MFE 3004 Mechatronics I

5. Actuation in Mechatronic Systems

5.1 Introduction

In the previous section we have looked at some basic aspects of measurement systems. We have also noted the fundamental importance of measurement systems within mechatronic products and processes and how they influence the design of such systems. In a similar manner, drives and actuators play a primary role in mechatronic systems and their design and development within the integrative nature of a mechatronic approach, is critical for a successful design process.

As sensors and transducers produce the input to the mechatronic system, drives and actuators provide the output of the system, influencing the system itself and its environment as depicted in figure 5.1.

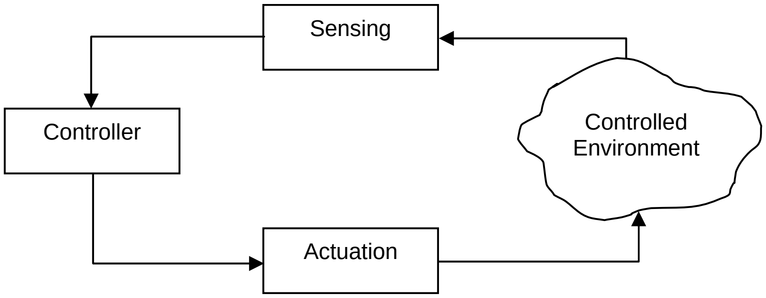
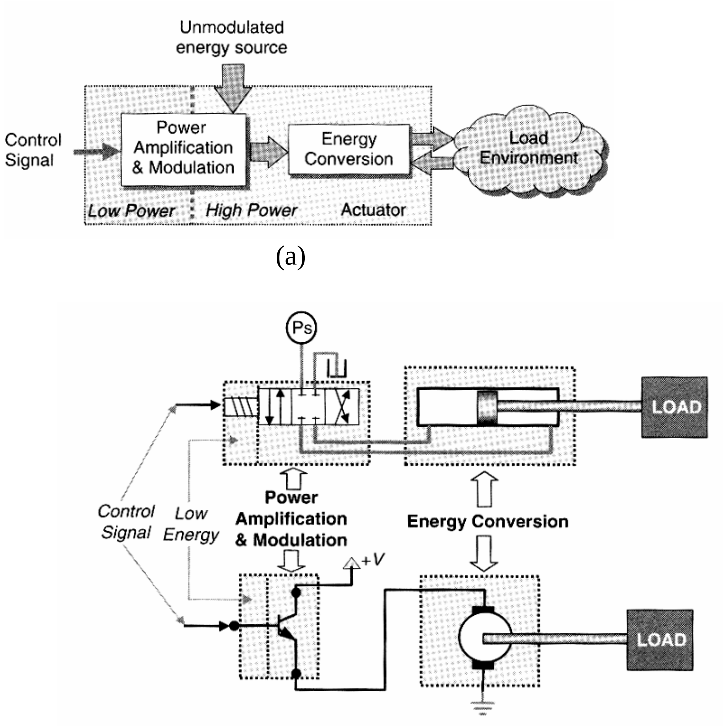


Figure 5.1 A Mechatronic System illustrating the interaction between controller and environment via sensing and actuation.

Typically actuators are considered as only energy conversion devices. For example an electrical motor converts electrical power to rotary motion. Similarly a hydraulic motor will convert hydraulic power (in the form of hydraulic fluid flow and pressure) into rotary motion. However, it is more common to take an inclusive view of actuators and consider the actuation systems instead. Here it is possible to distinguish two components of an actuation system;

1. ***The Power Amplification and Modulation Stage***
   This stage is concerned with converting the control signal (low power) into an appropriate signal that delivers the required input power to the energy conversion unit. In electrical drives, such an element will consist of a power electronic circuit, providing the appropriate high power switching to the electrical drive. On the other hand for a fluid power system such as a hydraulically powered drive, this stage will include appropriate valves (and hydraulic fluid supply), in order to convert the control signal to an appropriate hydraulic fluid flow and pressure to the hydraulic actuator.
2. ***The Energy Conversion Stage***
   This stage represents the physical actuator, i.e. the component that converts energy and produces work, acting on the controlled process or environment accordingly. In the case of an electrical drive, for example, one can be looking at an electrical motor, whereas for a hydraulic drive system, a hydraulic cylinder can be a typical example.

These elements of an actuation system are shown in figure 5.2 (a) while figure 5.2 (b) represents typical electrohydraulic and electrical actuation systems depicting these two components of an actuation system.



(a)

(b)

Figure 5.2 (a) Actuation System functional diagram, (b) Typical electrohydraulic and electrical actuators

In a number of instances, the output of the energy conversion unit may not be appropriate for a specific application and some form of motion conversion may be required. For example, electrical motors are often connected to gearboxes to provide a reduction in rotational speed whilst increasing the output torque.

5.2 Classification and Selection of Actuators

Actuation systems can be classified in three principal modes of energy transfer, these being the following;

- ***Electrical***
- ***Pneumatic Fluid Power***
- ***Hydraulic Fluid Power***

5.2 1Electrical Actuation

Electrical actuators primarily consist of electrical motors, although other types of electrical actuators such as solenoids are also used within mechatronic systems. There are a large variety of motors that are available for performing diverse tasks, with the various motor types offering specific performance characteristics. The physical principle of all electric motors is that when an electric current is passed through a conductor placed within a magnetic field, a force is exerted on the wire causing the wire to move. Typical electrical motor types include the following;

1. ***DC motors***
   DC motors operate through the use of a DC signal. DC motors can either have stator magnetic poles produced by a permanent magnet (generally found in small motors), or else the magnetic field is produced via a stator winding, in which case both the rotor armature and the stator winding have to be energised to drive the motor. DC motor speed is controlled by the voltage supplied to the armature. For motors with stator windings, speed control is also possible through varying the current to the stator. Standard DC motors tend to suffer from brush wear. Alternative DC motor designs include brushless motors where the brush and commutator are eliminated, and thus give a higher reliability.
2. ***AC motors***
   AC motors are driven by an alternating current supply to the stator windings. The rotor can either consist of a permanent magnet in the case of a synchronous AC motor, or of a simple closed-loop conductor (generally in the form of a ‘cage’) for asynchronous, induction motors. The speed of AC motors is determined by the input signal frequency. Thus speed control is obtained via variation of the signal frequency.
3. ***Stepper motors***
   stepper motors have the ability to rotate a specific number of revolutions or fractions of a revolution, thus being able to achieve a specific angular displacement rather than continuous rotation. There are various designs of stepper motors but primarily all require the sequential switching of a number of stator coils to provide rotation. This sequential switching is generally provided with appropriate drive circuitry, the switching frequency determining the speed whereas the number of switching actions determining the angle of rotation.

Figure 5.3 illustrates a typical control set-up for a motor where both motor speed and output angular position are being controlled.

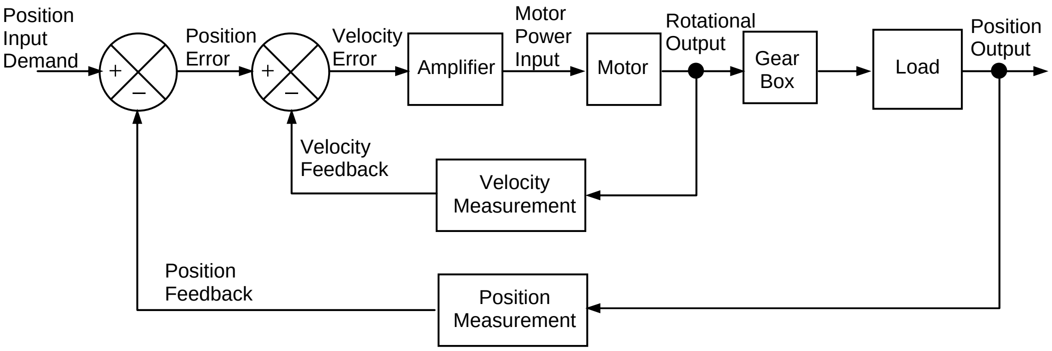


Figure 5.3 Motor drive system with velocity and angular position feedback

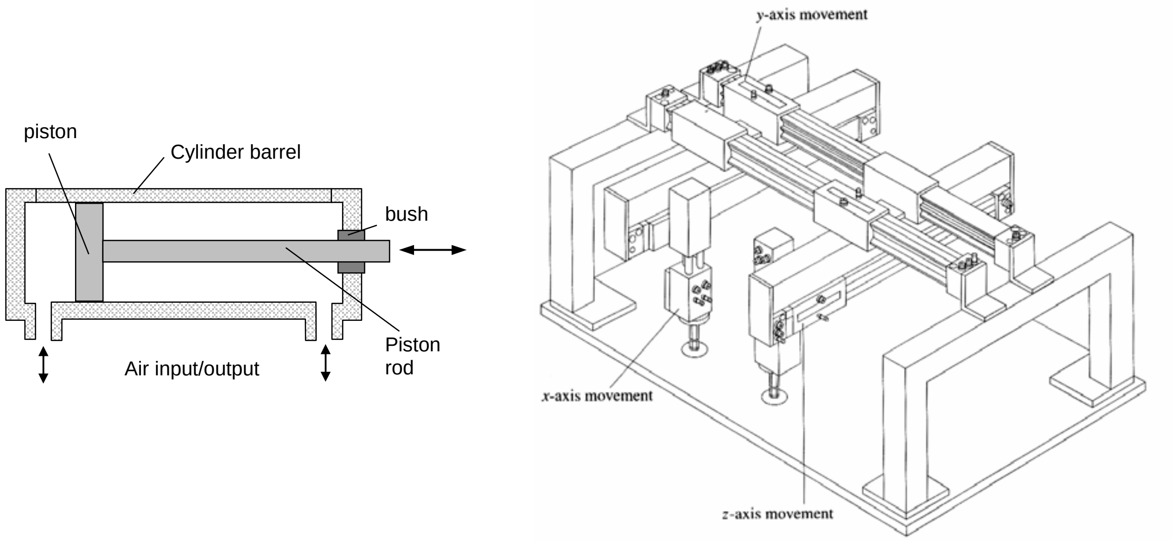
5.2.2 Pneumatic Power Actuation

Pneumatic actuation is widely used in the manufacturing industry primarily in the field of automated assembly, including jig and robot end-effector operation. Pneumatic power generally utilises pressurised air as the power transfer medium. The principle advantage of pneumatic power lies is the simplicity of the components used both for pneumatic power modulation as well as for energy transfer devices, particularly in the case of linear motion actuators. The use of air as the operating fluid also allows the use of a central power generation and distribution system, with various equipment tapping into this power source. The primary type of energy transfer device found in pneumatics is the pneumatic cylinder, which basically consists of a cylindrical barrel, closed at both ends and with a piston that run the length of the cylinder, to which is generally attached a piston rod. Motion of the pneumatic cylinder piston and piston rod occurs by applying pressurised air at one of two ports found at the ends of the cylinder, as indicated in figure 5.4 (a). Pneumatic cylinders thus provide a very simple means of linear motion. Other pneumatic energy transfer devices include the limited rotation rotary actuators as well as air motors. In the case of the former, the actuator can provide back and forth (reciprocating) rotation through a fixed angle. Air motors on the other hand can provide continuous rotation.

Control of both linear and rotary pneumatic actuators in terms of pneumatic power modulation, is provided via appropriate valves which can control the direction of the air flow, the flow rate as well as the air pressure to the actuators. These valves can in most cases be controlled by electrical signals through the use of solenoids, thus providing an appropriate interface between the microprocessor based controller and the pneumatic actuator.

The use of air allows pneumatic actuators to operate at relatively high speeds, due to the negligible viscosity and high compressibility. However air compressibility also means that high precision positioning of pneumatic actuators can be quite difficult and substantial losses during pneumatic power generation means that the operating pressure of pneumatics is relatively low, thus limiting the power output available from such actuators.

Figure 5.4 (b) illustrates a typical pick-and-place pneumatic system, consisting of three axes of operation, each with its own appropriate pneumatic linear actuator.



(a) (b)

Figure 5.4 Pneumatic actuation (a) Pneumatic Cylinder, (b) A pick-and-place pneumatic system.

5.2.3 Hydraulic Power Actuation

Hydraulic fluid power basic operating principles are quite similar to those of pneumatic fluid power systems. The difference in operating fluid, i.e. from air or gas in pneumatic systems to liquids (generally oil) in hydraulics, though, results in performance characteristics that are quite different. Primarily, the use of liquids allows the achievement of very high operating pressures, which means that hydraulic actuators can give a very high power output. Indeed the main application of hydraulic power tends to occur where large forces and torques need to be applied.

Again, hydraulic actuators can both be of a linear as well as a rotary nature. Linear actuators generally consist of cylinders (sometimes referred to as rams) with the same basic construction of pneumatic cylinders. The difference lies in the robustness of the cylinders, which for hydraulics are designed to withstand the much higher operating pressures and thus are made from steel with appropriate wall thickness (compared to thin-walled aluminium cylinders in the case of pneumatics). Rotary actuators can once more be of the limited rotation type as well as of the continuous rotation type, the latter being referred to as hydraulic motors. Hydraulic motors are quite commonly used where large torques need to be transmitted and generally offer a higher power-to-weight ratio when compared to electrical motors.

One advantage of hydraulic actuation systems is that the presence of an incompressible operating fluid results in the possibility of accurate positioning of the actuator, which is generally achieved via appropriate feedback loops. This is shown in figure 5.5 illustrates such a control loop. The presence of the viscous fluid, though results in much lower operating speeds when compared to pneumatic systems.

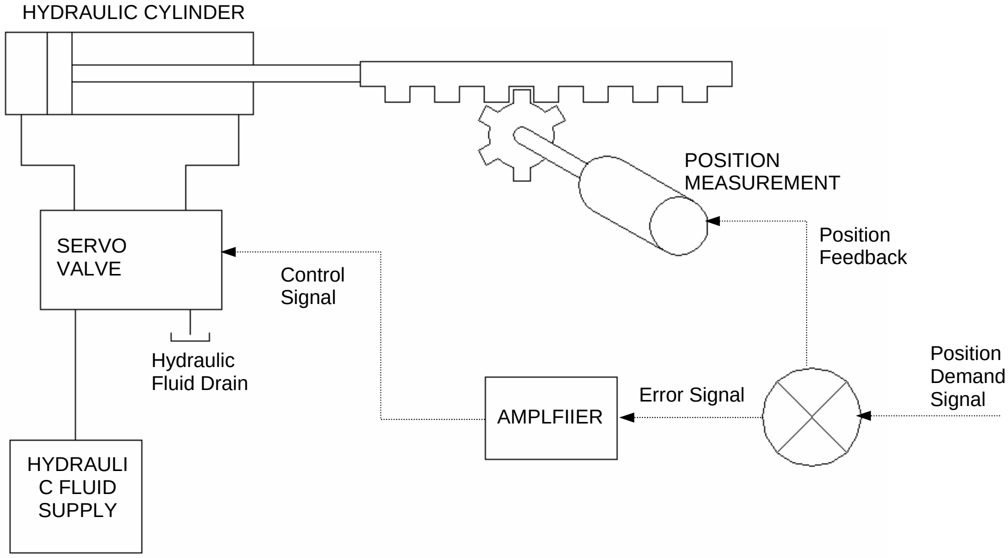


Figure 5.5 A Schematic diagram of an electro-hydraulic actuation system with position control

A comparison of the characteristics of these drive systems in given in table 5.1. Figure 5.6 illustrates a broad classification of power amplification and control devices, energy conversion devices, and related motion converters. Motion converters are mechanical power transmission systems and are necessary in order to convert actuator outputs to forms that are adequate to the type of motions required by the system. Typical motion conversion requirements may be speed reduction or conversion from rotary to linear motion.

Table 5.1 *A Simple Comparison of Drive System Characteristics*

	Hydraulic	**Pneumatics**	**Electrical**
Working Fluid	Mineral Oil	Air	Voltage-Current
Working Pressure	500 Bar (maximum	6-7 Bar	Up to 11kV
Available Force	100MN	10kN	100kN
Speed	Low	High	Very High
Conversion Efficiency	Over 70%	Under 20%	Over 80%
Capital Costs	High	Low	Intermediate
Proportional Control	Easy	Difficult	Easy
Hold Load Power-Off/ Stability	Possible	No (air is compressible)	Possible
Precise Positioning	Easy	Difficult	Easy
Environmental Influences	Sensitive in case of temperature fluctuation, risk of fire in case of leakage	Explosion proof, Insensitive to temperature	Risk of explosion in certain areas, insensitive to temperature
Energy storage	Limited with the help of compressed gases	Easy	Difficult, only in small quantities using batteries
Linear Motion	Simple using cylinders	Simple using cylinders	Difficult and expensive – with motion converter
Rotary Motion	Simple	Simple	Simple

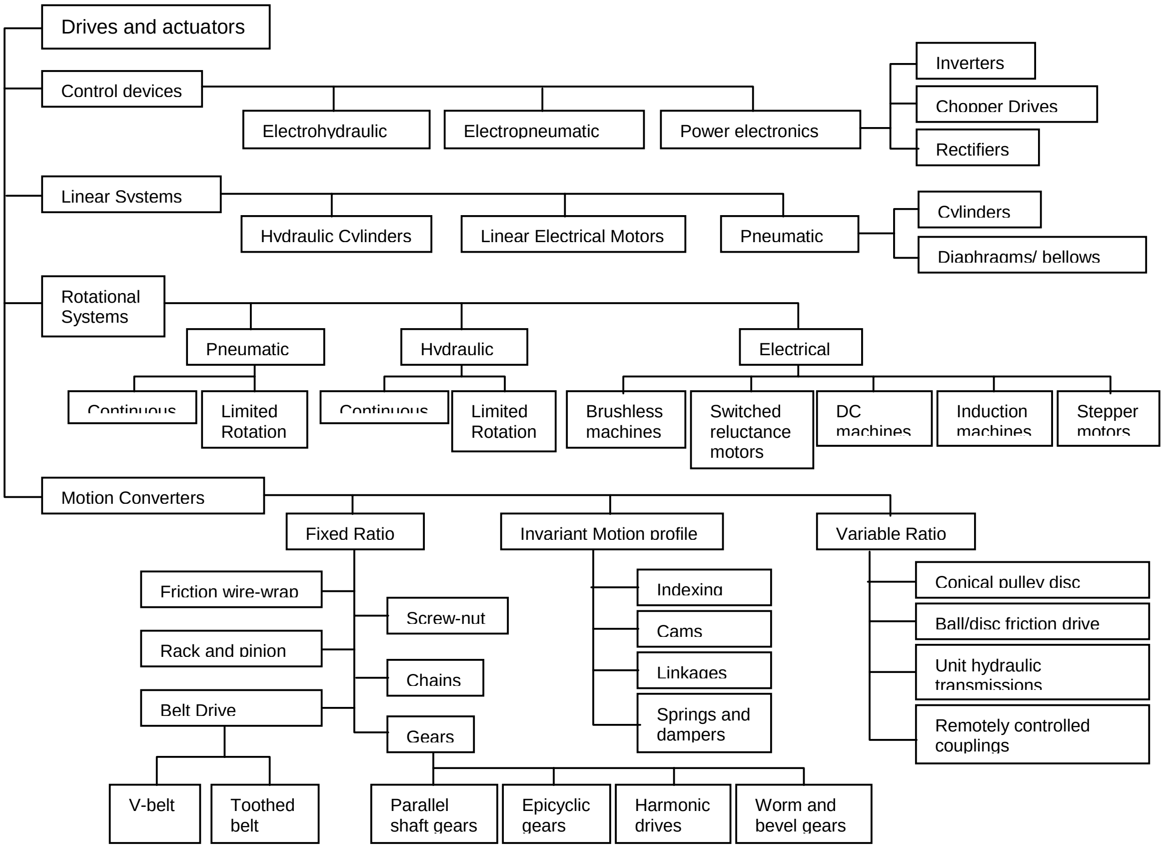


Figure 5.6 A General classification of drives and actuators

Figure 5.7 illustrates what possible force and displacement may be provided by the different actuators. Speed may be a further consideration in this case. For rotary actuators, the main selection criteria are the angular velocity and torque that needs to be provided by the actuator. Figure 5.8 illustrates the possible torque and velocity outputs possible by the different types of rotary actuators. Motion converter requirements may also be classified according to the output speed and torque that may be provided, as shown in figure 5.9.

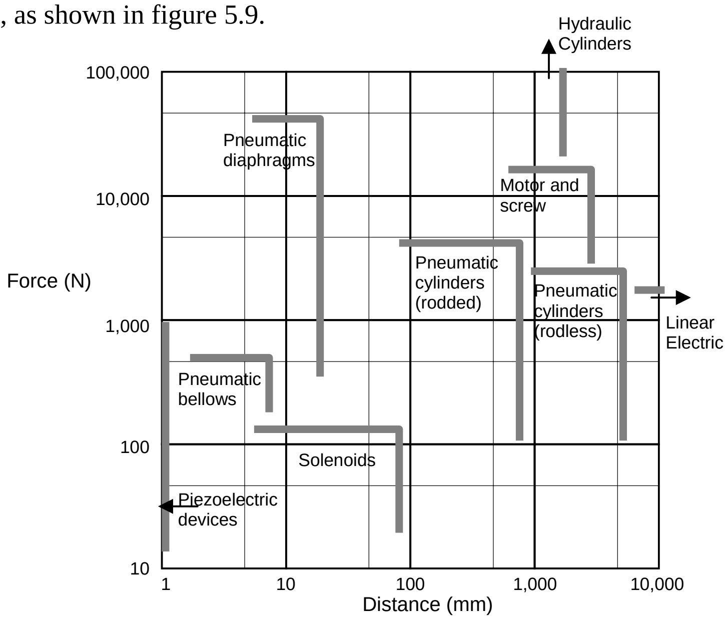


Figure 5.7 *Linear* Actuator classification according to available force and travel

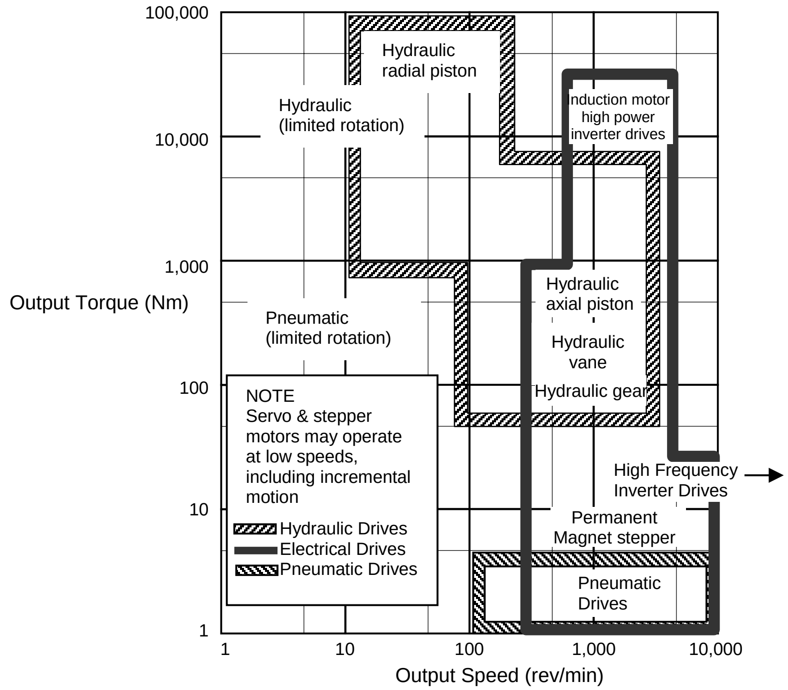


Figure 5.8 Rotary Actuator classification according to output torque and speed

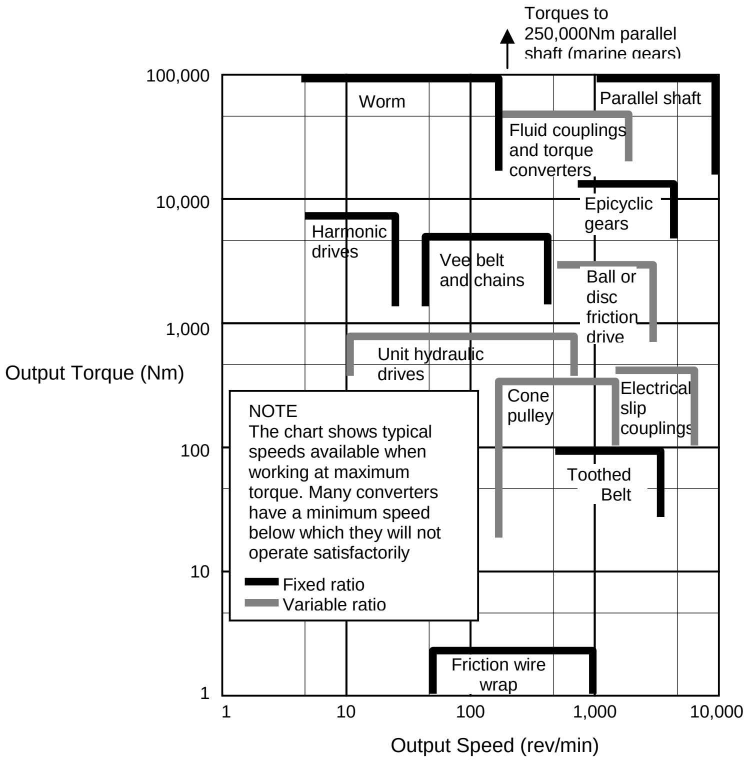


Figure 5.9 Motion converter classification according to output torque and speed.

5.3 Performance Characteristics of Actuators

There are a number of factors that influence the selection of an actuator from a performance and functional perspective. A number of these selection criteria are given hereunder;

Motion Requirements

One of the primary requirements when selecting an actuation system is the type of motion required, primarily whether linear or rotary motion is required or both. Furthermore stroke lengths or angles of rotation need to be defined. Additionally, routing requirements, i.e. the route necessary to be taken by the actuator, may have to be identified.

Velocity

Velocity requirements may vary from application to application. For example in pick-and-place systems high velocity requirements are generally made. On the other hand, the velocity requirements for a robot with limbs might be limited for safety reasons. Angular velocity requirements are also a functional factor. Related to velocity is the need to define acceleration and deceleration characteristics. High acceleration and deceleration requirements would generally be required in a pick-and-place system, where the mechanism would have to go from zero up to the maximum speed and vice-versa in as minimum a time as possible.

Operational Power

The power developed by the actuator will have to be sufficient for the application, i.e. to produce the required force or torque. For example, a transportation system might need to move heavy loads, whereas an actuator on a camera for focusing purposes will only require a limited amount of power. Power production might have to take into account for variable loading, where during the actuator’s operation the load on the actuator may be varying substantially.

Resolution, Accuracy and repeatability

These parameters define the precision with which the actuation system will operate. Resolution is defined as the smallest controllable change in output possible by the actuator. A typical example of resolution requirements would be that of a pick-and-place robot used for locating components in a printed circuit board with a separation of 2mm minimum, in which case the robot’s positioning resolution will have to be not more than 2mm.

Accuracy determines how closely to the intended target an actuator is expected to locate and thus is representative of the error between the demanded output and the actual output achieved by the actuator. Accuracy generally depends on internal actuator factors, such as the looseness of mechanical couplings, stiction of components, etc., but may also be dependent on external forces such as sliding friction.

Repeatability defines the ability of the actuator to return repeatedly to the same point. Component rigidity in an actuation system generally affects the repeatability of the system, especially when system loading changes. Repeatability is also greatly affected by actuator hysteresis, and system backlash.

Dynamic Behaviour/Responsiveness

The dynamic response of an actuator to the demand imposed on it is partly a combination of the actuator’s velocity and acceleration characteristics. The dynamic response is also greatly dependent on the effectiveness of feedback from the device’s sensors and control system, and is a major parameter in defining the dynamic characteristics of the actuator. Appropriate first, second or higher order models can be used to analyse the dynamic behaviour of an actuator, where such system models can then be appropriately analysed either through the use of step response analysis or frequency response analysis, generally depending on the type of application of the actuator.

Compliance

Compliance is the movement of a component in reaction to a force exerted on it. Compliance may be defined as the stiffness of the system (low compliance), or sponginess/softness (high compliance) of the actuation system. Differing compliance requirements may be present for different actuation systems. For example actuation systems in machine tools would require high stiffness and therefore low compliance in order to ensure the required machine tool precision during machining. On the other hand a positioning system, such as a system used to place a tool in a tool holder would require high compliance so as to allow the tool to be inserted with ease into its tool holder.

5.3.1 Non-Linearities

Earlier on, the representation of actuator errors in the form of an accuracy value had been stipulated. Errors generally occur because of the assumption generally taken in most actuation systems, where they are considered to be linear in nature. Linear systems exhibit the property of superposition, where if a system response to an input A is output A, and for an input B one gets output B, then for an input C = (input A + input B), the response obtained will be output C = (output A + output B). The vast majority of actuation systems are designed to exhibit this property as close as possible. However most of such systems do exhibit non-linearities that introduce errors in the expected output of the actuator. The following outlines some of these non-linearities

Static and Coulomb Friction

When analyzing linear systems, it is often assumed that friction is directly proportional to velocity (viscous friction), and therefore the friction force is zero when the system is stationary. In reality, such systems generally exhibit a certain amount of static or Coulomb friction, which has to be overcome before the system starts ‘moving’. Thus, some of the actuator torque or force is wasted to overcome this friction force. Also, as the actuator reaches its final location, the velocity approaches zero and the actuator force/ torque will approach a value that exactly balances the frictional load, thus causing the actuator to stop somewhere off the desired position. Since such static friction can take various values, the actuator will come to a slightly different final resting position each time, resulting in a loss of repeatability. The effect of static friction is shown in figure 5.10(a).

Eccentricity

This generally applies in the context of rotational devices, primarily motion converters such as gears and pulleys. The ideal relationships for gears, pulleys and the like assume that the point of gear or belt contact remains at a fixed distance from the center of rotation for each gear. In reality there will always be some manufacturing error between the center of rotation and the true center of the gear pitch circle, which will cause some eccentricity. The eccentricity can cause a deviation from the ideal input and output angular position relation as indicated in figure 5.10(b).

Backlash

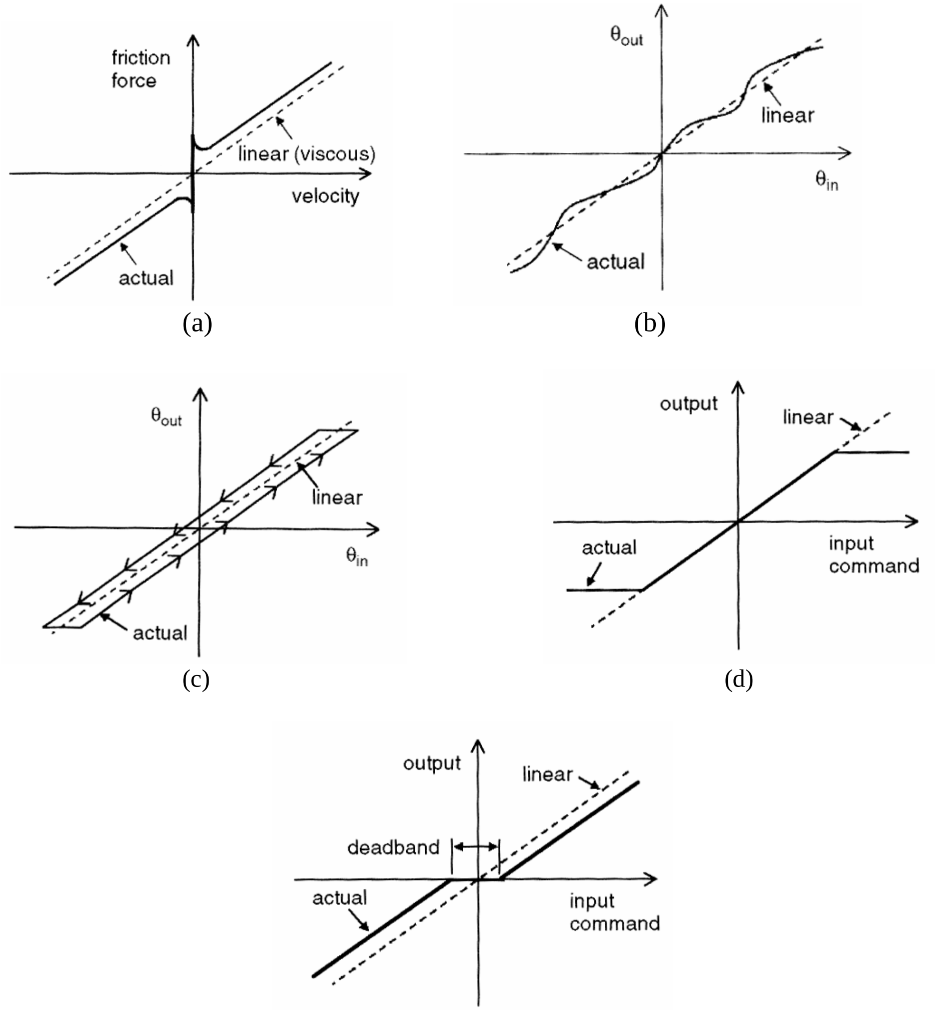
Backlash is a common problem particularly in gear transmission systems as well as in various other mechanical systems and occurs when the direction of motion is changed. Gear backlash is just one of many phenomena that can be characterized as hysteresis. Other examples include clearances between shafts and bearings. Figure 5.10(c) illustrates such a phenomenon.

Saturation

All actuators have some maximum output capability, regardless of the input demand imposed. This is clearly depicted in figure 5.10(d) where once a specific input limit is exceeded, the actuator output remains constant no matter whether the input increases any further or not. This results in a nonlinear behaviour of the actuator once the saturation point is reached. Saturation problems must be appropriately considered when looking at closed loop control in mechatronic systems, since the demand imposed on the actuator may be too high, causing the actuator to reach saturation.

Deadband

Deadband also occurs in actuators and is a region where the output remains zero for a specific range of input values. This generally occurs when the input value itself is close to zero. Once the input travels outside the deadband than the output will increase or decrease accordingly. This phenomenon is depicted in figure 5.10(e). This typically occurs in hydraulic servo valves, i.e. valves that allow a fluid flow proportional to the signal fed to the valve but also control the direction of flow. Here, for signal a certain range of input signals, the value remains closed (i.e. no flow in either direction).



(a) (b)

(c) (d)

(e)

Figure 5.10. Nonlinearity effects exhibited in actuators (a) static and coulomb friction, (b) eccentricity, (c) backlash, (d) saturation, (e) deadband

5.3.2 Other Selection Parameters of Interest

Apart from the performance characteristics discussed above, additional factors that influence actuator choice are given hereunder;

Control Parameters

These parameters define the mode in which the actuator will be controlled. Such parameters will therefore define the transfer function of the actuator, and will include mass and inertia effects of both the actuator and the load, acceleration and deceleration profiles, frequency response, bandwidth and the intended control strategy to be applied.

Power Source Requirements

Generally power source availability may vary depending on the location of the application. A stationary application might easily be supplied with electrical power. However, in mobile applications, particularly outdoor applications, with large power requirements are necessary, electrical power might not be available, and alternative power sources such as the use of an internal combustion engine for hydraulic power generation may be used.

Method of measurement for speed, position, force or torque to be used

Measurement requirements are fundamental in the selection of the actuator since this will influence the sensor selection as well.

System Integration

Various system integration factors come into play in the selection of actuators for mechatronic systems. Apart from spatial aspects such as size and mounting, other factors are considered such as necessary guidance requirements, interfacing requirements with other system elements, heat transfer and cooling required and other thermal effects, vibration and interference, etc..

Costs

Costs factors come into play in any system component selection, considerations here being given to the initial cost and running cost, which includes the efficiency in energy conversion of the actuator.

Safety

Various safety factors are considered in the selection of actuators, depending on the application area. Amongst such considerations, one may include safe power down of actuators in case of emergencies, the modes in which the actuator can fail and how such modes may influence other system components (such as noise generation and other environmental factors, or electro-magnetic interference), protection, reliability, and even maintenance considerations.

References

Robert H. Bishop (Ed.), The Mechatronics Handbook, CRC Press, 2000

George Rzevski (Ed.), Mechatronics, Perception, Cognition and Execution, Butterworth-Heinemann, 1995

W. Bolton, Mechatronics, Electronic Control Systems in Mechanical and Electrical Engineering, 2nd Ed, Longman, 1999

D. A. Bradley, D. Dawson, N.C.Burd, A.J.Loader, 'Mechatronics, Electronics in Products and Processes', Chapman & Hall, 1993