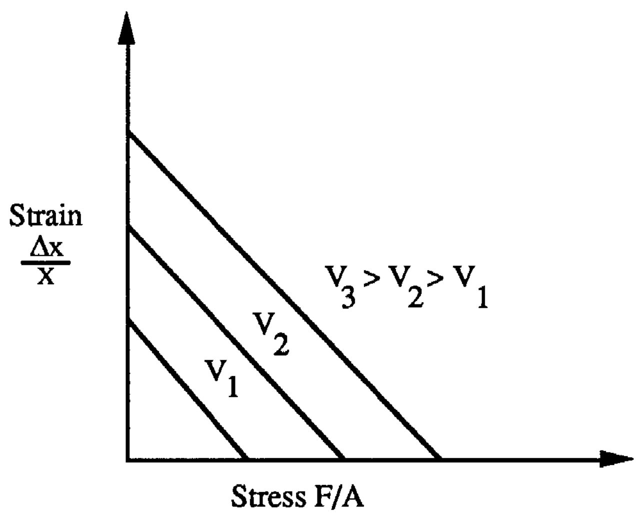


Fig. 4.5 Stress-strain curve for a piezoelectric block [4.1]

Piezoelectric elements are essentially capacitors. During static operation, current is not drawn and power is not consumed to maintain a state of actuation. Power is required only to change the voltage. Piezoelectric ceramics dissipate power in proportion to dielectric loss in the crystal, which is defined as the ratio of the effective series resistance to the effective series reactance. This factor varies from 0.02 for soft ceramics to 0.0005 for hard ceramics at 1000 Hz. At low frequency, this factor is negligible, making these materials suitable for vacuum applications.

Piezoelectric actuator designs vary depending on the application (stroke length, linear motion, rotary motion, etc.). A common design is a linear actuator with a stroke of 6 to 8 inches. Figure 4.6 shows the principle of operation of one such actuator. When voltage is applied to the first element, it clamps the shaft. A variable-rate voltage is then applied to element 2, causing it to change length in discrete steps at a few nanometers per step. Voltage is then applied to element 3, causing it to grip the shaft. If necessary, 1 may be unclamped, 2 contracted, 1 clamped and 3 unclamped to reach the initial configuration. This sequence can be repeated until the desired stroke

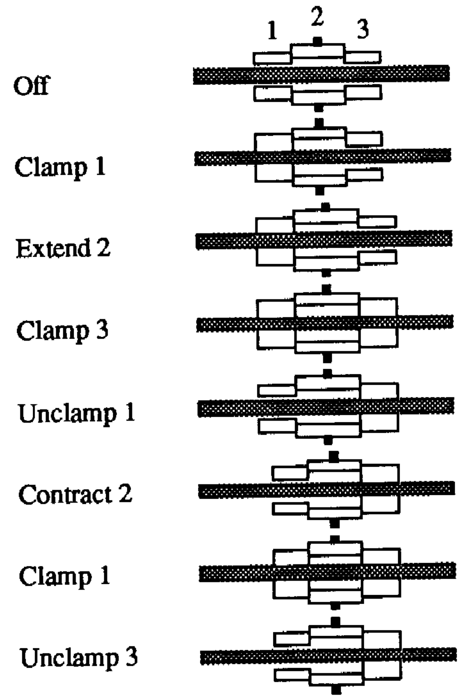


Fig. 4.6 Operation of a Piezoelectric Linear Actuator
(The Inchworm™ from Burleigh Instruments, Inc. [4.1])

is reached. The actuator is mounted at element 2. For a clamp frequency of 400 Hz, speeds exceeding 1 mm/s can be achieved.

Piezoelectric devices are inherently simple and can be made with good outgassing properties. This factor, coupled with their high heat dissipation, makes them excellent actuators in vacuum at low speeds and torques. Piezoelectric actuators for high resolution positioning normally use a high driving voltage (approximately 1000 volts) which makes them less sensitive to electrical noise, resulting in less jitter. When operating these devices in vacuum, the voltage must be turned off when the artificial vacuum chamber is being evacuated because there is a danger of electrical arcing as the pressure goes through the corona region (0.1 to 100 Torr). [Note: arcing leaves carbon deposits, and therefore creates the possibility of permanently shorting the actuator.] One disadvantage in employing such actuators is that the mechanical contact produces contamination undesirable in a vacuum environment.

Shape Memory Alloy (SMA) Actuator

After an apparent plastic deformation, certain metallic materials will return to their original shape when heated. This phenomenon is known as the shape memory effect. A part which is deformed or stretched at one temperature will completely recover its original shape when heated to a second temperature. In the process, the moving alloy delivers a force.

Shape memory is a behavior unique to alloys which undergo martensitic transformation. The martensite phase in these alloys, unlike martensite phase in steel, is thermoelastic; i.e., it continually appears and disappears with falling and rising temperatures. Figure 4.7 shows the stages for producing the shape memory effect in a copper alloy. The temperature at which martensite starts to form, after cooling from the parent phase temperature, is called M_S. The temperature at which the bulk transforms is M_f. When the alloy is heated, the initial parent phase reforms at A_S and is completed at A_f. Some common alloys are Ni-Ti, Cu-Zn-Al and Cu-Ni-Al.

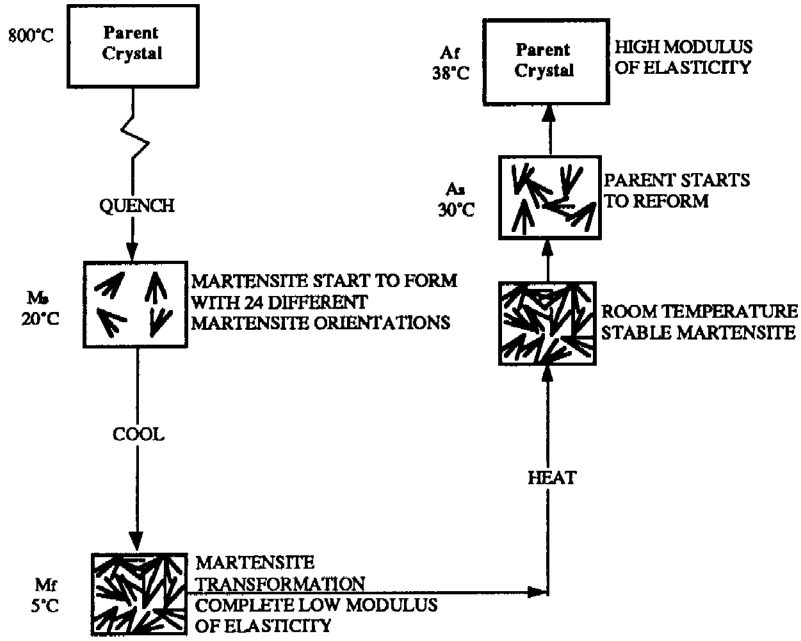


Figure 4.7 Stages for producing the shape memory effect in a copper alloy (From [4.3]).

The M_S of these alloys can be varied from -105°C to 170°C. Alloy heating can be accomplished by contact with a heating element or by passing current through the shape memory alloy itself. Cooling is accomplished naturally or with the aid of convective devices (e.g fans), or by contact.

Figure 4.8 shows two manifestations of the shape memory effect: one-way memory and two-way memory. In one-way memory, the deformed SMA can be heated to its original shape. In two-way memory, the deformed SMA cycles between the original shape and the deformed shape, depending on whether it is heated or cooled. The latter can be used for two-state applications.

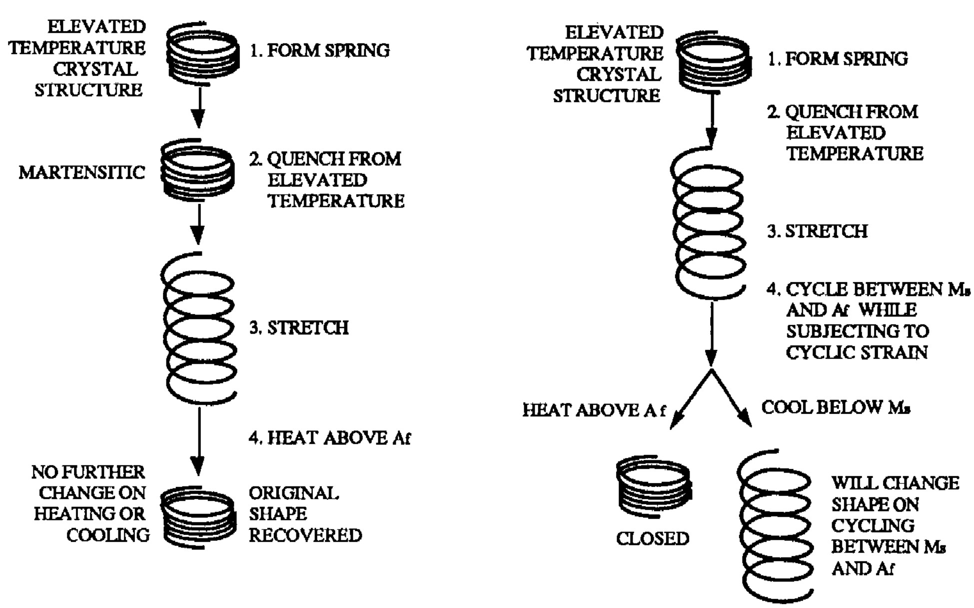


Fig. 4.8 Shape memory (From [4.3])

The Ni-Ti alloy has been found to be suitable for vacuum applications. It has a low vapor pressure, a low rate of outgassing, and a relatively high transformation temperature. It also has a cleanliness rating equivalent to class 10 or better. This alloy has been used in ultra-high vacuum to open and close a shutter mechanism, as discussed in the reprint by Jardine *et al.* [4.2] included at the end of this chapter. For repeated operations, the alloy must be cooled and heated. If the cycle time is long (>30 mins), radiation effects are sufficient to cool the alloy. For shorter cycle times, forced convection is necessary. This poses several design problems because the coolant must be passed through the vacuum envelope in a vacuum-compatible flexible tube. Also, a conduction path must be established between the SMA and the coolant while simultaneously preventing an electrical short circuit to the cooling tube. The tube may be copper or another conductive material.

4.2 Sensors

This section will discuss sensors other than the ones used for monitoring the vacuum and measuring particle contamination. Sensors are one of the means of monitoring the environment. They may be used to simply inform the human operator of the status of the system. Now, however, they are being used more and more to allow the system to behave intelligently.

Early automation attempts were repetitive and allowed operation only in a known, well-structured environment with little change in the process or handling mechanism. This level of performance was adequate in many situations, yet the automation equipment, e.g. robots, required a vast amount of programming and information about the environment. This was true, for example, in the spot welding of automobile bodies where each car that came along was secured to the same point on the floor. The robot did not need any sensory capabilities in order to locate welding spots.

Today's stringent requirements on the quality of industrial products, especially in microelectronics and other high-precision technologies, demands a more intelligent, flexible machine. Such a programmable machine allows the system to adapt itself to the environment by using information from sensors, thus interpreting the given commands to suit the situation. In a remotely operated system, such as an in-vacuum manipulator, or a telerobot, the operator or controller uses information from many sensors to control the robot manipulator in highly variable and essentially unpredictable situations (See Fig. 4.9). Position sensors identify the end-effector position, vision sensors recognize the position and orientation of the object to be handled, and other sensors can then be used to ensure proper control and stability of the system [4.5].

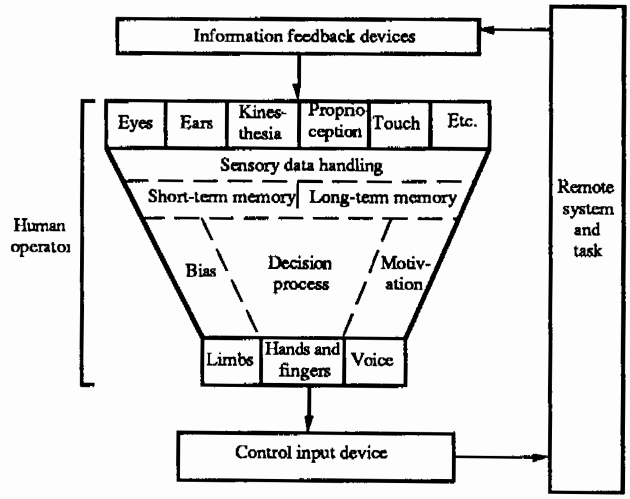


Fig. 4.9 Operator-centered view of teleoperation (from [4.4], p. 321)

The mechanism's performance and reliability are a function of the proper use of its components within specification. Many components are sensitive to temperature variations and tend to lose their effectiveness at extreme temperatures. An electric motor is specified to operate below a maximum temperature, and its efficiency decreases at high temperatures. In such situations, temperature feedback via sensors can be used to shut the system down. This is especially critical for vacuum-compatible mechanisms since air convection does not exist.

Sensor Applications for Vacuum Mechatronics

In controlling a mechanism in vacuum, a number of control variables must be monitored. These include geometric variables such as position and orientation, and fluid and thermal quantities, such as temperature and pressure. This section identifies the sensory systems which are the most appropriate for each parameter.

Position Sensors

The control of a robot manipulator and other mechatronic devices in a non-accessible environment requires position sensing and feedback. This information is used in determining the appropriate torque to apply to the manipulator joint in order to position the device. Angular position sensors are used at the joints of the robot, providing information to solve the forward kinematic relationship. Position sensors can also be used to identify the end-effector orientation relative to a reference frame, which is particularly important when an object must be grasped and manipulated.

A robot mechanism also possesses "robot singular configurations" in which the arm movement is constrained in particular directions where the load on the joints is very high. Angular position information can be used to prevent the robot arm from exceeding its singularity limits.

Other applications of robot position sensing involve obstacle avoidance. In these cases, the position of each object in the work area is established relative to a particular frame of reference. By using remote position sensors, which are either attached to the robot arm or stationed in the environment, the controller uses the sensor information to plan movements that will guide the robot to the desired position/configuration without collisions.

Vision Sensors

In robotics, computer vision is used for locating the position of objects in the environment, including the manipulator, and for inspecting objects for errors or defects. In manipulator control. the vision system is able to identify the workpiece position, orientation and condition. This enables the robot to handle inaccurately positioned objects with variable orientation. Accuracy of the system depends on the resolution of its vision; resolution improves by reducing the field of view through the use of magnifying lenses, or by using vision components with higher resolution. The latter is more expensive.

A vision inspection system helps in identifying surface defects such as cracks, voids, and stains. It can also be used for measuring the critical dimensions of mechanical parts and even for gauging "wear and tear." The data on the various defects is categorized by type, size, location, etc., and is readily stored in databases for analysis.

It is important to have a remote global sensor such as a camera in the vacuum chamber in order to monitor the movements of all robots and/or objects. Other applications include end-point positioning, where the workpiece must be positioned accurately relative to a reference frame which is attached to the chamber. *In-Situ* inspection during in-vacuum manufacturing is another application which may include vision sensors.

Temperature Sensors

One purpose of in-vacuum manufacturing is to assemble clean parts with close tolerances. High accuracy and repeatability (typically less than 10 μm) are required for many of these tasks. Energy waste, resulting from friction and driving mechanism losses, raises the temperature of the components and may affect their physical stability. For example, when using aluminum 6061-T6 or stainless steel 304, a linear expansion of manipulator links on the order of 20μm/m per °C occurs. Accounting for this expansion during operation in vacuum is therefore critical. Other material properties that are sensitive to temperature variation, such as the tensile and torsional modulus of elasticity, must be accounted for when designing mechanisms for the space environment.

Heat generated during operation in vacuum is primarily dissipated by conduction. Some heat is carried out through leads, increasing their temperature. This heat, if excessive, can melt solder from joints and loosen connections. The temperature can be controlled by cutting power to idle circuits. It is recommended that thermocouples be incorporated into the mechanism's design.

Sensor Types

The vacuum chamber interior is considered an "inaccessible" environment, and thus requires a large number of vacuum-compatible sensors in order to perform an intelligent task. Most sensors used in vacuum have the same operating principles as those used under normal atmospheric conditions. The key parameters in the design of sensors for vacuum are proper surface materials and an adequate cooling system for the electrical components. Various low vapor pressure coatings must protect the surfaces that are exposed to vacuum. For example, soldered joints are coated to reduce outgassing. Vacuum-compatible components must be highly efficient in order to prevent the heat generation. Forced convection methods are normally used to cool electro-mechanical components with a large power consumption. Such methods are discussed in section 3.3.

Robotic sensors may be functionally divided into two kinds: contact and non-contact. Contact sensors include touch, tactile, and force/torque sensors. Non-contact sensors include proximity, range, and vision sensors. These sensors might be used separately or in various combinations.

Contact

Contact sensors are responsive to actual physical contact. In robotics, touch sensors are used partly in determining the relationship between the object and the manipulator "hand", thereby allowing control of the exerted force on the object. They are compliant devices, and transform the strain in a material to electrical signals. For example, the UCSB Hand uses an advanced form of force-torque sensor with strain-gauge bridge circuits to measure contact pressure [4.6]. Each finger of the three-fingered "hand" can sense and measure force and moments in three dimensions. Other methods of measuring strain include optical systems and lasers. Optical systems have a sensitivity threshold of 0.04 grams [4.7, 4.8]. Laser devices possess higher resolution but are more expensive [4.9].

Slip sensors measure the distribution of pressure between a robot hand and grasped objects. They are of two types: single point and array. Transducers used in this type of sensor are strain gauges, pressure-conductive elastomers, capacitive and piezoelectric elements [4.4].

Force and torque sensors are used in measuring the reaction forces at robot wrists and joints. Deflection is one possible result of applying external forces to a robot. The wrist sensor is positioned between the tip of the robot arm and the end-effector, and consists of various strain-gauge bridge circuits that measure deflection of the sensor's structure. This type of sensor normally has a stiffer structure and is used to measure larger forces than the touch sensor. Joint sensors estimate the total actuator force supplied to any joint. When a DC motor is driving the joint, the joint sensor measures the motor's current as well. When hydraulics or pneumatic actuators are used, the back pressure is measured.

Non-Contact

A non-contact sensor outputs a signal proportional to the electromagnetic or acoustic radiation in the environment. Many non-contact sensing devices have been designed for aerospace and vacuum environment applications, including electromagnetic, microwave, infrared (IR), laser, imaging, and particle sensors. New sensors are continually being designed, while simultaneously the older models are being improved. Hord [4.10] lists many of the sensors used for space technology and makes predictions on future sensor developments.

Microwave systems are used in sensing environmental conditions such as temperature, windspeed, humidity and precipitation. IR sensors are used for remote sensing, such as in reading planetary surfaces and industrial furnace temperatures. Laser systems are used primarily for the range detection of atmospheric and chemical species, and for their profile measurements. Charge-Coupled Device (CCD) imaging has been used for remote sensing, attitude and orbit control, and target detection [4.11]. Charged particles traversing a magnetic field are measured by a magnetic spectrometer particle detector.

Proximity, range, and vision sensors are also used in vacuum mechatronics, enabling mechanisms to interact in vacuum, by indicating the presence or absence of objects. Proximity sensors generally have binary output and utilize either electro-optical or electromagnetic measurement principles. Electro-optical proximity sensing consists of a light emitter (typically a light emitting diode or a low-power laser) which acts as a transmitter and a photodetector receiver. Electromagnetic proximity sensing devices can be in the form of inductive, Hall-effect, and capacitive sensing units. The inductive and Hall-effect sensors detect only ferromagnetic materials, but capacitive sensors are capable of detecting all solid and liquid materials. Each type may be used in vacuum, assuming proper material and thermal design.

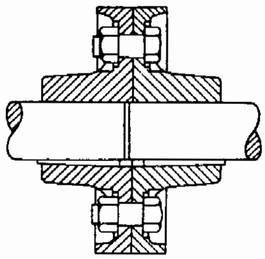
Range sensors are used for measuring the distance from reference points to objects. Triangulation and time-of-flight techniques are used, along with electro-optical and acoustic principles, to estimate the desired range. Refer to Nof [4.4] for a description of these techniques.

Cameras are visual sensors. Vidicon and solid-state array are the two types of cameras that are used in robotics. Solid-state array cameras are used most often, even though they are slightly more expensive than Vidicons. Advantages of the solid state imaging devices include: lighter weight, smaller size, longer life, and lower power consumption. However, some Vidicon cameras have resolutions beyond the capabilities of solid state cameras. The resolution of CCD cameras ranges from 32x32 to 1024x1024. Reference [4.12] describes the principles of operation of both cameras. For black and white cameras, a video signal proportional to the intensity of input image is produced, and for color cameras a composite color image with red, green and blue components is output.

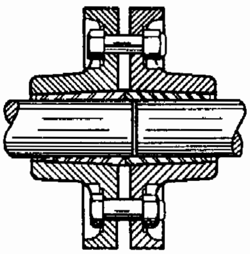
In addition to weight and resolution, vacuum-compatible cameras have the following requirements:

- vacuum-compatible housing,
- low power consumption, and
- cooling.

The power consumed by the electronics and CCD array typically does not exceed 7 watts.



a. Flanged face coupling



b. Keyless compression coupling

Fig. 4.10 Rigid couplings (From [4.13])

4.3 Energy Transmission

Many types of transmission elements have been used in robotics to transmit mechanical power from a source to a load. The type of element used depends on the nature of the motion, power requirements and the geometry and configuration of the system. The factors involved in the transmission design are efficiency, stiffness, and cost [4.13]. In this section a number of transmission elements are presented.

Couplings

One method of transmitting the motion from one shaft to another is by means of a coupling, which may be rigid or flexible. A rigid coupling is used to connect the shafts with perfect alignment and is rigid in axial, radial and tangential directions. They possess different shapes depending on the configuration of the shafts' end-faces and the alignment method used. Figure 4.10 shows two types of rigid couplings. The flanges are either keyed to the shafts or to a tapered cone-shaped sleeve for automatic centering of the shafts. This type of coupling introduces an additional dynamic load and moment, which are functions of the alignment tolerances on the shaft support bearings.

The flexible coupling employs a spring or rubber material which provides flexibility in the axial and radial directions but has high rigidity in the torsional direction. This type of coupling is useful for misaligned shafts in the lateral and/or angular direction. A helical flexible coupling is shown in Fig. 4.11. This type of coupling eliminates the dynamic loads and moments produced by misaligned shafts, but may fail with excessive vibration, acceleration or braking loads.

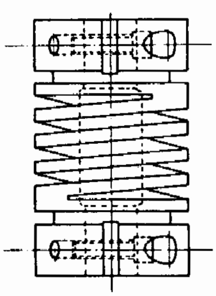


Fig. 4.11 Helical coupling (From [4.4, p. 60])

Brakes/Clutches

Brakes are used to convert the kinetic energy of a moving mass to heat or other forms of energy. Mechanical and electromagnetic principles are used to slow down, or in emergency situations, stop the motion of the motor shaft. Mechanical brakes are commercially available in different types: block, cone, disk, and spring. They are generally constructed with a stationary part which is clamped to the mechanism's body and a free part which is attached to the moving mass. The friction between the two parts creates the braking action.

Electromagnetic brakes are more widely used in computer-controlled mechanisms. Commercially available electrical brakes include eddy-current and magnetically actuated brakes. The eddy-current brake is used with flywheels where high braking power is necessary to reduce kinetic energy. Electrically actuated magnetic poles create a magnetic flux that permeates the gap and the iron of the wheel rim. The kinetic energy of the fly wheel is converted to heat in this manner. The magnetic type of brake includes an electric coil, springs, a rotating member attached to the shaft, and a stationary plate attached to the housing. The brake force is generated by the springs and counteracted by the magnetic force of the coil. This is mostly used in fail-safe brake designs. These types of brakes/clutches are important for use in vacuum-compatible mechanisms in order to reduce the heat generation at joints during a holding mode.

Mechanical motion is sometimes transmitted from one component to another by means of a clutch. When both members must be connected and disconnected frequently, a clutch is the most useful device. The principal of operation is the same as a brake, but with no stationary parts involved.

It is important to note that the effectiveness of a brake or clutch is dependent on its ability to convert power to thermal energy and dispose of the frictional heat. The amount of energy to be dissipated is proportional to the frictional force and the speed. Special cooling methods may be necessary to remove the heat. Particles are generated from the frictional effects which must be trapped in a housing enclosure around the device.

Gears

Motion can be transferred from one shaft to another and a definite ratio between the velocities of the shafts can be maintained if a gear assembly is used. Gears are commercially available in many forms and are grouped according to the tooth forms, shaft arrangement, pitch and quality. The following summarizes these properties:

Tooth form	*Shaft arrangement*
Spur	Parallel
Helical	Parallel or skew
Worm	Skew
Bevel	Intersecting
Hypoid	Skew

Available types: Coarse (for $P_d \leq 20$),
Fine (for $P_d > 20$),
where P_d is the diametral pitch, defined as the ratio of the number of teeth in the gear to the pitch circle diameter.

Available classes: Commercial,
Precision, and
Ultra-precision.

Material and Designation	Tensile strength (psi)	Yield strength (psi)	Hardness (BHN)	Condition
Cast irons:				
ASTM 20	22,000	.....	156	As cast
30	31,000	.....	201	As cast
60	62,5000	.....	262	As cast
Plain carbon steels:				
AISI 1020	55,000	30,000	110	Hot-rolled
1020	78,000	66,000	155	Cold-worked
1040	76,000	42,000	150	Hot-rolled
1040	123,000	93,000	350	Cold-worked
1080	112,000	61,000	230	Hot-rolled
1080	189,000	142,000	385	Cold-rolled
1117	62,000	34,000	120	Hot-rolled
1117	80,000	68,000	163	Cold-worked
Alloy steels:				
AISI 3140	105,000	90,000	280	Heat-treated
3140	228,000	209,000	450	Heat-treated
4140	145,000	120,000	290	Normalized
4140	215,000	190,000	440	Heat-treated
4820	150,000	125,000	325	Heat-treated
4820	206,000	166,000	415	Heat-treated
6120	125,000	94,000	....	Heat-treated
8620	122,000	98,000	245	Normalized
8620	173,000	142,000	375	Heat-treated
9310	152,000	120,000	350	Heat-treated
9310	180,000	140,000	375	Heat-treated
Stainless steels:				
AISI 303	90,000	35,000	160	Annealed
303	110,000	75,000	240	Cold-worked
416	75,000	40,000	155	Annealed
416	160,000	140,000	350	Heat-treated
Bronzes:				
Aluminum bronze ASTMB139	105,000	60,000	B100	
Phosphor bronze ASTMB1397	60,000	45,000	B70	
Silicon bronze ASTMB 99	58,000	25,000	B100	
Aluminum alloys:				
2024-T4	68,000	47,000	120	Heat-treated 1/2 hard
7075-T6	83,000	73,000	150	Heat-treated 3/4 hard
Non-metallics:				
Phenolic laminate				
NEMA, Grade C	11,000	.....	M-103*	
NEMA, Grade L	14,000	.....	M-105*	
Nylon				
ASTM6	8,700	6,000	M-100	2.5% moisture
ASTM 66	11,000	8,500	M-108	2.5% moisture

*Rockwell

Table 4.1 Typical Gear Materials (From [4.13], p. 8-117)

Considerations in designing geared transmissions include gear ratio, type of gear, gear shaft support, backlash, and lubrication. Backlash is important for precision machines. It normally arises due to the fabrication tolerances of the tooth thickness, and the clearance between meshing teeth allowed for lubricant and thermal expansion. Backlash results in the loss of motion when reversing the gear rotation. Backlash is also a function of the change in distance between the centers of the mating gears and the pressure angle:

$$B = 2(\Delta C) \cdot \tan \Phi$$

Where ΔC = Small change in center distance, and

Φ = Pressure angle.

Typical gear materials and their physical properties are listed in Table 4.1.

A harmonic drive assembly is a transmission that has a high gear ratio and near zero backlash, but has high static friction. It consists of three components: 1) a wave generator, 2) a flexible spline, and 3) a circular spline which has teeth of the same pitch as the flexible spline (see Fig. 4.12). The wave generator includes an elliptical cam and a ball bearing with a flexible outer ring. A motor shaft drives the wave generator. The cam motion deforms the flexible spline and causes meshing of some involute teeth on the flexible spline with those on the circular spline. The circular spline is attached to the housing and is stationary. The difference in the number of teeth on the splines creates a small motion in the flexible spline of one revolution per cam rotation. This motion is transmitted to the output by the flexible spline body. The harmonic drive is used with in-line parallel shafts. It is commercially available in compact form and is used as a speed reducer for precision machines. It is usually immersed in oil while operating.

Several factors must be considered when using gears in vacuum. Material selection and lubrication are the most important. Significant mechanical and physical properties of the material include:

- yield strength
- surface hardness
- contact pressure fatigue resistance
- damping capabilities
- wear resistance
- machinability.

The first three characteristics determine the load-carrying capacity of the gear. The vibration of

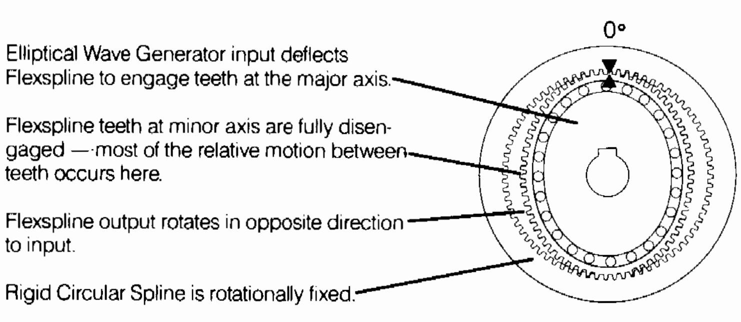


Fig. 4.12 Harmonic drive assembly (From [4.14])

gears is also material dependent. Noise is reduced and damping is increased by using non-metallic gears. Wear-resistant material must be used to increase the life of the gear and reduce contamination. Good machinability is required in order to obtain good geometric tolerances.

A lubricating mechanism must be provided for the gear teeth in order to decrease friction and wear. The choice of a lubricant is a function of the gear load, speed, temperature, and ease of implementation. The lubricant is either wet or dry coated on the gear. The selection criteria for coatings includes:

- absence of scuffing in vacuum
- low wear rate
- low coefficient of friction
- lack of geometric modification during and after coating
- good adhesion between coating and substrate. [4.15]

Teflon gears do not require lubricants, and are useful for designing lubricant-free gear trains. They can be used as idler gears between stainless steel drivers and other driven components. The drawback of this method is that the power transmission is a function of the properties of Teflon, which is weaker and more temperature-sensitive than stainless steel.

Chain Drives

Motion can also be transmitted via chain drives, which can have high efficiency (98 to 99%) and no slippage. Two sprocket wheels (driver and follower) are used with the chain. The power rating of the chain depends on the number of teeth and rotary speed of the smaller sprocket. Multiple strand chains can be used for applications requiring high power. It is important to pre-load the chain properly to avoid drooping or breakage. For vacuum applications the chain drive assembly must be lubricated, and, in order to reduce particle contamination, cannot have direct exposure to the surroundings. An appropriate vacuum grease is the most widely used lubricant for this purpose.

4.4 Machine Elements

The design of vacuum-compatible mechanisms involves the use of machine elements that are suitable for that environment. This section identifies seals, bearings, linkages and joints with their vacuum properties.

Seals

In vacuum systems, static seals are needed where flanges are joined. Dynamic seals are used to transmit motion through the vacuum envelope. Characteristics of current dynamic sealing methods used in mechanical feedthroughs have been covered in section 4.1.

Static seals include elastic and metal gaskets. The former are used for pressures down to 7.5×10^{-9} Torr (10^{-7} Pa) and temperatures up to 300 °C, making them suitable for the baking cycle of the flange. In addition to these characteristics, the gasket material is chosen according to the outgassing rate and gas permeability. Table 1 in the reprint by Weston shows the properties of some synthetic materials used for vacuum seals.

The leak rate of an elastic gasket can be reduced by applying a high vacuum grease (e.g. silicone grease) to the gasket surface. Figure 4.13 shows the effect that the amount of squeeze has on the

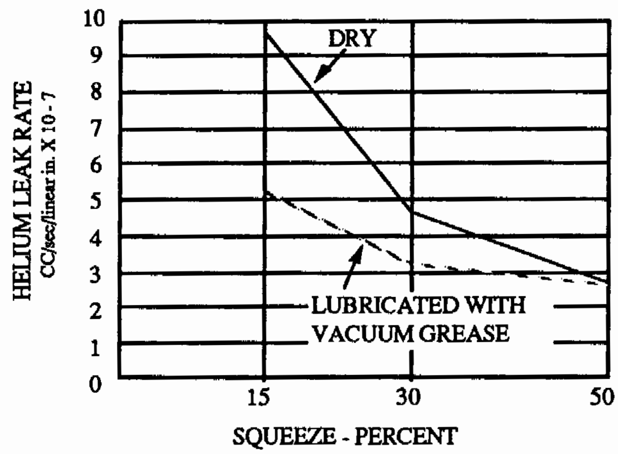


Fig. 4.13 Percent squeeze on the O-ring vs. leak rate (Adapted from [4.17])

leak rate. The groove design for this type of gasket requires a surface finish smoother than 16 μm to reduce the leak rate significantly.

Metal seals are mainly used for lower pressures and higher temperatures (up to 500°C). Gold, copper, indium, aluminium, and silver are sometimes used as metallic gaskets. A sharp knife-edge or other irregularity on the flange face is used to deform the soft gasket material beyond its elastic limit into the plastic region. Care must be taken to avoid damaging the high surface finish of the flange face. This type of seal is not re-usable.

Another type of metal gasket uses the springy characteristics of some metals, e.g., monel and stainless steel. These materials are coated with softer materials such as indium or copper and are compressed against the flange faces in the groove. This type of seal is re-usable but more expensive. The surface cleanliness, flatness, and finish are even more important than that for elastic gaskets. Weissler and Carlson [4.16] present a thorough explanation of vacuum flanges.

Bearings

There are three general types of bearings, classified according to the type of support they provide:

1) Journal bearings, which support a rotating shaft in the radial direction,
2) Thrust bearings, which support a rotating shaft in the axial direction, and
3) Guide bearings, which support a non-rotating shaft in the radial direction.

The following parameters should be considered when selecting bearings for vacuum-compatible mechanisms:

- frictional torque,
- thermal conductance across the races,
- bearing stiffness,
- material, and
- contamination.

Ideally, bearings do not show friction in the direction of motion. This can be achieved by using a non-contact levitating system (see section 4.5). The design and operation of roller and slider bearings are explained in the text by Shigley and Mitchell [4.18]. The contact friction in these types of bearings converts power to heat, which is especially undesirable in vacuum. The generated heat is conducted to the sink through the bearing. If thermal conductance of the bearing is low, the temperature rise will cause thermal expansion and an additional load on the bearing mount. Experiments have shown that the frictional torque and the thermal conductance is a function of the type and amount of lubricant [4.19]. Methods of reducing friction and increasing thermal conductance are discussed in chapter 3. Dry lubrication methods for different types of bearings have been studied, and some examples are shown in Table 4.2.

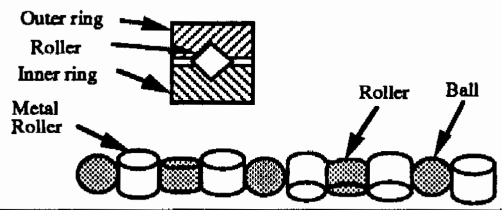
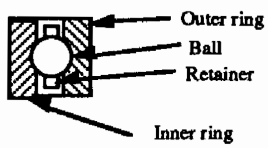
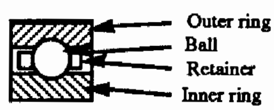
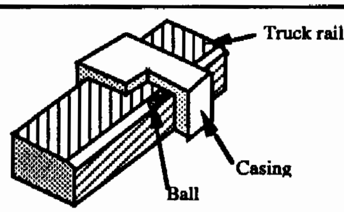
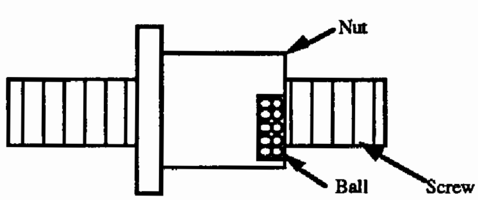
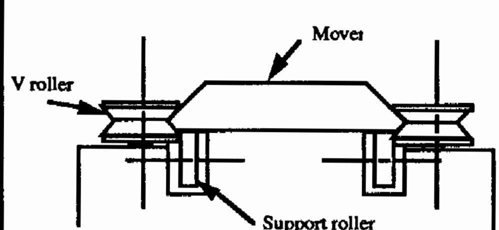
Classification	Dry Lubricantion Method	Configuration
Cross Roller	Outer ring, Inner ring, Roller] WS_2 Surface process by Dicronite inc. of U.S.A. Roller and ball : Sintered alloy	
Thrust	Outer ring, Inner ring, Ball] Sputtered MoS_2 Retainer : Sintered alloy	
Ball	Outer ring, Inner ring, Ball] Sputtered MoS_2 Retainer : Sintered alloy	
Linear guide	Truck rail, Casing, Ball] Burnished MoS_2	
Ball Screw	Screw, Nut, Ball] Burnished MoS_2	
V roller	Outer ring: Sputtered MoS_2 Mover: PTFE	
Support roller	Same as the thrust bearing outer ring : Burnished MoS_2	

Table 4.2. Possible dry lubrication methods for various bearing types (adapted from [4.21])

The bearing stiffness is determined by measuring the bearing moment compliance. It is defined as the amount of torque exerted on the bearing per deflection angle of the bearing's inner race relative to the outer race. The bearing's frictional torque, thermal conductance, and stiffness are also a function of the preloading effects provided by the cage and external fit. The use of clearance fit for a four point ball bearing with adjustable clamps has been recommended to be able to control these parameters more closely [4.19].

The bearing material is typically stainless steel or other hard material with a high compressive and fatigue strength. Contamination results from the debris generated by the wear of moving components and absorbed foreign particles during assembly. Bearing seals are used primarily to reduce contamination due to lubricants and component wear.

A number of bearing types are available for vacuum, e.g., slider and sealed ball bearings. Slider bearings use fluorocarbon plastics, typically PTFE (Teflon), with a metal sleeve to reduce friction and provide support for the shaft. The metal sleeve also minimizes the effects of thermal expansion by the slider and increases the heat transfer rate to the housing. This type of bearing is typically used over a temperature range of -40 °F to 250 °F. The plastic slider will stick to the shaft at high temperatures. Some experiments have shown that the PTFE might rotate with the sleeve [4.20]. The PTFE can be locked to a perforated metallic sleeve because PTFE can expand through the holes when compressed. This type of bearing is maintenance-free for repeated cyclic temperature variation.

Stainless steel and ball and roller bearings for use in vacuum mechanisms are typically lubricated with vacuum grease. They are mainly used for high temperature applications or where a large variation in the temperature variations are expected. Ball and roller bearings are also more rigid and offer a higher stiffness than slider bearings.

Linkages/Joints

A mechanism is made up of a number of linkages which are connected together through joints. These links can be configured in different shapes to produce the desired outputs. They can be considered as transmission elements with a variable transmission ratio throughout the workspace. An important property of a link is its stiffness, which must be quite high for precise positioning and handling. This is specifically true when long links are used for moving loads. The space shuttle arm uses thin-walled multiple graphite-epoxy tubes with aluminum joint interfaces which provide an overall stiffness of 10 lb/in. (1760 N/m) [4.22]. Other desirable properties include low mass and thermal expansion, and oxidation resistance. Glass-ceramic matrix composites have been developed which exhibit these properties, but they are fragile and their manufacturing costs are high.

Revolute and prismatic joints are the types used most for industrial robots. Rotation about an axis is performed by the revolute joint and translation along an axis is allowed by the prismatic joint. Each has one degree of freedom. The joint design for vacuum environment includes the choice of materials, seals and geometry. Seals are necessary to reduce the contamination. The shape of the joint must be such that the seals are most effective.

4.5 Magnetic Levitation

Magnetic suspension/levitation maintains the position of a body along or about one or more axes attached to a certain reference frame. The levitation is a result of the force actions of various magnetic fields, and achieves the completely contactless support of its critical components, thereby eliminating mechanical friction [4.23].

Ever since Holmes [4.24] showed that a vertical ferromagnetic needle could be supported in macroscopic equilibrium by magnetic force alone (using a variable magnetic field) many theories and experiments have come about in an effort to broaden the "state of the art" of magnetic levitation systems. Among these, the magnetic suspension and balance system for wind tunnel models received early and extensive attention [4.25,4.26]. The different applications of contactless suspension and levitation to high-speed ground transportation, however, continue to be most compelling to scientists and the media [4.27].

The most recent application research trend in engineering has been the development of active mechanisms for critical applications in superclean, vacuum, and space environments. Motivation for this practice is the predominating need to meet the rapidly increasing demand for high cleanliness levels and flexible automation. As these demands are met, the more general intrinsic assets of magnetic levitation are also discovered and exploited.

Features of Magnetic Levitation

Because of their completely contactless support of critical components, magnetic levitation systems are considered important mechanisms for flexible and precise positioning and force control, especially in superclean and vacuum environments. As they are also contactless, they have no mechanical friction, and thus are useful for high-speed rotating axes. Levitation systems are wear-free and maintenance-free, and have no backlash. They thereby lend themselves to potential use in contamination-free and high-precision mechanisms. Multi-degree-of-freedom joints can be built using magnetic levitation.

Magnetic levitation systems generate no particle contaminants, and thus are highly suitable for operation in superclean environments, such as VLSI manufacturing and biotechnology experiments. Because no lubrication is necessary, and since vacuum-compatible materials may be employed, magnetic levitation systems are certain to become indispensable in vacuum applications.

On a commercial scale, magnetically levitated passenger trains are fast, power-conserving, comfortable, and quiet [4.28], but they are also more expensive to build, operate and maintain than conventional trains. Research is continually under way to make these magnetically levitated trains more cost-effective. Although various principles have been studied and a variety of prototypes designed, only two types of magnetically levitated vehicles have been built and presently operate: electromagnetic systems (in both Germany and Japan) and superconductivity (in Japan). The trains in Europe run on magnets that attract each other, and the trains in the Orient employ magnets that mutually repel.

Any magnetic levitation system is inherently unstable without proper control, so either analog control or fast digital control is imperative in making such a system stable. On the other hand, the dynamics of the levitation system are highly nonlinear and coupled, placing a heavy burden on controller speed. This, of course, contributes to the high cost.

Classifications of Magnetic Levitation

Magnetic levitation is classified into three types, depending on the type of magnet used. They may be electromagnets or permanent magnets or utilize super-conductivity/diamagnetism. Permanent magnet systems are the most economical, while superconductivity is the most expensive but the most energy-conserving. Electromagnets are the most flexible and currently the easiest to control; they are therefore the most widely used.

Magnetic levitation is further classified according to the types of magnetic fields employed:

1. Magnetic levitation with a constant field utilizes repulsive forces from either permanent magnets or super-conductivity/diamagnetism. The system can be stable without active control, but the control can be very difficult to achieve.

2. Magnetic levitation in a passive-variable field is achieved either by restoring forces of DC electromagnets, with eddy current repulsion of AC electromagnets or by using the resonant circuit of AC electromagnets.

3. Magnetic levitation with an active variable field utilizes attractive forces from actively controlled DC electromagnets. This type allows the most flexibility and controllability, and presently is very widely used.

Current Advances in Magnetic Levitation

With the recent rapid advances in solid-state electronics and in analog and digital control technology, many applications of magnetic levitation have become viable. Many published papers report a wide range of results from recent application research, as discussed in this section.

Using magnetic levitation to develop new types of actuators and sensors is a very attractive research topic. These types of actuators have all the good features of magnetic levitation, including cleanliness, and the lack of contact, friction and wear. Additionally, they have no lubrication requirements, and can be either linear or rotational. In [4.29] Maresca realized an integrated magnetic bearing actuator and sensor using a specially designed ferrite pole piece. The sensors have < 0.25 μm resolution and negligible temperature drift, each actuator providing a controllable force of 0-10 N.

Matsumura, *et al.* [4.30] designed a moving-magnet type of linear DC motor, which is completely levitated by the moving magnets. The chief operating characteristics of this motor are: short stroke, high accuracy, high response-speed, and large damping-force.

Higuchi, *et al.*[4.31] developed a new type of stepping motor with the rotor suspended, actuated and positioned without contact. They accomplished this by employing feedback-controlled magnetic forces. The researchers project that these motors will be useable as direct-drive motors for ultra-clean and vacuum environments.

Because of the absence of friction, magnetic bearings have been used in mechanisms with high-speed rotating axes [4.32] such as turbo-molecular pumps and centrifugal separators. Ulbrich [4.33] studied the theory and application of magnetically-supported rotors and subsequently discussed their modeling, measurement and control.

Richards, *et al.* [4.34] described the self-generated rotation of magnetic levitators using a proximity height detector, in which the supporting DC electromagnet provides a torque about the vertical axis, so that the floating object rotates continuously. In a more recent paper Ciric, *et al.* [4.35] demonstrated theoretically the stable electromagnetic levitation of spinning conducting cylindrical rotors and analyzed quantitatively the stability conditions, losses, torque/speed characteristics and high-speed rotation.

A much smaller mechanism, but equally complicated to design, would be a magnetically levitated multi-degree-of-freedom robotic hand. By employing magnetic levitation, a robot hand could have remote center compliance, fine position control, fine force control, variable damping and stiffness for several degrees of freedom at the same time. A magnetically supported intelligent hand (MSIH) as proposed in [4.36] has five degrees of freedom (three translational and two rotational) and is electromagnetically feedback-controlled, using magnetic gap sensors for both position-sensing and force-sensing.

A similar example is the IBM "magic wrist" [4.37] a six degree-of-freedom magnetically levitated fine-motion wrist. The wrist's floater is a hexagonal aluminum structure with embedded coils, and a stator with permanent magnets holds and controls the floater by passing and changing current through the coils. The positioning and orientation of the wrist are achieved with an optical sensing system that employs projecting co-planar beams from three LEDs attached to the wrist 120° apart. By changing parameters, the wrist can serve as either an RCC (remote compliance center) device, translator, rotator, slider, or plunger.

To meet the various requirements of flexible automation, it is necessary to integrate the above components into a reliable, flexible, intelligent robot. From the proper utilization of magnetic levitation, robots can exhibit greatly improved abilities and will be able to do precise manipulation, especially in superclean and vacuum environments. Higuchi, *et al.* [4.38, 4.39] have designed and constructed an experimental closed-loop five link robot with the two base joints direct-driven by two conventional step motors and the two upper joints composed of magnetic bearings capable of small-range, fine positioning. More practical magnetically levitated robots will most likely appear, and will play a pivotal role in manufacturing within the vacuum environment.

Considerations for Vacuum Applications

Being contactless, frictionless, and requiring no lubrication, magnetic levitation mechanisms have a promising future in terms of their applications to vacuum environments. In these applications, the working temperature range, efficiency of energy transfer, and the choice of materials all have to be considered. In a magnetic levitation system, most of the parts are steel, but the magnetic materials can be coated for high-vacuum applications without loss of magnetic performance. The insulation of windings, a concern in the operation of vacuum motors, warrants particularly close consideration.

The working temperature and power efficiency depend mainly on the structure and the control. In designing the structure, heat generation and dissipation must be considered and minimized. Once the choice of hardware is determined, the main factor influencing both temperature and efficiency is the control scheme employed, which can make a considerable difference. For example, if the local linearization technique is used, large operating currents are required, and many of the forces from these currents are cancelled in pairs, without any work output resulting. The wiring resistance, however, will then consume a large part of the input energy, reducing the efficiency and unnecessarily generating heat. Employing non-linear control reduces this energy consumption dramatically, and will usually bring it to a minimum.

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