

Actuator Mechanical Devices in Electrical Engineering

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Chapter 1

Air Core Gauge and Amplified Piezoelectric Actuator

Air core gauge



An auto tachometer has a sweep of about 240-250 degrees and typically uses an air core gauge.

An **air core gauge** is a specific type of rotary actuator in an analog display gauge that allows an indicator to rotate a full 360 degrees. It is used in gauges and displays, most commonly automotive instrument clusters.

A typical automotive application is shown at the right. The air core gauge is a type of "air-core motor". It may be considered a "gauge movement" or "pointer indication device".

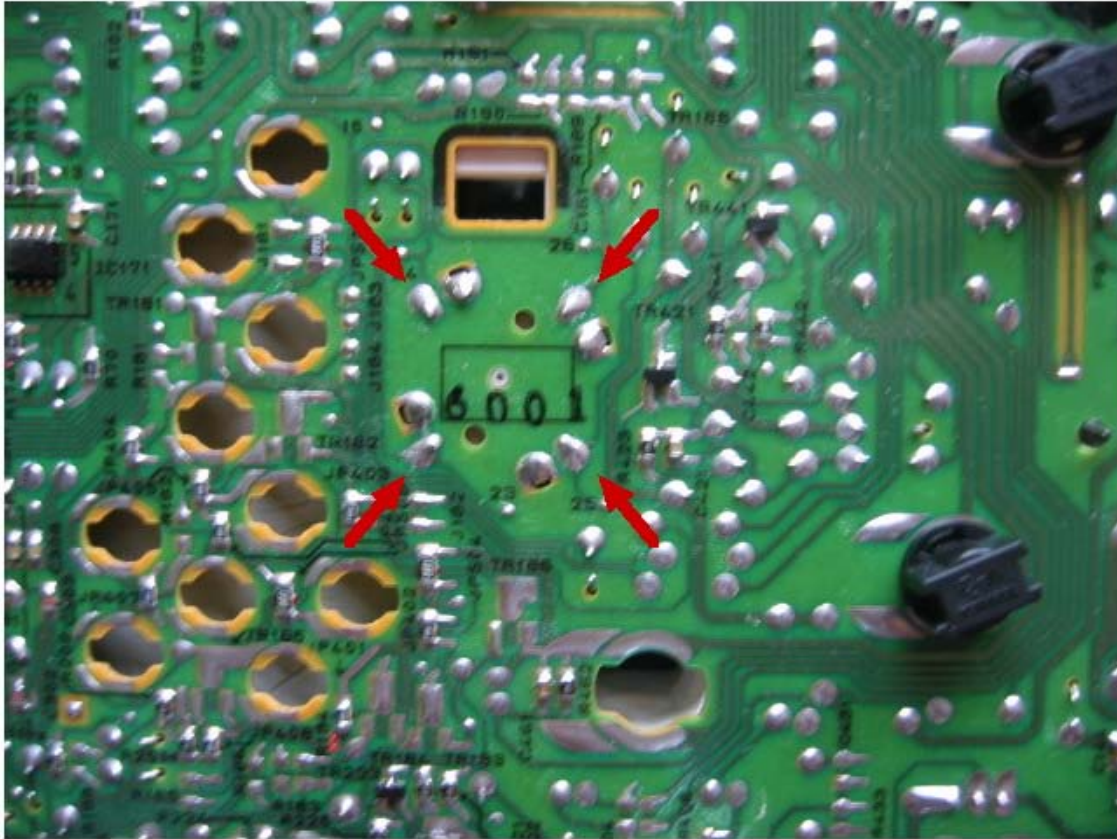
Background

There are four common types of rotary actuators :

- Physical gauges, in which the needle is attached directly to the value being measured; for example, a mechanical pressure gauge
- Analog volt meters or d'Arsonval movements, which consist of a coil and a permanent magnet
- Stepper motors, which move in one-notch increments or steps
- Air-core motors, as described below.

Construction and operation

The air core gauge consists of two independent, perpendicular coils surrounding a hollow chamber. A needle shaft protrudes into the chamber, where a permanent magnet is affixed to the shaft. When current flows through the perpendicular coils, their magnetic fields superimpose and the magnet is free to align with the combined fields.



Back side of an auto instrument cluster showing four mounting terminals for an air core gauge.

A typical air core gauge has four terminals, two for each coil, as shown. The two coils are identified as the sine coil and the cosine coil.

Theory

The direction θ of the overall magnetic field is approximately:

$$\theta = \arctan\left(\frac{y}{x}\right)$$

Where x and y are the coils' respective currents. The permanent magnet aligns itself with that field, eventually settling near θ . In this way, by proportioning the current through each coil, the needle can reach all 360° of rotation.

Example

If the sin coil current is 50 mA and the cos current is 29 mA:

The coil current ratio is 0.58, and $\arctan 0.58 = 30$ degrees.

Drivers

Air core gauges require special electronics to properly drive the coils. Driver integrated circuits typically have a serial input data port and two pair of output lines. One pair of the output lines drives the sin coil and one pair drives the cos coil.

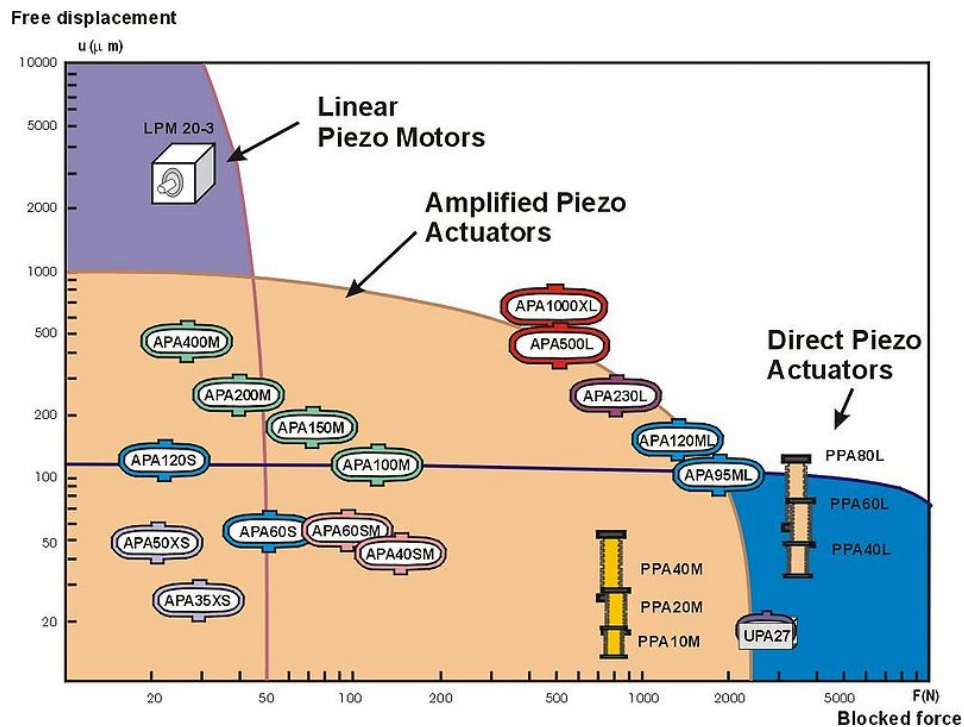
The input data defines:

- The quadrant to which the actuator will point. This defines the polarity of the voltage to the sin coil and the cos coil.
- The desired number of degrees within the quadrant.

Some typical driver ICs include:

- On Semiconductor CS4172 16 pin dual inline package
- On Semiconductor CS4192 surface mount package
- Melexis MLX10407
- Melexis MLX10420

Amplified piezoelectric actuator



Panorama of piezoelectric actuators, classified on a stroke over force map

Amplified piezoelectric actuators (APA) are specific actuators using piezoelectric materials as active material, and having a specific design to overcome traditional limitations of classical direct piezoelectric actuator, the limited stroke. As classical piezoelectric materials have a strain of 0.1%, it is practically impossible to reach significant stroke without displacement amplification (1 mm displacement would require 1 meter of piezoelectric material). The solution to reach middle range stroke is to use an amplification system.

Single-cell actuator



APA200M

APA™ is a trade mark of Cedrat Technologies using a patented design to create an amplification of the displacement. The principle is based on the deformation of an elliptic shell to amplify the ceramic strain. The ceramic stack is aligned with the great axis of the

ellipse. A small deformation of the great axis creates a large displacement of the small axis. The amplification ratio can typically reach 20 times, that means such actuators can reach strokes of 1 mm.

The goal of the elliptic shell is not only to amplify the displacement. It has also to apply the correct pre-stress to the piezoelectric material in order to allow dynamic and precise motion. The other advantage is that this kind of flextentional actuators are very reliable.

Multi-cell actuator

In diamond shaped amplifiers, using 4 piezo crystals instead of one increases control of movement, particularly in changing temperatures. More movers result in more force at similar displacement.

Example of application

Piezoelectric actuators, and especially amplified piezo electric actuators are historically studied and used in aerospace application. NASA for example studied flextensional and test its own actuators for cryogenic application. Other organisations like ESA or ISRO are also studying such solution. Space agency's interest for amplified piezoelectric actuators is due to the high power density of these actuators, their reliability and low power losses when used in quasi-static operation. This is definitely a key advantage for vacuum application. Compare for example to magnetic actuators. Controlling helicopter rotor blades using active flaps has been investigated for some time without being put into production, and *amplified piezoelectric actuators* is the most common technology used.

Other solutions

Other solutions are possible to amplify the stroke within the actuator. The first solution is to use lever arm. This classical solution is simple in its principle, but requires specific know-how to be reliable. Its main disadvantage is it can hardly allow dynamic displacement. One other solution is to use a specific shell for the displacement amplification, typically known as a dog bone, and to had an external pre-stress. As the pre-stress is not controlled by the shell, it has to have a stiffness as low as possible. One classical solution is to use flexural hinge to reduce the shell stiffness.

Chapter 2

Ball Screw and Carbon Nanotube Actuators

Ball screw

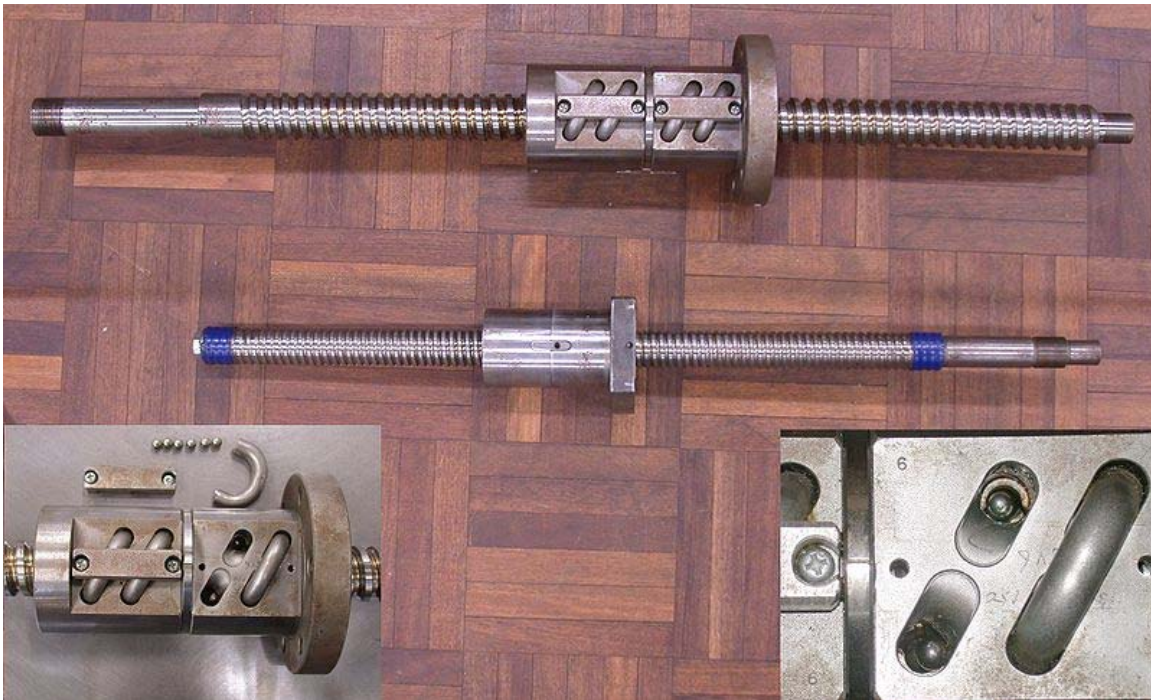


Photo showing two ball screws. Inset images are close-up photos of the ball assembly of the top screw. Left inset: recirculating tube removed showing retainer bracket, loose balls and tube. Right inset: closer view of the nut cavity.

A **ball screw** is a mechanical linear actuator that translates rotational motion to linear motion with little friction. A threaded shaft provides a helical raceway for ball bearings which act as a precision screw. As well as being able to apply or withstand high thrust loads, they can do so with minimum internal friction. They are made to close tolerances and are therefore suitable for use in situations in which high precision is necessary. The ball assembly acts as the nut while the threaded shaft is the screw.

Ball screws are used in aircraft and missiles to move control surfaces, especially for electric fly by wire. They are also used in machine tools, robots and precision assembly equipment. High precision ball screws are used in steppers for semiconductor manufacturing.

In contrast to conventional leadscrews, ballscrews tend to be rather bulky, due to the need to have a mechanism to re-circulate the balls.

To maintain their inherent accuracy and ensure long life, great care is needed to avoid contamination with dirt and abrasive particles. This may be achieved by using rubber or leather bellows to completely or partially enclose the working surfaces. Another solution is to use a positive pressure of filtered air when they are used in a semi-sealed or open enclosure.

While reducing friction, ball screws can operate with some preload, effectively eliminating backlash (slop) between input (rotation) and output (linear motion). This feature is essential when they are used in computer-controlled motion-control systems, e.g. CNC machine tools and high precision motion applications (e.g. wire bonding).

Depending upon their lead angle, ball screws can be back-driven due to their low internal friction (i.e. the screw shaft can be driven linearly to rotate the ball nut). They are usually undesirable for hand-fed machine tools, as the stiffness of a servo motor is required to keep the cutter from grabbing the work and self feeding, that is, where the cutter and workpiece exceed the optimum feedrate and effectively jam or crash together, ruining the cutter and workpiece. Cost is also a major factor as Acme screws are cheaper to manufacture.

Low friction in ball screws yields high mechanical efficiency compared to alternatives. A typical ball screw may be 90 percent efficient, versus 50 percent efficiency of an Acme lead screw of equal size. The higher cost of ball screws may thus be offset by lower power requirements for the same net performance.

Ball screw shafts may be fabricated by rolling, yielding a less precise, but inexpensive and mechanically efficient product. Rolled ball screws have a positional precision of several thousandths of an inch per foot.

High-precision screw shafts are typically precise to one thousandth of an inch per foot or better. They have historically been machined to gross shape, case hardened and then ground. The three step process is needed because high temperature machining distorts the work-piece. Hard whirling is a recent (2008) precision machining technique that minimizes heating of the work, and can produce precision screws from case-hardened bar stock.

Instrument quality screw shafts are typically precise to 250 nanometers per centimeter. They are produced on precision milling machines with optical distance measuring equipment and special tooling. Similar machines are used to produce optical lenses and

mirrors. Instrument screw shafts are generally made of Invar, to prevent temperature from changing tolerances too much.

Historically, the first precise screwshafts were produced by starting with a low precision screwshaft, and then lapping the shaft with several spring-loaded nut laps. By rearranging and inverting the nut laps, the lengthwise errors of the nuts and shaft were averaged. Then, the very repeatable shaft's pitch is measured against a distance standard. A similar process is sometimes used today to produce reference standard screw shafts, or master manufacturing screw shafts.

Ball return systems

The bearing balls travel inside the screw and nut thread. If the ball nut did not have a return mechanism the balls would fall out of the end of the ball nut when they reached the end of the nut. For this reason several different recirculation methods have been developed.

An external ballnut employs a stamped tube which picks up balls from raceway with use of small pick up finger. Balls travel inside of tube and are then replaced back in thread raceway.

An internal button ballnut employs a machined or cast button style return which allows balls to exit raceway track and move one thread and reenter raceway.

An endcap return ballnut employs a cap on the end of ball nut. The cap is machined to pick up balls out of the end of nut and direct them down holes which are bored transversely down the ballnut. The compliment cap on the other side of nut directs balls back into raceway.

Equations

$$T = \frac{Fl}{2\pi v}$$

Where T is torque applied to screw or nut, F is linear force applied, l is ball screw lead, and v is ball screw efficiency.

Carbon nanotube actuators

The exceptional electrical and mechanical properties of **carbon nanotubes** have made them alternatives to the traditional electrical actuators for both microscopic and macroscopic applications. Carbon nanotubes are very good conductors of both electricity and heat, and they are also very strong and elastic molecules in certain directions. These properties are difficult to find in the same material and very needed for high performance actuators. For current carbon nanotube actuators, multi-walled carbon nanotubes (MWNTs) and bundles of MWNTs have been widely used mostly due to the easiness of handling and robustness. Solution dispersed thick films and highly ordered transparent films of carbon nanotubes have been used for the macroscopic applications.

Microscopic applications

Carbon nano-tweezers

Carbon nanotube tweezers have been fabricated by deposition of MWNT bundles on isolated electrodes deposited on tempered glass micropipettes. Those nanotube bundles can be mechanically manipulated by electricity and can be used to manipulate and transfer micro- and nano-structures. The nanotube bundles used for tweezers are about 50 nm in diameter and 2 μm in lengths. Under electric bias, two close sets of bundles are attracted and can be used as nanoscale tweezers.

Nanotube on/off switches and random access memory

Harvard researchers have used the electrostatic attraction principle to design on/off switches for their proposed nanotube Random Access Memory devices. They used carbon nanotube bundles of ~ 50 nm in diameter to fabricate their proof-of-concept prototypes. One set of MWNT bundles are laid on the substrate and another set of bundles is trenched on top of the underlying nanotube bundles with air gap in between. Once electrical bias is applied the sets of nanotube bundles are attracted, thus changing the electrical resistance. These two states of resistance are on and off states. They have managed to get more than 10 times difference between off and on state resistances. This idea can be used as very highly packed arrays of nanoswitches and random access memory devices if they can be applied to arrays of single-walled carbon nanotubes, which are about 1 nm in diameter and hundreds of micrometres in length. The current technical challenge with this design is the lack of control to place arrays of carbon nanotubes on substrate.

Macroscopic applications

Nanotube sheet electrodes as actuators

Researchers of AlliedSignal initially demonstrated the possibility of electrically powered actuators fabricated by carbon nanotube sheets. They taped carbon nanotube sheets on

two sides of a double sided scotch tape and applied potential on the nanotube sheets in a NaCl electrolyte solution. Nanotube sheets are used as electrolyte-filled electrodes of a super capacitor. Nanotube sheets are electrically charged by the double layer formation at the nanotube-electrolyte interface without any need of ion intercalation. Therefore electrically driven actuators of nanotube sheets are superior to the conjugated polymer actuators which involve solid-state dopant diffusion and structural changes limiting rate, cycle life and energy conversion efficiencies. On the other hand, ferroelectric and electrostrictive materials are also very useful for direct energy conversion, but they require high operation voltages and ambient temperature of a limited range. Nanotube sheet actuators were shown to operate at low voltages (~1 Volts or less) and provide higher work densities per cycle than other alternative technologies. Later Baughman et al. showed that actuator response can be observed up to switching rates of 1 kHz and cycling the nanotube actuator at constant rate of 1 Hz for 140000 cycles decreases the stroke by ~33%. 0.75 MPa of stress were measured on the nanotube sheet actuators, which is greater than the maximum stress (0.3 MPa) that can be loaded on a human muscle.

The maximum actuator strain for electrically driven actuators of carbon nanotube sheets can be improved up to 0.7% in a 1 M electrolyte once the sheets are annealed in an inert atmosphere at very high temperatures (1100 °C) in contrast to once reported 0.1% or less for low electrochemical potentials (~1 V or less). The maximum strain for the carbon nanotube sheet actuators at low voltages is greater than that of the high modulus ferroelectric ceramic actuators (~0.1%), but it is lower than that of the low voltage (~0.4 V) conducting polymer actuators (~3% film direction, 20% thickness direction). Strokes were reported as high as 215% for strain biased low modulus electrostrictive rubbers under biases greater than 1kV (corresponding to an electric field 239 MV/m for the geometry mentioned in the reference paper). Spinks et al. realized pneumatic actuation from the carbon nanotube sheets in electrolyte solutions with high electrochemical potential (1.5 V), which cause gas generation in the electrolyte. The released gas dramatically increases the actuator stroke from the carbon nanotube sheet. Thickness of the carbon nanotube sheet expands by ~300% and the sheet plane contracts by 3%.

Artificial muscles and giant strokes by MWNT aerogel sheets

Highly ordered free standing aerogel sheets of MWNTs can be realized by simply drawing the sheet from the sidewalls of CVD grown MWNT forests. UT researchers came up with the conventional method where they attach an adhesive tape to the sidewalls of MWNT forests and they pull the tape at a constant rate as fast as 7 meters per minute to get 3–5 cm wide aerogel sheets of aligned MWNTs which have exceptional mechanical and optical properties. The aerogel sheets have a density of ~1.5 mg/cm³, an areal density of 1-3 µg/cm² and a thickness of ~20 µm. The thickness is decreased to ~50 nm by liquid-based densification to decrease the volume. The aerogel sheets can be stretched as much as three times along the width while low-modulus rubber like behavior is remained.

Having aerogel sheets of MWNTs, UT researchers fabricated actuators with giant strokes (~180% actuation along the width) with 5 ms delay time between applying the potential

and observing the maximum stroke. Therefore the actuation rate is slightly better than that of the human muscle. This is a very important achievement considering the actuation rate for artificial muscles used in robots is typically much slower. Furthermore the use of carbon nanotubes as the building blocks as an artificial muscle also helps in terms of strength and robustness by making the artificial muscle stronger than steel in one direction and more flexible than rubber in the other two directions. The lack of electrolyte solution and temperature robustness of the aerogel sheet in inert ambient makes high temperature operation possible. The actuation stroke decreases by only 50% from its room temperature value to 1344 °C. Thus, this design of artificial muscles can be quite useful for many industrial applications with the drawback of high voltage operation for giant strokes.

Challenges and future applications

As a result, carbon nanotubes have been shown to be great materials for actuation related applications. The subfield of carbon nanotube actuators have been quite successful and ready for scalable applications considering there are quite a few conventional and scalable methods for the synthesis of large scale carbon nanotubes. Carbon nanotube sheets used as electrodes in electrolyte solutions offered low voltage operations at room temperature with actuation strokes and rates comparable to the conducting polymer actuators, but with higher work densities per cycle and life times. However the actuation strokes are much smaller than those of the electrostrictive rubbers which operate at three orders of magnitude higher voltages. On the other hand, realization of carbon nanotube aerogels made giant strokes possible comparable to electrostrictive rubbers at room temperature, but carbon nanotube aerogels can perform at a very wide range of temperatures, and with very high actuation rates, which are even better than the actuation rate of the human muscles.

Chapter 3

Hoist (Device)



Overhead crane with a Wire Rope **hoist (device)** in blue suspended from bridge crane girder

A **hoist** is a device used for lifting or lowering a load by means of a drum or lift-wheel around which rope or chain wraps. It may be manually operated, electrically or pneumatically driven and may use chain, fiber or wire rope as its lifting medium. The load is attached to the hoist by means of a lifting hook.

Types of Hoist

The basic hoist has two important characteristics to define it: Lifting medium and power type. The lifting medium is either wire rope, wrapped around a drum, or load-chain, raised by a pulley with a special profile to engage the chain. The power type can be either electric motor or air motor. Both the wire rope hoist and chain hoist have been in common use since the 1800s. however; Mass production of an electric hoist did not start until the early 1900's and was first adapted by Germany. A hoist can be built as one integral-package unit, designed for cost-effective purchasing and moderate use, or it can be built as a built-up custom unit, designed for durability and performance. The built-up hoist will be much more expensive, but will also be easier to repair and more durable. Package units are where once regarded as being designed for light to moderate usage, but since the 60's this has changed. Built-up units are designed for heavy to severe service, but over the years that market has decreased in size since the advent of the more durable packaged hoist. A machine shop or fabricating shop will use an integral-package hoist, while a Steel Mill or NASA would use a built-up unit to meet durability, performance, and repairability requirements. NASA has also seen a change in the use of package hoists. The NASA Astronaut training pool for example utilizes cranes with packaged hoists.

Wire Rope Hoist or Chain Hoist



Wire Rope hoist on an overhead crane being used in typical machine shop. The hoist is operated via a wired pushbutton station to move system and the load in any direction



Builder's hoist, with small petrol engine

More commonly used hoist in today's worldwide market is an electrically powered hoist. These are either the chain type or the wire rope type. **Demag Cranes & Components Corp.** was one of the first companies in the world to mass-produce hoists. The first units large in size date back in 1819 and was powered by steam.

Now many hoists are package hoists, built as one unit in a single housing, generally designed for ten-year life, but the life calculation is based on an industry standard when calculating actual life. In today's modern world for the North American market there are a few governing bodies for the industry. The Overhead Alliance is a group that represents Crane Manufacturers Association of America (CMAA), Hoist Manufacturers Institute (HMI), and Monorail Manufacturers Association (MMA). These product counsels of the

Material Handling Industry of America have joined forces to create promotional materials to raise the awareness of the benefits to overhead lifting. The members of this group are marketing representatives of the member companies.

Common small portable hoists are of two main types, the *chain hoist* or *chain block* and the wire rope or cable type. Chain hoists may have a lever to actuate the hoist or have a loop of operating chain that one pulls through the block (known traditionally as a chain fall) which then activates the block to take up the main lifting chain.

A hand powered hoist with a ratchet wheel is known as a "ratchet lever hoist" or, colloquially, a "Come-A-Long". The original hoist of this type was developed by Abraham Maasdam of Deep Creek, Colorado about 1919, and later commercialized by his son, Felber Maasdam, about 1946. It has been copied by many manufacturers in recent decades. A similar heavy duty unit with a combination chain and cable became available in 1935 that was used by railroads, but lacked the success of the cable only type units.



A ratchet lever hoist (Come-A-Long).

Ratchet lever hoists have the advantage that they can usually be operated in any orientation, for pulling, lifting or binding. Chain block type hoists are usually suitable only for vertical lifting.

For a given *rated load* wire rope is lighter in weight per unit length but overall length is limited by the drum diameter that the cable must be wound onto. The lift chain of a chain hoist is far larger than the liftwheel over which chain may function. Therefore, a high-performance chain hoist may be of significantly smaller physical size than a wire rope hoist rated at the same working load.

Both systems fail over time through fatigue fractures if operated repeatedly at loads more than a small percentage of their tensile breaking strength. Hoists are often designed with internal clutches to limit operating loads below this threshold. Within such limits wire rope rusts from the inside outward while chain links are markedly reduced in cross section through wear on the inner surfaces. Regular lubrication of both tensile systems is recommended to reduce frequency of replacement. High speed lifting, greater than about 60 feet per minute (18.3 m/min), requires wire rope wound on a drum, because chain over a pocket wheel generates fatigue-inducing resonance for long lifts.

The unloaded wire rope of small hand powered hoists often exhibits a snarled "set", making the use of a chain hoist in this application less frustrating, but heavier. In addition, if the wire in a wire hoist fails, it can whip and cause injury, while a chain will simply break.

Construction hoists



A hoist on the Trump International Hotel & Tower-Chicago

Also known as a Man-Lift, Buckhoist, temporary elevator, Alimak or construction elevator, this type of hoist is commonly used on large scale construction projects, such as high-rise buildings or major hospitals. There are many other uses for the construction elevator. Many other industries use the buckhoist for full time operations. The purpose being to carry personnel, materials, and equipment quickly between the ground and higher floors, or between floors in the middle of a structure.

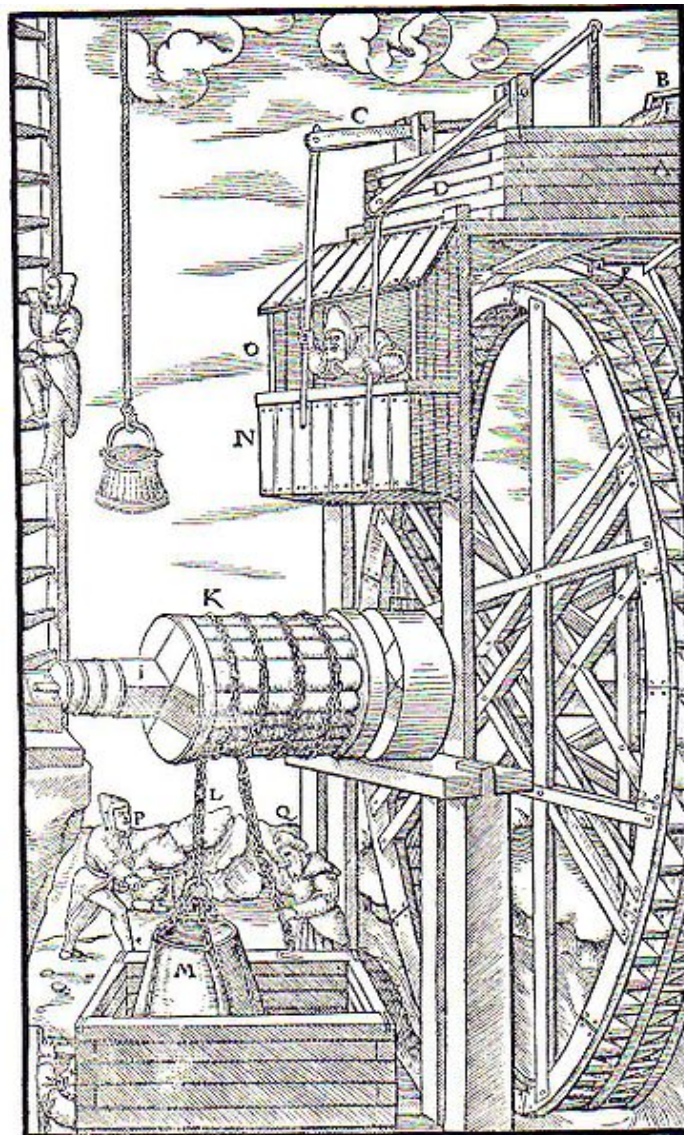
The construction hoist is made up of either one or two cars (cages) which travel vertically along stacked mast tower sections. The mast sections are attached to the structure or building every 25 feet (7.62 m) for added stability. For precisely controlled travel along

the mast sections, modern construction hoists use a motorized rack-and-pinion system that climbs the mast sections at various speeds.

While hoists have been predominantly produced in Europe and the United States, China is emerging as a manufacturer of hoists to be used in Asia.

In the United States and abroad, General Contractors and various other industrial markets rent or lease hoists for a specific projects. Rental or leasing companies provide erection, dismantling, and repair services to their hoists to provide General Contractors with turnkey services. Also the rental and leasing companies can provide parts and service for the elevators that are under contract.

Mine hoists



A water-powered mine hoist used for raising ore from *De re metallica*.

In underground mining a **hoist** or **winder** is used to raise and lower conveyances within the mine shaft. Human, animal and water power were used to power the mine hoists documented in Agricola's *De Re Metallica*, published in 1556. Stationary steam engines were commonly used to power mine hoists through the 19th century and into the 20th, as at the Quincy Mine, where a 4-cylinder cross-compound Corliss engine was used. Modern hoists are powered using electric motors, historically with direct current drives utilizing solid-state converters (thyristors), however modern large hoists use alternating current drives that are variable frequency controlled. There are three principal types of hoists used in mining applications, Drum Hoists, Friction (or Kope) hoists and Blair multi-rope hoists.

Chapter 4

Hydraulic Cylinder



The hydraulic cylinders on this excavator control the machine's linkages.

A **Hydraulic cylinder** (also called a linear hydraulic motor) is a mechanical actuator that is used to give a unidirectional force through a unidirectional stroke. It has many applications, notably in engineering vehicles.

Operation

Hydraulic cylinders get their power from pressurized hydraulic fluid, which is typically oil. The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth. The barrel is closed on each end by the cylinder bottom

(also called the cap end) and by the cylinder head where the piston rod comes out of the cylinder. The piston has sliding rings and seals. The piston divides the inside of the cylinder in two chambers, the bottom chamber (cap end) and the piston rod side chamber (rod end). The hydraulic pressure acts on the piston to do linear work and motion.

Flanges, trunnions, and/or clevises are mounted to the cylinder body. The piston rod also has mounting attachments to connect the cylinder to the object or machine component that it is pushing.

A hydraulic cylinder is the actuator or "motor" side of this system. The "generator" side of the hydraulic system is the hydraulic pump which brings in a fixed or regulated flow of oil to the bottom side of the hydraulic cylinder, to move the piston rod upwards. The piston pushes the oil in the other chamber back to the reservoir. If we assume that the oil pressure in the piston rod chamber is approximately zero, the force F on the piston rod equals the pressure P in the cylinder times the piston area A :

$$F = P \cdot A.$$

The piston moves instead downwards if oil is pumped into the piston rod side chamber and the oil from the piston area flows back to the reservoir without pressure. The pressure in the piston rod area chamber is (Pull Force) / (piston area - piston rod area).

Parts of a hydraulic cylinder

A hydraulic cylinder consists of the following parts:

Cylinder barrel

The cylinder barrel is mostly a seamless thick walled forged pipe that must be machined internally. The cylinder barrel is ground and/or honed internally.

Cylinder Bottom or Cap

In most hydraulic cylinders, the barrel and the bottom portion are welded together. This can damage the inside of the barrel if done poorly. Therefore some cylinder designs have a screwed or flanged connection from the cylinder end cap to the barrel. In this type the barrel can be disassembled and repaired in future.

Cylinder Head

The cylinder head is sometimes connected to the barrel with a sort of a simple lock (for simple cylinders). In general however the connection is screwed or flanged. Flange connections are the best, but also the most expensive. A flange has to be welded to the pipe before machining. The advantage is that the connection is bolted and always simple to remove. For larger cylinder sizes, the disconnection of a screw with a diameter of 300 to 600 mm is a huge problem as well as the alignment during mounting.

Piston

The piston is a short, cylinder-shaped metal component that separates the two sides of the cylinder barrel internally. The piston is usually machined with grooves to fit elastomeric or metal seals. These seals are often O-rings, U-cups or cast iron rings. They prevent the pressurized hydraulic oil from passing by the piston to the chamber on the opposite side. This difference in pressure between the two sides of the piston causes the cylinder to extend and retract. Piston seals vary in design and material according to the pressure and temperature requirements that the cylinder will see in service. Generally speaking, elastomeric seals made from nitrile rubber or other materials are best in lower temperature environments while seals made of Viton are better for higher temperatures. The best seals for high temperature are cast iron piston rings.

Piston Rod

The piston rod is typically a hard chrome-plated piece of cold-rolled steel which attaches to the piston and extends from the cylinder through the rod-end head. In double rod-end cylinders, the actuator has a rod extending from both sides of the piston and out both ends of the barrel. The piston rod connects the hydraulic actuator to the machine component doing the work. This connection can be in the form of a machine thread or a mounting attachment such as a rod-clevis or rod-eye. These mounting attachments can be threaded or welded to the piston rod or, in some cases, they are a machined part of the rod-end.

Rod gland

The cylinder head is fitted with seals to prevent the pressurized oil from leaking past the interface between the rod and the head. This area is called the rod gland. It often has another seal called a rod wiper which prevents contaminants from entering the cylinder when the extended rod retracts back into the cylinder. The rod gland also has a rod wear ring. This wear ring acts as a linear bearing to support the weight of the piston rod and guides it as it passes back and forth through the rod gland. In some cases, especially in small hydraulic cylinders, the rod gland and the rod wear ring are made from a single integral machined part.

Other parts

- Cylinder bottom connection
- Seals
- Cushions

A hydraulic cylinder should be used for pushing and pulling only. No bending moments or side loads should be transmitted to the piston rod or the cylinder. For this reason, the ideal connection of a hydraulic cylinder is a single clevis with a spherical ball bearing. This allows the hydraulic actuator to move and allow for any misalignment between the actuator and the load it is pushing.

Hydraulic Cylinder Designs

There are primarily two styles of hydraulic cylinder construction used in industry: tie rod style cylinders and welded body style cylinders.

Tie Rod Cylinders

Tie rod style hydraulic cylinders use high strength threaded steel rods to hold the two end caps to the cylinder barrel. This method of construction is most often seen in industrial factory applications. Small bore cylinders usually have 4 tie rods, while large bore cylinders may require as many as 16 or 20 tie rods in order to retain the end caps under the tremendous forces produced. Tie rod style cylinders can be completely disassembled for service and repair.

The National Fluid Power Association (NFPA) has standardized the dimensions of hydraulic tie rod cylinders. This enables cylinders from different manufacturers to interchange within the same mountings.

Welded Body Cylinders

Welded body cylinders have no tie rods. The barrel is welded directly to the end caps. The ports are welded to the barrel. The front rod gland is usually threaded into or bolted to the cylinder barrel. This allows the piston rod assembly and the rod seals to be removed for service.



A Cut Away of a Welded Body Hydraulic Cylinder showing the internal components

Welded body cylinders have a number of advantages over tie rod style cylinders. Welded cylinders have a narrower body and often a shorter overall length enabling them to fit better into the tight confines of machinery. Welded cylinders do not suffer from failure due to tie rod stretch at high pressures and long strokes. The welded design also lends itself to customization. Special features are easily added to the cylinder body. These may include special ports, custom mounts, valve manifolds, and so on.

The smooth outer body of welded cylinders also enables the design of multi-stage telescopic cylinders.

Welded body hydraulic cylinders dominate the mobile hydraulic equipment market such as construction equipment (excavators, bulldozers, and road graders) and material

handling equipment (forklift trucks, telehandlers, and lift-gates). They are also used in heavy industry such as cranes, oil rigs, and large off-road vehicles in above-ground mining.

Piston Rod construction

The piston rod of a hydraulic cylinder operates both inside and outside the barrel, and consequently both in and out of the hydraulic fluid and surrounding atmosphere.

Metallic coatings

Smooth and hard surfaces are desirable on the outer diameter of the piston rod and slide rings for proper sealing. Corrosion resistance is also advantageous. A chromium layer may often be applied on the outer surfaces of these parts. However, chromium layers may be porous, thereby attracting moisture and eventually causing oxidation. In harsh marine environments, the steel is often treated with both a nickel layer and a chromium layer. Often 40 to 150 micrometer thick layers are applied. Sometimes solid stainless steel rods are used. High quality stainless steel such as AISI 316 may be used for low stress applications. Other stainless steels such as AISI 431 may also be used where there are higher stresses, but lower corrosion concerns.

Ceramic coatings

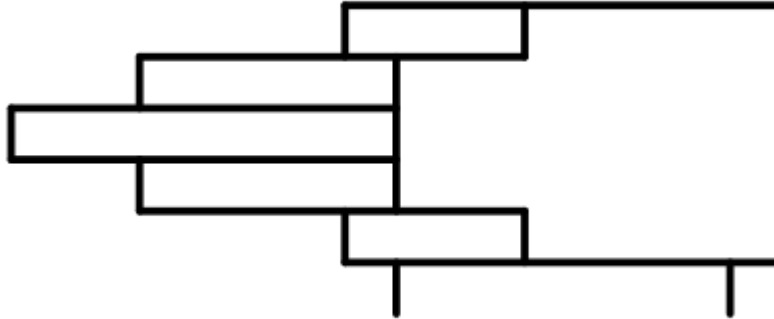
Due to shortcomings of metallic materials, ceramic coatings were developed. Initially ceramic protection schemes seemed ideal, but porosity was higher than projected. Recently the corrosion resistant semi ceramic Lunac 2+ coatings were introduced. These hard coatings are non porous and do not suffer from high brittleness.

Lengths

Piston rods are generally available in lengths which are cut to suit the application. As the common rods have a soft or mild steel core, their ends can be welded or machined for a screw thread.

Special hydraulic cylinders

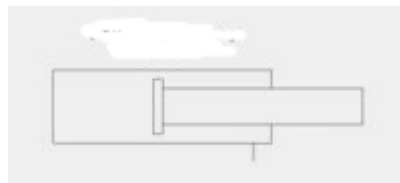
Telescopic cylinder



Telescopic cylinder (ISO 1219 symbol)

The length of a hydraulic cylinder is the total of the stroke, the thickness of the piston, the thickness of bottom and head and the length of the connections. Often this length does not fit in the machine. In that case the piston rod is also used as a piston barrel and a second piston rod is used. These kind of cylinders are called telescopic cylinders. If we call a normal rod cylinder single stage, telescopic cylinders are multi-stage units of two, three, four, five and even six stages. In general telescopic cylinders are much more expensive than normal cylinders. Most telescopic cylinders are single acting (push). Double acting telescopic cylinders must be specially designed and manufactured.

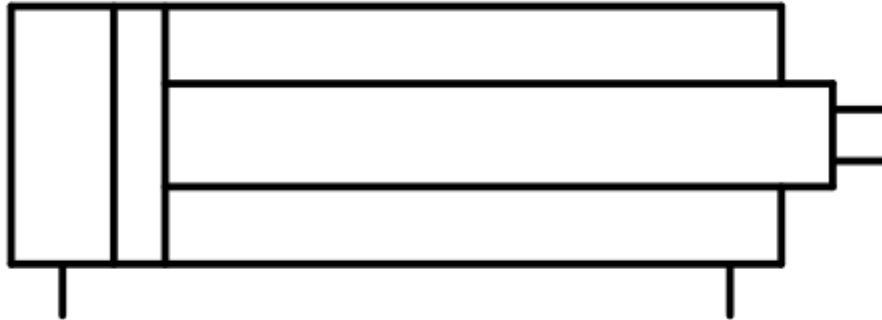
Plunger cylinder



Plunger cylinder

A hydraulic cylinder without a piston or with a piston without seals is called a plunger cylinder. A plunger cylinder can only be used as a pushing cylinder; the maximum force is piston rod area multiplied by pressure. This means that a plunger cylinder in general has a relatively thick piston rod.

Differential cylinder



Differential cylinder (ISO 1219 symbol)

A differential cylinder acts like a normal cylinder when pulling. If the cylinder however has to push, the oil from the piston rod side of the cylinder is not returned to the reservoir, but goes to the bottom side of the cylinder. In such a way, the cylinder goes much faster, but the maximum force the cylinder can give is like a plunger cylinder. A differential cylinder can be manufactured like a normal cylinder, and only a special control is added.

Rephasing cylinder

Rephasing cylinders are two or more cylinders plumbed in series or parallel, with the bores and rods sized such that all rods extend and/or retract equally when flow is directed to the first, or last, cylinder within the system.

In "parallel" applications, the bore and rod sizes are always the same, and the cylinders are always used in pairs. In "series" applications, the bore and rod sizes are always different, and two or more cylinders may be used. In these applications, the bores and rods are sized such that all rods extend or retract equally when flow is applied to the first or last cylinder within the system.

This hydraulic synchronization of rod positions eliminates the need for a flow divider in the hydraulic system, or any type of mechanical connection between the cylinder rods to achieve synchronization.

Position sensing "smart" hydraulic cylinder

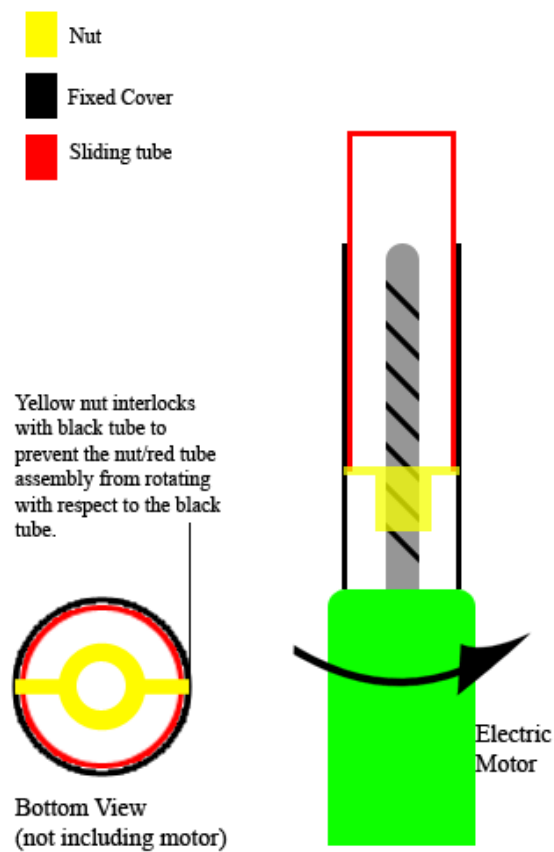
Position sensing hydraulic cylinders eliminate the need for a hollow cylinder rod. Instead, an external sensing "bar" utilizing Hall-Effect technology senses the position of the cylinder's piston. This is accomplished by the placement of a permanent magnet within the piston. The magnet propagates a magnetic field through the steel wall of the cylinder, providing a locating signal to the sensor.

A note about popular terminology

At least in the USA, popular usage sometimes refers to the whole assembly of cylinder, piston, and piston rod (or more) collectively as a "piston", which is incorrect. See, for instance, "Hydraulic piston raises the table from 19 (in.) to 26 (in.)" Marine Tables, Inc. (Select item 3 of 8, near the bottom.)

Chapter 5

Linear Actuator



Conceptual design of a basic traveling-nut linear actuator. Note that in this example the lead screw (gray) rotates while the lead nut (yellow) and tube (red) do not.

A **linear actuator** is an actuator that, when driven by a non-linear motion, creates linear motion (as opposed to rotary motion, e.g. of an electric motor). Mechanical and hydraulic actuation are the most common methods of achieving the linear motion.

Types

Mechanical actuators



A mechanical linear actuator with digital readout.

Mechanical linear actuators operate by conversion of rotary motion into linear motion. Conversion is commonly made via a few simple types of mechanism:

- **Screw:** Screw jack, ball screw and roller screw actuators all operate on the principle of the simple machine known as the screw. By rotating the actuator's nut, the screw shaft moves in a line.
- **Wheel and axle:** Hoist, winch, rack and pinion, chain drive, belt drive, rigid chain and rigid belt actuators operate on the principle of the wheel and axle. By rotating a wheel/axle (e.g. drum, gear, pulley or shaft) a linear member (e.g. cable, rack, chain or belt) moves.
- **Cam:** Cam actuators function on a principle similar to that of the wedge, but provide relatively limited travel. As a wheel-like cam rotates, its eccentric shape provides thrust at the base of a shaft.

Some mechanical linear actuators only pull (e.g. hoist, chain drive and belt drive) and others only push (e.g. cam actuator).

Mechanical actuators typically convert rotary motion of a control knob or handle into linear displacement via screws and/or gears to which the knob or handle is attached. A jackscrew or car jack is a familiar mechanical actuator. Another family of actuators are based on the segmented spindle. Rotation of the jack handle is converted mechanically into the linear motion of the jack head. Mechanical actuators are also frequently used in the field of lasers and optics to manipulate the position of linear stages, rotary stages, mirror mounts, goniometers and other positioning instruments. For accurate and repeatable positioning, index marks may be used on control knobs. Some actuators even include an encoder and digital position readout. These are similar to the adjustment knobs

used on micrometers except that their purpose is position adjustment rather than position measurement.

Hydraulic actuators

Hydraulic actuators or hydraulic cylinders typically involve a hollow cylinder having a piston inserted in it. The two sides of the piston are alternately pressurized/de-pressurized to achieve controlled precise linear displacement of the piston and in turn the entity connected to the piston. The physical linear displacement is only along the axis of the piston/cylinder. This design is based on the principles of hydraulics. A familiar example of a manually operated hydraulic actuator is a hydraulic car jack. Typically though, the term "hydraulic actuator" refers to a device controlled by a hydraulic pump.

Pneumatic actuators

Pneumatic actuators, or pneumatic cylinders, are similar to hydraulic actuators except they use compressed gas to provide pressure instead of a liquid.

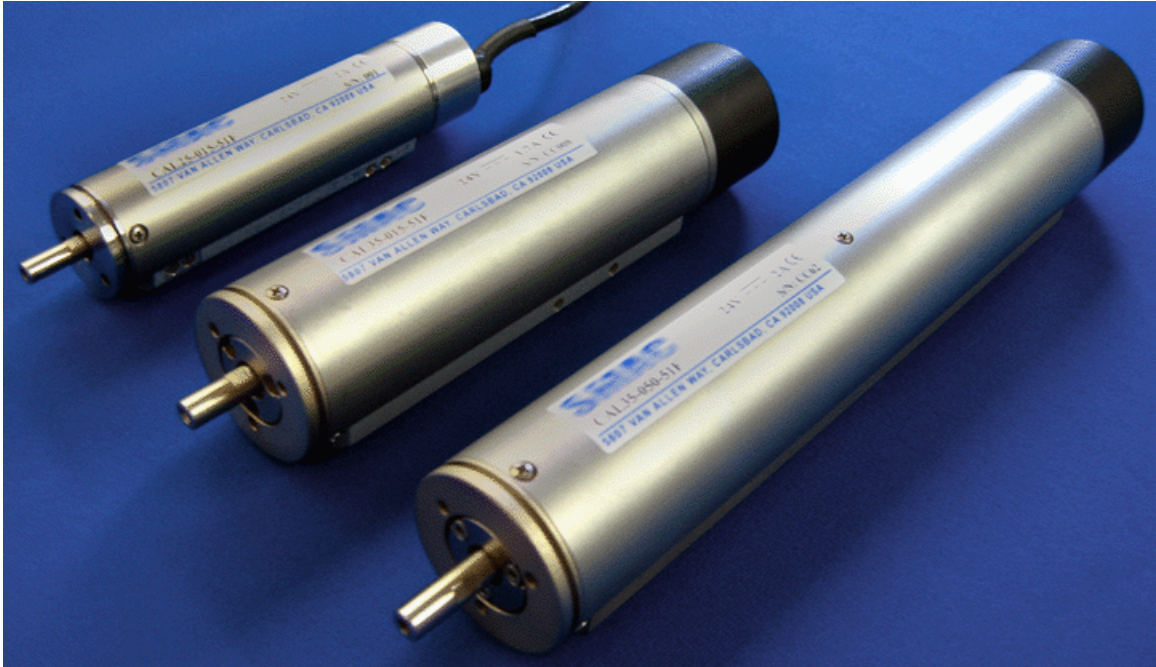
Piezoelectric actuators

The piezoelectric effect is a property of certain materials in which application of a voltage to the material causes it to expand. Very high voltages correspond to only tiny expansions. As a result, piezoelectric actuators can achieve extremely fine positioning resolution, but also have a very short range of motion. In addition, piezoelectric materials exhibit hysteresis which makes it difficult to control their expansion in a repeatable manner.

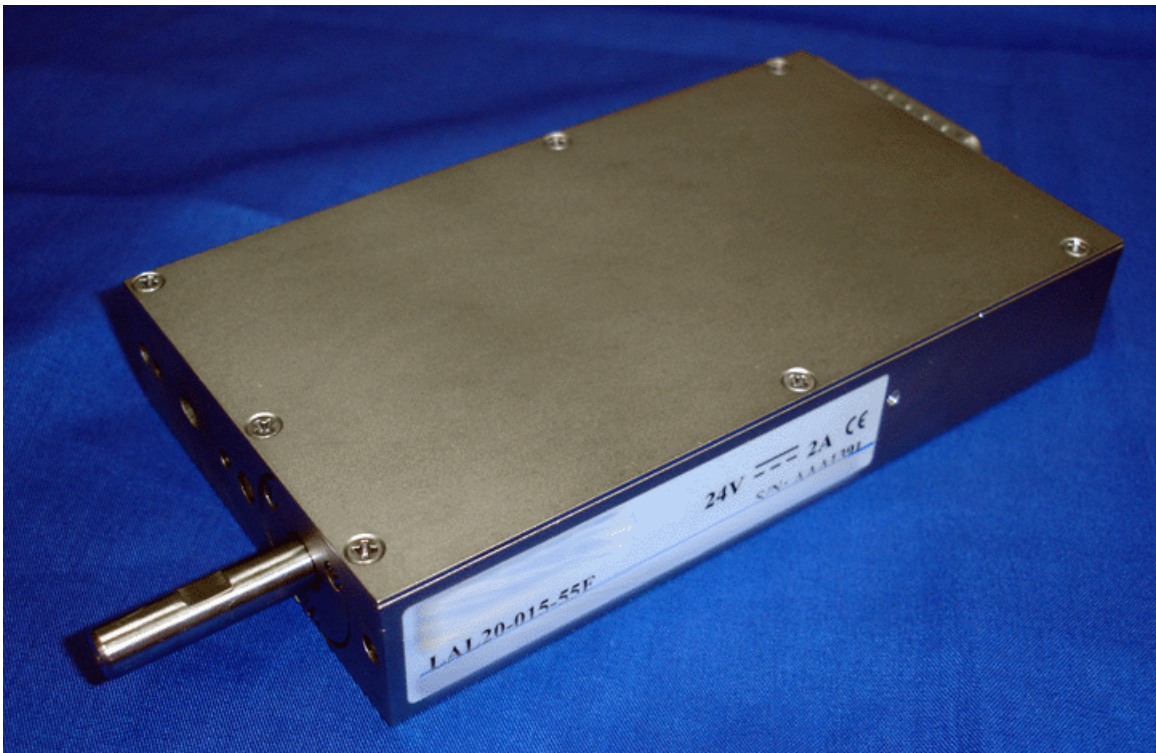
Electro-mechanical actuators



A miniature electro-mechanical linear actuator where the lead nut is part of the motor. The lead screw does not rotate, so as the lead nut is rotated by the motor, the lead screw is extended or retracted.



Typical compact cylindrical linear electric actuator



Typical linear or rotary + linear electric actuator



Moving coil linear, rotary and linear + rotary actuators at work in various applications

Electro-mechanical actuators are similar to mechanical actuators except that the control knob or handle is replaced with an electric motor. Rotary motion of the motor is converted to linear displacement of the actuator. There are many designs of modern linear actuators and every company that manufactures them tends to have their own proprietary method. The following is a generalized description of a very simple electro-mechanical linear actuator.

Simplified design

Typically, a rotary driver (e.g. electric motor) is mechanically connected to a lead screw so that the rotation of the electric motor will make the lead screw rotate. A lead screw has a continuous helical thread machined on its circumference running along the length (similar to the thread on a bolt). Threaded onto the lead screw is a lead nut or ball nut with corresponding helical threads. The nut is prevented from rotating with the lead screw (typically the nut interlocks with a non-rotating part of the actuator body). Therefore, when the lead screw is rotated, the nut will be driven along the threads. The direction of motion of the nut will depend on the direction of rotation of the lead screw. By connecting linkages to the nut, the motion can be converted to usable linear displacement. Most current actuators are built either for high speed, high force, or a compromise between the two. When considering an actuator for a particular application, the most important specifications are typically travel, speed, force, accuracy, and lifetime.

There are many types of motors that can be used in a linear actuator system. These include dc brush, dc brushless, stepper, or in some cases, even induction motors. It all depends on the application requirements and the loads the actuator is designed to move. For example, a linear actuator using an integral horsepower AC induction motor driving a lead screw can be used to actuate a large valve in a refinery. In this case, accuracy and move resolution down to a thousandth isn't needed, but high force and speed is. For electromechanical linear actuators used in laboratory instrumentation robotics, optical and laser equipment, or X-Y tables, fine resolution into the micron region and high

accuracy may require the use of a fractional horsepower stepper motor linear actuator with a fine pitch lead screw. There are many variations in the electromechanical linear actuator system. It's critical to understand the design requirements and application constraints to know which one would be best.

Principles

In the majority of linear actuator designs, the basic principle of operation is that of an inclined plane. The threads of a lead screw act as a continuous ramp that allows a small rotational force to be used over a long distance to accomplish movement of a large load over a short distance.

Variations

Many variations on the basic design have been created. Most focus on providing general improvements such as a higher mechanical efficiency, speed, or load capacity. There is also a large engineering movement towards actuator miniaturization.

Most electro-mechanical designs incorporate a lead screw and lead nut. Some use a ball screw and ball nut. In either case the screw may be connected to a motor or manual control knob either directly or through a series of gears. Gears are typically used to allow a smaller (and weaker) motor spinning at a higher rpm to be geared down to provide the torque necessary to spin the screw under a heavier load than the motor would otherwise be capable of driving directly. Effectively this sacrifices actuator speed in favor of increased actuator thrust. In some applications the use of worm gear is common as this allow a smaller built in dimension still allowing great travel length.

A traveling-nut linear actuator has a motor that stays attached to one end of the lead screw (perhaps indirectly through a gear box), the motor spins the lead screw, and the lead nut is restrained from spinning so it travels up and down the lead screw.

A traveling-screw linear actuator has a lead screw that passes entirely through the motor. In a traveling-screw linear actuator, the motor "crawls" up and down a lead screw that is restrained from spinning—the only spinning parts are inside the motor, and may not even be visible from the outside.

Some lead screws have multiple "starts". This means that they have multiple threads alternating on the same shaft. One way of visualizing this is in comparison to the multiple color stripes on a candy cane. This allows for more adjustment between thread pitch and nut/screw thread contact area, which determines the extension speed and load carrying capacity (of the threads), respectively.

Linear motors

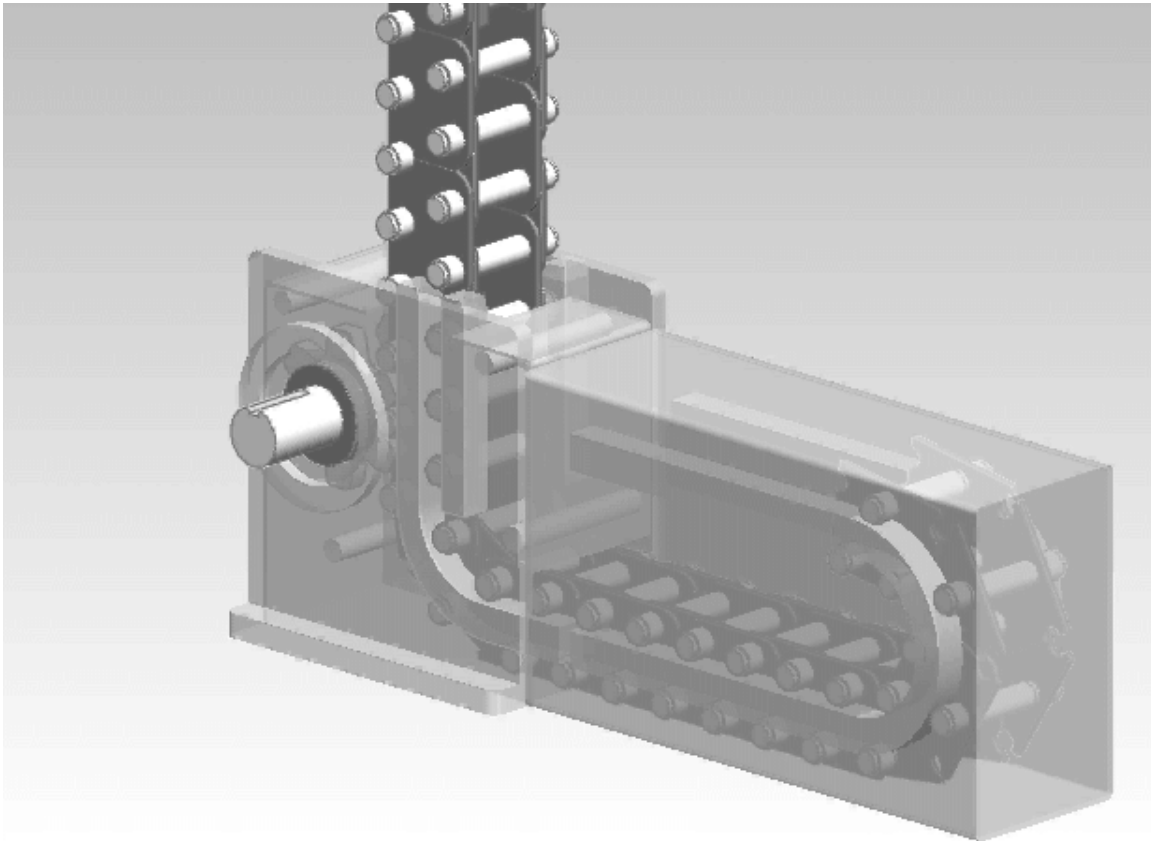
A linear motor is essentially a rotary electric motor laid down on flat surface. Since the motor moves in a linear fashion to begin with, no lead screw is needed to convert rotary

motion to linear. While high capacity is possible, the material and/or motor limitations on most designs are surpassed relatively quickly. Most linear motors have a low load capacity compared to other types of linear actuators.

Wax motors

A wax motor typically uses an electric current to heat a block of wax causing it to expand. A plunger that bears on the wax is thus forced to move in a linear fashion.

Telescoping linear actuator



Rigid chain actuator

Telescoping linear actuators are specialized linear actuators used where space restrictions or other requirements require. Their range of motion is many times greater than the unextended length of the actuating member.

A common form is made of concentric tubes of approximately equal length that extend and retract like sleeves, one inside the other, such as the telescopic cylinder.

Other more specialized telescoping actuators use actuating members that act as rigid linear shafts when extended, but break that line by folding, separating into pieces and/or uncoiling when retracted. Examples of telescoping linear actuators include:

- Helical band actuator
- Rigid belt actuator
- Rigid chain actuator
- Segmented spindle

Advantages and disadvantages

Actuator Type	Advantages	Disadvantages
Mechanical	Cheap. Repeatable. No power source required. Self-contained. Identical behaviour extending or retracting.	Manual operation only. No automation.
Electro-mechanical	Cheap. Repeatable. Operation can be automated. Self-contained. Identical behaviour extending or retracting. DC or stepping motors. Position feedback possible.	Many moving parts prone to wear.
Linear motor	Simple design. Minimum of moving parts. High speeds possible. Self-contained. Identical behaviour extending or retracting.	Low force.
Piezoelectric	Very small motions possible.	Requires position feedback to be repeatable. Short travel. Low speed. High voltages required. Expensive. Good in compression only, not in tension.
Hydraulic	Very high forces possible.	Can leak. Requires position feedback for repeatability. External hydraulic pump required. Some designs good in compression only.
Pneumatic	Strong, light, simple, fast.	Precise position control impossible except at full stops
Wax motor	Smooth operation.	Not as reliable as other methods.
Segmented spindle	Very compact. Range of motion greater than length of actuator.	Both linear and rotary motion.
Moving coil	Force, position and speed are controllable and repeatable. Capable of high speeds and precise positioning. Linear, rotary, and linear + rotary actions possible.	Requires position feedback to be repeatable.
MICA (moving iron controllable actuator)	High force and controllable. Higher force and less losses than moving coils. Losses easy to dissipate. Electronic driver easy to design and set up.	Stroke limited to several millimeters, less linearity than moving coils

Chapter 6

Nanotube Nanomotor

A device generating linear or rotational motion using carbon nanotube(s) as the primary component, is termed a nanotube nanomotor. Nature already has some of the most efficient and powerful kinds of nanomotors. Some of these natural biological nanomotors have been re-engineered to serve desired purposes. However, such biological nanomotors are designed to work in specific environmental conditions (pH, liquid medium, sources of energy, etc). Man-made nanotube nanomotors on the other hand are significantly more robust and can operate in diverse environments including varied frequency, temperature, mediums and chemical environments. The vast differences in the dominant forces and criteria between macroscale and micro/nanoscale offer new avenues to construct tailor-made nanomotors. The various beneficial properties of carbon nanotubes makes them the most attractive material to base such nanomotors on.

History

Just fifteen years after making the world's first micron sized motor Dr. Alex Zettl led his group at University of California at Berkeley to construct the very first nanotube nanomotor in 2003. A few concepts and models have been spun off ever since including the nanoactuator driven by a thermal gradient as well as the conceptual Electron Windmill, both of which were revealed in 2008.

Size effects

Electrostatic Forces

Coulomb's law states that the electrostatic force is inversely proportional to the square of the distance between two objects. Hence, as the distance is reduced to less than a few microns, a large force can be generated from seemingly small charges on two bodies. However electrostatic charge scales quadratically thereby resulting in the quadratic scaling of the electrostatic force as the following equations show:

$$\text{Capacitance}(C) = \frac{\epsilon A}{d} \propto L$$

$$\text{Electrostatic Field}(E) \propto L^0$$

$$\text{Voltage}(V) = \text{electrostatic field} * \text{length} = E * L \propto L$$

$$\text{Charge} = CV \propto L^2$$

$$\text{Electrostatic Force}(F) = \text{area} * E^2 \propto L^2$$

Alternatively

$$\text{Electrostatic Force}(F) = \frac{Q_1 * Q_2}{d^2} \propto \frac{L^2 * L^2}{L^2} \propto L^2$$

Despite the scaling nature of the electrostatic force it is one of the major mechanisms of sensing and actuation in the field of Micro-Electro-Mechanical Systems (MEMS) and is the backbone for the working mechanism of the first NEMS nanomotor. The quadratic scaling is alleviated by increasing the number of units generating the electrostatic force as seen in comb drives in many MEMS devices.

Friction

Just as the electrostatic force, the frictional force scales quadratically with size:

$$\text{Frictional Force} \propto L^2$$

Friction is an ever plaguing problem regardless of the scale of a device. It becomes all the more prominent when a device is scaled down. In the nano scale it can wreak havoc if not accounted for because the parts of a Nano-Electro-Mechanical-Systems (NEMS) device are sometimes only a few atoms thick. Furthermore such NEMS devices typically have a very large surface area-to-volume ratio. Surfaces in the nanoscale resemble a mountain range, where each peak corresponds to an atom or a molecule. Friction at the nanoscale is proportional to the number of atoms that interact between two surfaces. Hence, friction between perfectly smooth surfaces in the macroscale is actually similar to large rough objects rubbing against each other.

In the case of nanotube nanomotors however, the intershell friction in the multi walled nanotubes (MWNT) is remarkably small. Molecular dynamics studies show that, with the exception of small peaks, the frictional force remains almost negligible for all sliding velocities until a special sliding velocity is reached. Simulations relating the sliding velocity, induced rotation, inter-shell frictional force to the applied force provide explanations for the low inter-wall friction. Contrary to macroscale expectations the speed at which an inner tube travels within an outer tube does not follow a linear

relationship with the applied force. Instead, the speed remains constant (as in a plateau) despite increasing applied force occasionally jumping in value to the next plateau. No real rotation is noticed in nonchiral inner tubes. In the case of chiral tubes a true rotation is noticed and the angular velocity also jumps to plateaus along with the jumps in the linear velocity. These plateaus and jumps can be explained as a natural outcome of frictional peaks for growing velocity, the stable (rising) side of the peak leading to a plateau, the dropping (unstable) side leading to a jump. These peaks occur due to parametric excitation of vibrational modes in the walls of the tubes due to the sliding of the inner tube. With the exception of small peaks, that correspond to the speed plateaus, the frictional force remains almost negligible for all sliding velocities until a special sliding velocity. These velocity plateaus correspond to the peaks in the frictional force. The sudden rise in sliding velocity is due to a resonance condition between a frequency that is dependent on the inter-tube corrugation period and particular phonon frequencies of the outer tube which happen to possess a group velocity approximately equal to the sliding velocity.

First NEMS nanomotor

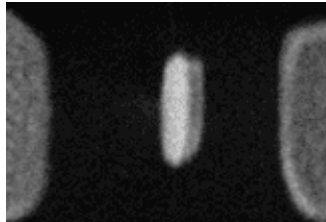


Figure 1.1: Image showing the metal rotor rotating around the MWNT axis

The first nanomotor can be thought of as a scaled down version of a comparable microelectromechanical systems (MEMS) motor. As Figure 1.1 and Figure 1.2 show, the nanoactuator consists of a gold plate rotor, rotating about the axis of a multi-walled nanotube (MWNT). The ends of the MWNT rest on a SiO₂ layer which form the two electrodes at the contact points. Three fixed stator electrodes (two visible 'in-plane' stators and one 'gate' stator buried beneath the surface) surround the rotor assembly. Four independent voltage signals (one to the rotor and one to each stators) are applied to control the position, velocity and direction of rotation. Empirical angular velocities recorded provide a lower bound of 17 Hz (although capable of operating at much higher frequencies) during complete rotations.

Fabrication

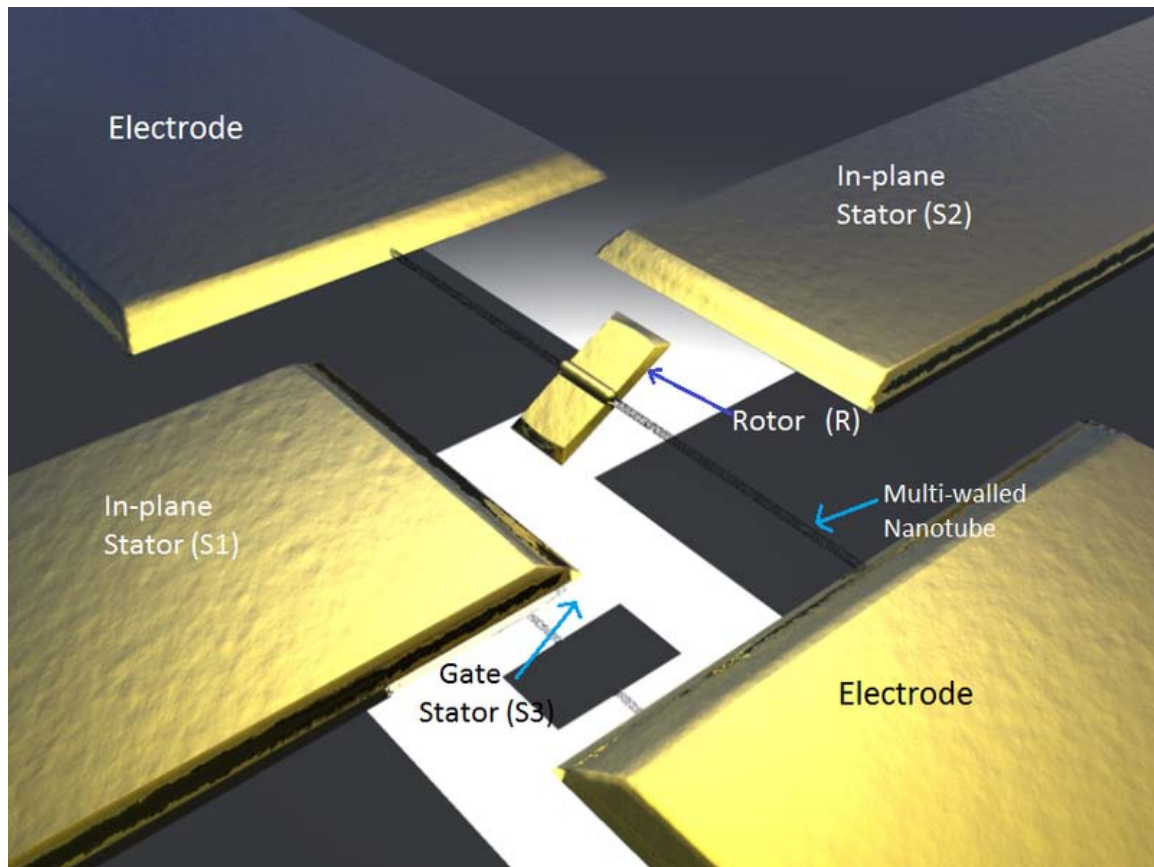


Figure 1.2: Schematic showing basic layout of the nanomotor

The MWNTs are synthesized by the arc-discharge technique, suspended in 1,2-dichlorobenzene and deposited on degenerately doped silicon substrates with a $1\mu\text{m}$ of SiO_2 . The MWNT can be aligned according to pre-made markings on the substrate by using an atomic force microscope (AFM) or a Scanning electron microscope. The rotor, electrodes and the 'in-plane' stators are patterned using electron beam lithography using an appropriately masked photo-resist. Gold with a chromium adhesion layer is thermally evaporated, lifted off in acetone and then annealed at 400°C to ensure better electrical and mechanical contact with the MWNT. The rotor measures 250-500 nm on a side. An HF etch is then used to remove sufficient thickness (500 nm of SiO_2) of the substrate to make room for the rotor when it rotates. The Si substrate serves as the gate stator. The MWNT at this point displays a very high torsional spring constant (10^{-15} to 10^{-13} N m with resonant frequencies in the tens of megahertz), hence, preventing large angular displacements. To overcome this, one or more outer MWNT shells are compromised or removed in the region between the anchors and the rotor plate. One simple way to accomplish this is by successively applying very large stator voltages (around 80 V d.c) that cause mechanical fatigue and eventually shear the outer shells of the MWNT. An alternative method involves the reduction of the outermost MWNT tubes to smaller, wider concentric nanotubes beneath the rotor plate.

The smaller nanotube(s) are fabricated using the Electrical driven vaporization (EDV) which is a variant of the electrical-breakdown technique. Passing current between the two electrodes typically results in failure of the outermost shell only on one side of the nanotube. Current is therefore passed between one electrode and the center of the MWNT which results in the failure of the outermost shell between this electrode and the center. The process is repeated on the opposite side to result in the formation of the short concentric nanotube that behaves like a low friction bearing along the longer tube.

Arrays of Nanoactuators

Due to the miniscular magnitude of output generated by a single nanoactuator the necessity to use arrays of such actuators to accomplish a higher task comes into picture. Conventional methods like chemical vapor deposition (CVD) allow the exact placement of nanotubes by growing them directly on the substrate. However, such methods are unable to produce very high qualities of MWNT. Moreover, CVD is a high temperature process that would severely limit the compatibility with other materials in the system. A Si substrate is coated with electron beam resist and soaked in acetone to leave only a thin polymer layer. The substrate is selectively exposed to a low energy electron beam of a scanning electron microscope (SEM) that activates the adhesive properties of the polymer later. This forms the basis for the targeting method. The alignment method exploits the surface velocity obtained by a fluid as it flows off a spinning substrate. MWNTs are suspended in orthodicholrobenzene (ODCB) by ultrasonication in a aquasonic bath that separates most MWNT bundles into individual MWNTs. Drops of this suspension are then pipetted one by one onto the center of a silicon substrate mounted on a spin coater rotating at 3000 rpm. Each subsequent drop of the suspension is pipetted only after the previous drop has completely dried to ensure larger density and better alignment of the MWNTs (90% of the MWNTs over 1 μm long lie within 1°). Standard electron beam lithography is used to pattern the remaining components of the nanoactuators.

Arc-Discharge Evaporation technique

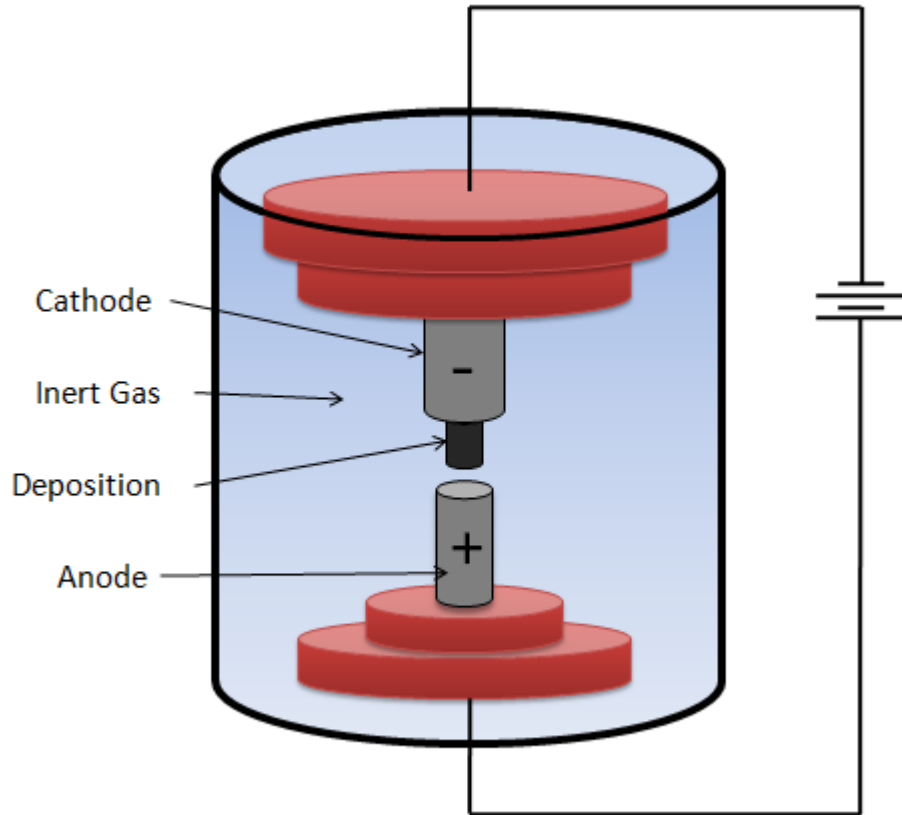


Figure 1.3: Cartoon showing the basic experimental setup for the Arc-Discharge technique of large scale carbon nanotube synthesis

This technique is a variant of the standard arc-discharge technique used for the synthesis of fullerenes in an inert gas atmosphere. As Figure 1.3 shows, the experiment is carried out in a reaction vessel containing an inert gas such as helium, argon, etc flowing at a constant pressure. A potential of around 18V is applied across two graphite electrodes (diameters of the anode and cathode are 6 mm and 9 mm) separated by a short distance of usually 1–4 mm within this chamber. The amount of current (usually 50-100 A) passed through the electrodes to ensure nanotube formation depends on the dimensions of the electrodes, separation distance and the inert gas used. As a result, carbon atoms are ejected from the anode and are deposited onto the cathode hence shrinking the mass of the anode and increasing the mass of the cathode. The black carbonaceous deposit (a mixture of nanoparticles and nanotubes in a ratio of 1:2) is seen growing on the inside of the cathode while a hard grey metallic shell forms on the outside. The total yield of nanotubes as a proportion of starting graphitic material peaks at a pressure of 500 torr at which point 75% of graphite rod consumed is converted to nanotubes. The nanotubes formed range from 2 to 20 nm in diameter and few to several microns in length. There are several advantages of choosing this method over the other techniques such as laser ablation and chemical vapor deposition such as fewer structural defects (due to high

growth temperature), better electrical, mechanical and thermal properties, high production rates (several hundred mg in ten minutes), etc.

Electrical-breakdown technique

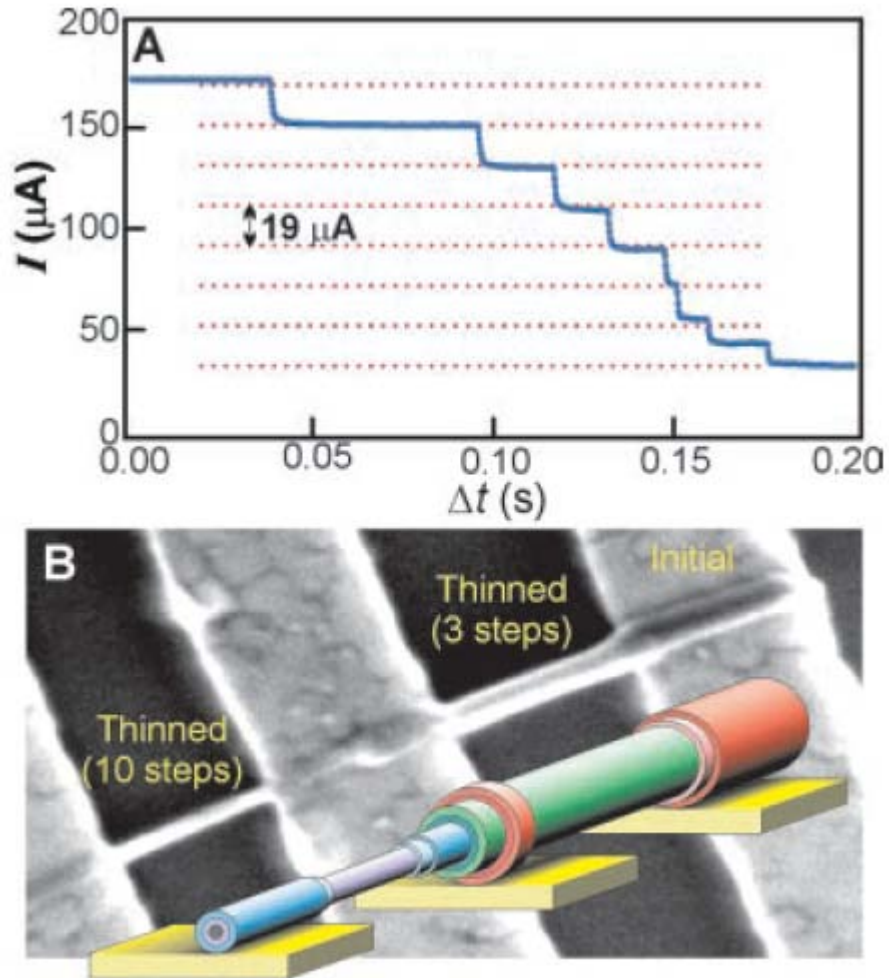


Figure 1.4: (A) Graph showing remarkably discrete, constant drops in conductance for the removal of each subsequent carbon shell under constant voltage (B) Images of partially broken MWNTs show clear thinning, with a decrease in radius equal to the intershell spacing (0.34 nm) times the number of completed breakdown steps. The two segments of this sample were independently thinned by 3 and 10 shells, as depicted by the color overlays

Large-scale synthesis of carbon nanotubes typically results in a randomly varied proportion of different types of carbon nanotubes. Some may be semiconducting while others may be metallic in their electrical properties. Most applications require the use of such specific types of nanotubes. Electrical-breakdown technique provides a means for separating and selecting desired type of nanotubes. Carbon nanotubes are known to withstand very large current densities up to 10^9 A/cm^2 partly due to the strong sigma bonds between carbon atoms. However, at sufficiently high currents the nanotubes fail

primarily due to rapid oxidation of the outermost shell. This results in a partial conductance drop that becomes apparent within a few seconds. Applying an increased bias displays multiple independent and stepwise drops in conductance (figure 1.4) resulting from the sequential failure of carbon shells. Current in a MWNT typically travels in the outermost shell due to the direct contact between this shell and the electrodes. This controlled destruction of shells without affecting disturbing inner layers of MWNTs permits the effective separation of the nanotubes.

Principle

The rotor is made to rotate using electrostatic actuation. An out-of-phase common frequency sinusoidal voltages to two in-plane stators S_1 , S_2 , a doubled frequency voltage signal to the gate stator S_3 and a dc offset voltage to the rotor plate R are applied as shown below:

$$S_1 = V_0 \sin(\omega t)$$

$$S_2 = V_0 \sin(\omega t - \pi)$$

$$S_3 = V_0 \sin\left(2\omega t + \frac{\pi}{2}\right)$$

$$R = -V_0$$

By the sequential application of these asymmetrical stator voltages (less than 5 V) the rotor plate can be drawn to successive stators hence making the plate complete rotations. The high proximity between the stators and the rotor plate is one reason why a large force is not required for electrostatic actuation. Reversing the bias causes the rotor to rotate in the opposite direction as expected.

Applications

- The rotating metal plate could serve as a mirror for ultra-high-density optical sweeping and switching devices as the plate is at the limit of visible light focusing. An array of such actuators, each serving as a high frequency mechanical filter, could be used for parallel signal processing in telecommunications.
- The plate could serve as a paddle for inducing or detecting fluid motion in microfluidic applications. It could serve as a bio-mechanical element in biological systems, a gated catalyst in wet chemistry reactions or as a general sensor element.
- A charged oscillating metal plate could be used as a transmitter of electromagnetic radiation.

Thermal Gradient driven Nanotube actuators

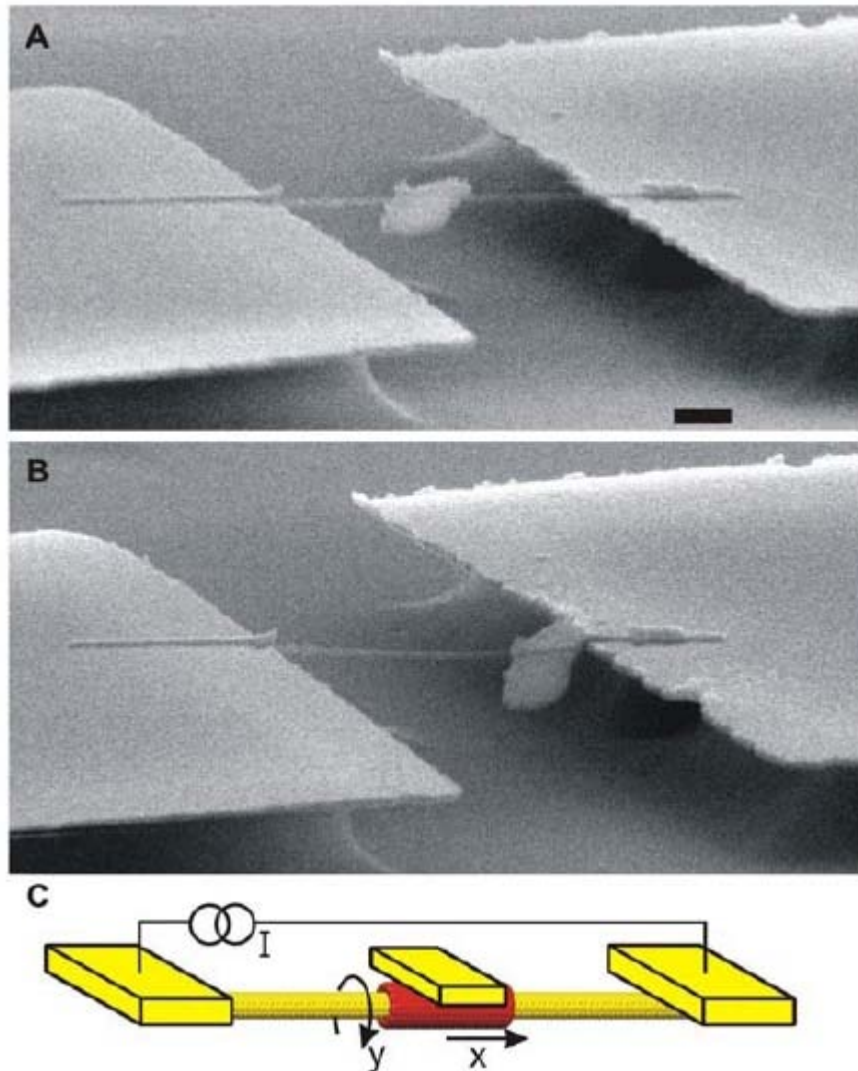


Figure 2.1: Thermal gradient driven nanomotor. (A & B): Scanning Electron microscope (SEM) images of experimental setup. (C) Schematic of the nanomotor also displaying degrees of freedom

The nanoactuator, as shown in Figure 2.1 comprises two electrodes connected via a long MWNT. A gold plate acts as the cargo and is attached to a shorter and wider concentric nanotube. The cargo moves towards the cooler electrode (Figure 2.2) due to the thermal gradient in the longer nanotube induced by the high current that is passed through it. The maximum velocity was approximated to $1\mu\text{m} / \text{sec}$ which is comparable to the speeds attained by kinesin biomotors.

Fabrication

The MWNT are fabricated using the standard arc-discharge evaporation process and deposited on an oxidized silicon substrate. The gold plate in the center of the MWNT is patterned using electron-beam lithography and Cr/Au evaporation. During the same process, the electrodes are attached to the nanotube. Finally, electrical-breakdown technique is used to selectively remove a few outer walls of the MWNT. Just as the nanoactuator from the Zettl group, this enables low friction rotation and translation of the shorter nanotube along the axis of the longer tube. The application of the electrical-breakdown technique does not result in the removal of the tube(s) below the cargo. This might be because the metal cargo absorbs the heat generated in the portion of the tube in its immediate vicinity hence delaying or possibly even preventing tube oxidation in this part.

Principle

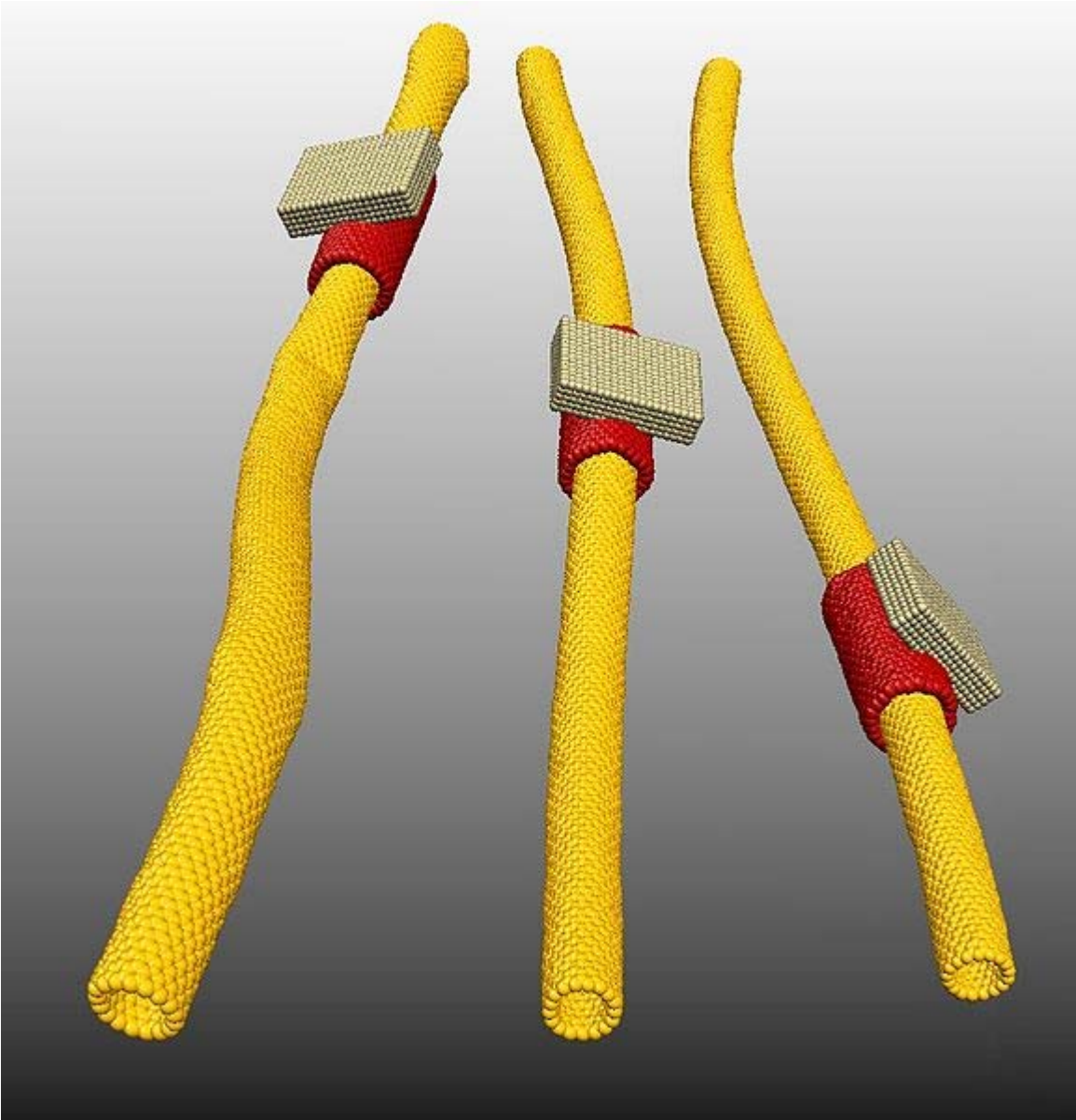


Figure 2.2: Motion of shorter nanotubes (red) along the longer tubes (yellow) from the hotter(top) section of the nanotube to the cooler (bottom) section of the nanotube carrying the metal cargo (gray)

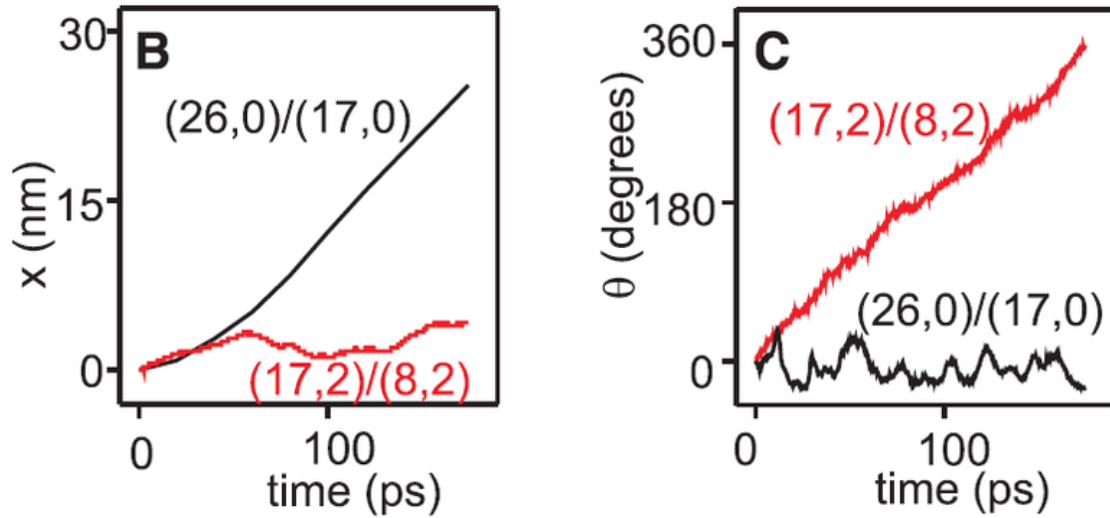


Figure 2.3: Degree of translational and rotation are dependent on the chiralities of the two nanotubes

The interaction between the longer and shorter tubes generates an energy surface that confines the motion to specific tracks - translation and rotation. The degree of translational and rotational motion of the shorter tube are highly dependent on the chiralities of the two tubes as shown in Figure 2.3. Motion in the nanoactuator displayed a proclivity of the shorter tube to follow a path of minimum energy. This path could either have a roughly constant energy or have a series of barriers. In the former case, friction and vibrational motion of atoms can be neglected whereas a stepwise motion is expected in the latter scenario.

Stepwise motion

The stepwise motion can be explained by the existence of periodic energy barriers for relative motion between the longer and shorter tubes. For a given pair of nanotubes, the ratio of the step in rotation to the step in translation is typically a constant, the value of which depends on the chirality of the nanotubes. The energy of such barriers could be estimated from the temperature in the nanotube, a lower bound for which can be estimated as the melting temperature of gold (1300 K) by noting that the gold plate melts (Figure 2.4) to form a spherical structure as current is passed through the nanomotor. The motion rate Γ can be written as a function of the attempt frequency ω , the Boltzmann's constant k , and temperature T as:

$$\Gamma = \frac{\omega}{2\pi} e^{\frac{-\Delta E}{kT}}$$

Taking $\Gamma \approx 1Hz$, using the approximation:

$$\omega = \sqrt{\frac{\Delta E}{ma_0^2}}$$

where m is the mass of the cargo and a_0^2 represents the contact area, the barrier height is obtained to be $\approx 17\mu eV$ per atom.

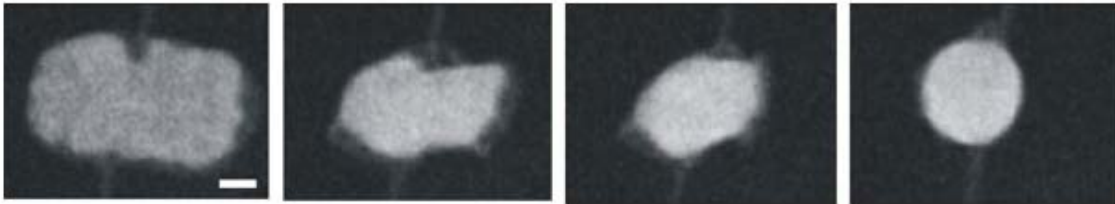


Figure 2.4: SEM images show the transformation of gold plate (left) into a ball (right) due to very high temperatures

Mechanism for actuation

Many proposals were made to explain the driving mechanism behind the nanoactuator. The high current (0.1 mA) required to drive the actuator is likely to cause sufficient dissipation to clean the surface of contaminants; hence, ruling out the possibility of contaminants playing a major role. The possibility of electromigration, where the electrons move atomic impurities via momentum transfer due to collisions, was also ruled out because the reversal of the current direction did not affect the direction of displacement. Similarly, rotational motion could not have been caused by an induced magnetic field due to the current passing through the nanotube because the rotation could either be left or right-handed depending on the device. Stray electric field effect could not be the driving factor because the metal plate staid immobile for high resistive devices even under a large applied potential. The thermal gradient in the nanotube provides the best explanation for the driving mechanism.

Thermal gradient induced motion

The induced motion of the shorter nanotube is explained as the reverse of the heat dissipation that occurs in friction wherein the sliding of two objects in contact results in the dissipation of some of the kinetic energy as phononic excitations caused by the interface corrugation. The presence of a thermal gradient in a nanotube causes a net current of phononic excitations traveling from the hotter region to the cooler region. The interaction of these phononic excitations with mobile elements (the carbon atoms in the shorter nanotube) causes the motion of the shorter nanotube. This explains why the shorter nanotube moves towards the cooler electrode. Changing the direction of the current has no effect on the shape of thermal gradient in the longer nanotube. Hence, direction of the movement of the cargo is independent of the direction of the bias applied. The direct dependence of the velocity of the cargo to the temperature of the nanotube is

inferred from the fact that the velocity of the cargo decreases exponentially as the distance from the midpoint of the long nanotube increases.

Shortcomings

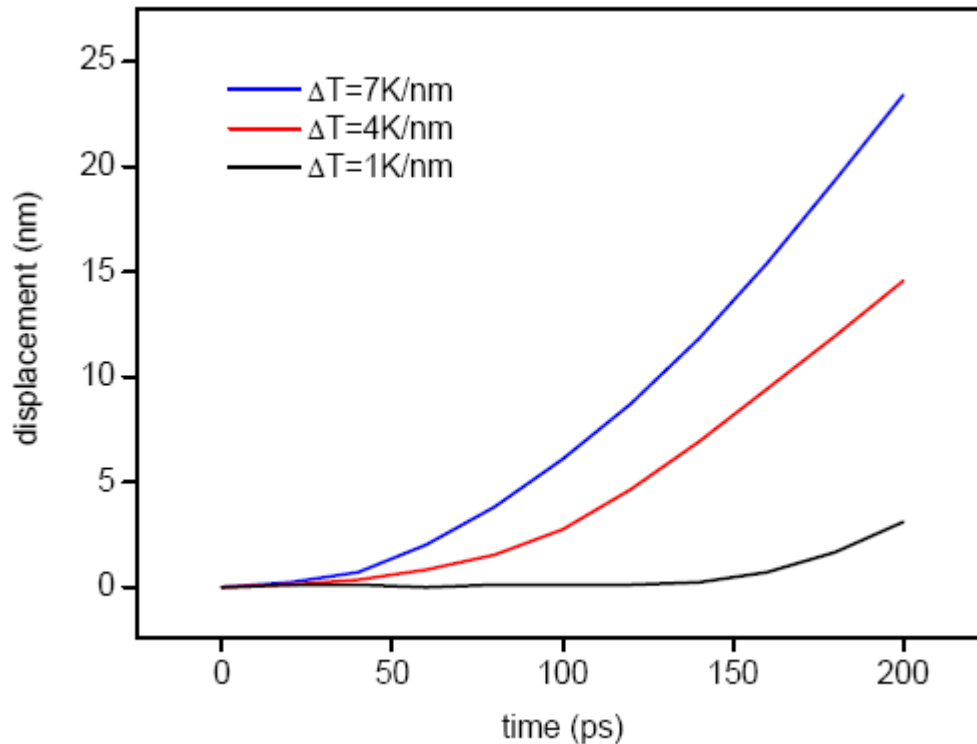


Figure 2.5: Graph demonstrating the direct relationship between the thermal gradient and the displacement of the shorter tube / cargo

The temperatures and the thermal gradient that the MWNT are subjected to are very high. On one hand, the high thermal gradient seems to have a highly detrimental effect on the lifetime of such nanoactuators. On the other hand, experiments show that the displacement of the shorter tube is directly proportional to the thermal gradient (see Figure 2.5). Therefore, a compromise needs to be reached to optimize the thermal gradient. The dimensions of movable nanotube is directly related to the energy barrier height. Although the current model excites multiple phonon modes, selective phonon mode excitation would enable lowering the phonon bath temperature.

Applications

1. Pharmaceutical / Nanofluidic - Thermal gradient could be used to drive fluids within the nanotubes or in nanofluidic devices as well as for drug delivery by nanosyringes.
2. Running bio engineered nanopores using heat generated from adenosine triphosphate (ATP) molecules.

Electron Windmill

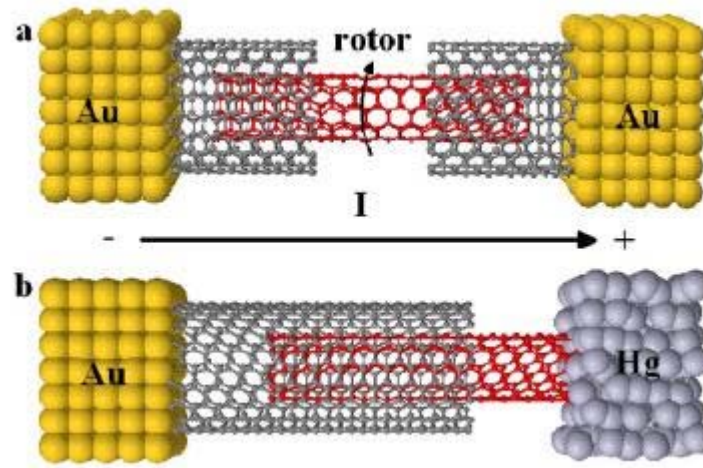


Figure 3.1: MWNT nanomotor(A) and nanodrill(B).

Structure

As figure 3.1 shows, the nanomotor consists of a double-walled CNT (DWNT) formed from an achiral (18,0) outer tube clamped to external gold electrodes and a narrower chiral (6,4) inner tube. The central portion of the outer tube is removed using the electrical-breakdown technique to expose the free-to-rotate, inner tube. The nanodrill also comprises an achiral outer nanotube attached to a gold electrode but the inner tube is connected to a mercury bath.

Principle

Conventional nanotube nanomotors make use of static forces that include elastic, electrostatic, friction and van der Waals forces. The electron windmill model makes use of a new "electron-turbine" drive mechanism that obviates that need for metallic plates and gates that the above nanoactuators require. When a dc voltage is applied between the electrodes, a "wind" of electrons is produced from left to right. The incident electron flux in the outer achiral tube initially possesses zero angular momentum, but acquires a finite angular momentum after interacting with the inner chiral tube. By Newton's third law, this flux produces a tangential force (hence a torque) on the inner nanotube causing it to rotate hence giving this model the name - "electron windmill". For moderate voltages, the tangential force produced by the electron wind is much greater than the associated frictional forces.

Applications

Some of the main applications of the electron windmill include:

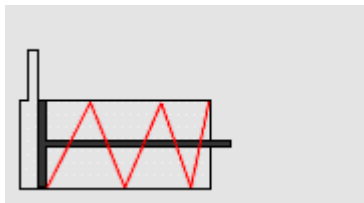
- A voltage pulse could cause the inner element to rotate at a calculated angle hence making the device behave as a switch or a nanoscale memory element.
- Modification of the electron windmill to construct a nanofluidic pump by replacing the electrical contacts with reservoirs of atoms or molecules under the influence of an applied pressure difference.

Further developments

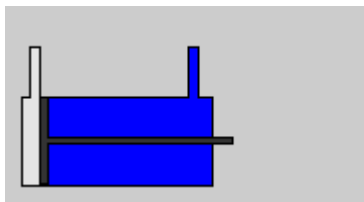
Although it has been demonstrated that synthetic nanotube nanoactuators can be built and are highly controllable, they are currently are not able to match the biological and macroscale nanomotors in terms of efficiency and scalability to accomplish higher tasks. However, further research, the electron windmill for example in this area promises to overcome this problem very soon.

Chapter 7

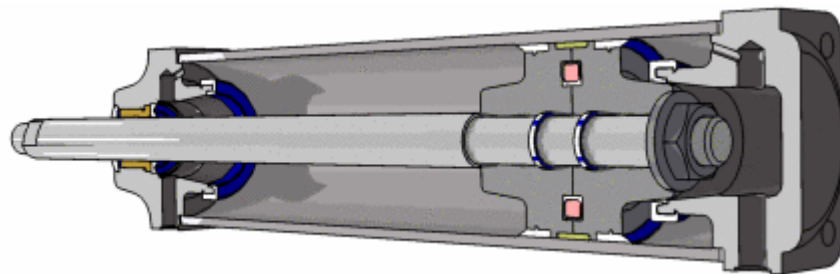
Pneumatic Cylinder



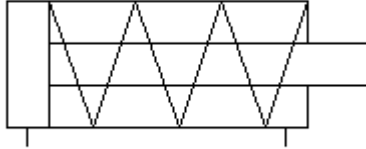
Operation diagram of a single acting cylinder. The spring (red) can also be outside the cylinder, attached to the item being moved.



Operation diagram of a double acting cylinder



3D image of pneumatic cylinder (CAD)



Schematic symbol for pneumatic cylinder with spring return

Pneumatic cylinders (sometimes known as **air cylinders**) are mechanical devices which produce force, often in combination with movement, and are powered by compressed gas (typically air).

To perform their function, pneumatic cylinders impart a force by converting the potential energy of compressed gas into kinetic energy. This is achieved by the compressed gas being able to expand, without external energy input, which itself occurs due to the pressure gradient established by the compressed gas being at a greater pressure than the atmospheric pressure. This air expansion forces a piston to move in the desired direction. The piston is a disc or cylinder, and the piston rod transfers the force it develops to the object to be moved.

A note about popular terminology

At least in the USA, popular usage sometimes refers to the whole assembly of cylinder, piston, and piston rod (or more) collectively as a "piston", which is incorrect. See, for instance, "Hydraulic piston raises the table from 19 (in.) to 26 (in.)" Marine Tables, Inc. (Select item 3 of 8, near the bottom.)

Operation

General

Once actuated, compressed air enters into the tube at one end of the piston and, hence, imparts force on the piston. Consequently, the piston becomes displaced (moved) by the compressed air expanding in an attempt to reach atmospheric pressure.

Fail safe mechanisms

Pneumatic systems are often found in settings where even rare and brief system failure is unacceptable. In such situations locks can sometimes serve as a safety mechanism in case of loss of air supply (or its pressure falling) and, thus, remedy or abate any damage arising in such a situation. Due to the leakage of air from input or output reduces the pressure and so the desired output.

Types

Although pneumatic cylinders will vary in appearance, size and function, they generally fall into one of the specific categories shown below. However there are also numerous other types of pneumatic cylinder available, many of which are designed to fulfill specific and specialised functions.

Single acting cylinders

Single acting cylinders (SAC) use the pressure imparted by compressed air to create a driving force in one direction (usually out), and a spring to return to the "home" position.

Double acting cylinders

Double Acting Cylinders (DAC) use the force of air to move in both extend and retract strokes. They have two ports to allow air in, one for outstroke and one for instroke.

Other types

Although SACs and DACs are the most common types of pneumatic cylinder, the following types are not particularly rare:

- Rotary air cylinders: actuators that use air to impart a rotary motion
- Rodless air cylinders: These have no piston rod. They are actuators that use a mechanical or magnetic coupling to impart force, typically to a table or other body that moves along the length of the cylinder body, but does not extend beyond it.

Rodless cylinders

Some rodless types have a slot in the wall of the cylinder. That slot is closed off for much of its length by two flexible metal sealing bands. The inner one prevents air from escaping, while the outer one protects the slot and inner band. The piston is actually a pair of them, part of a comparatively long assembly. They seal to the bore and inner band at both ends of the assembly. Between the individual pistons, however, are camming surfaces that "peel off" the bands as the whole sliding assembly moves toward the sealed volume, and "replace" them as the assembly moves away from the other end. Between the camming surfaces is part of the moving assembly that protrudes through the slot to move the load. Of course, this means that the region where the sealing bands are not in contact is at atmospheric pressure.

Another type has cables (or a single cable) extending from both (or one) end[s] of the cylinder. The cables are jacketed in plastic (nylon, in those referred to), which provides a smooth surface that permits sealing the cables where they pass through the ends of the cylinder. Of course, a single cable has to be kept in tension.

Still others have magnets inside the cylinder, part of the piston assembly, that pull along magnets outside the cylinder wall. The latter are carried by the actuator that moves the load. The cylinder wall is thin, to ensure that the inner and outer magnets are near each other. Multiple modern high-flux magnet groups transmit force without disengaging or excessive resilience.

1. ^ , (Catalog, 7.4 MB) Diagrams that show the principle are on Pages 6 and 7 (facing pair; it's worth configuring your reader). Only one piston is shown in the cutaway; the other is hidden; it is symmetrical, but reversed. Parker/Origa also makes similar cylinders with sealing bands.
2. ^ , Cable-type rodless cylinders
3. ^ , Commercial magnetically-coupled rodless cylinders

Sizes

Air cylinders are available in a variety of sizes and can typically range from a small 2.5 mm air cylinder, which might be used for picking up a small transistor or other electronic component, to 400 mm diameter air cylinders which would impart enough force to lift a car. Some pneumatic cylinders reach 1000 mm in diameter, and are used in place of hydraulic cylinders for special circumstances where leaking hydraulic oil could impose an extreme hazard.

Pressure, radius, area and force relationships

Although the diameter of the piston and the force exerted by a cylinder are related, they are not directly proportional to one another. Additionally, the typical mathematical relationship between the two assumes that the air supply does not become saturated. Due to the effective cross sectional area reduced by the area of the piston rod, the instroke force is less than the outstroke force when both are powered pneumatically and by same supply of compressed gas.

The relationship, between force on outstroke, pressure and radius, is as follows:

$$F = p(\pi r^2)$$

Cord

This is derived from the relationship, between force, pressure and **effective cross-sectional area**, which is:

$$F = p A,$$

With the same symbolic notation of variables as above, but also A represents the effective cross sectional area.

On instroke, the same relationship between force exerted, pressure and *effective cross sectional area* applies as discussed above for outstroke. However, since the cross sectional area is less than the piston area the relationship between force, pressure and *radius* is different. The calculation isn't more complicated though, since the effective cross sectional area is merely that of the piston less that of the piston rod.

For instroke, therefore, the relationship between force exerted, pressure, radius of the piston, and radius of the piston rod, is as follows:

$$F = p(\pi r_1^2 - \pi r_2^2) = p\pi(r_1^2 - r_2^2)$$

Where:

F represents the force exerted

r_1 represents the radius of the piston

r_2 represents the radius of the piston rod

π is pi, approximately equal to 3.14159.

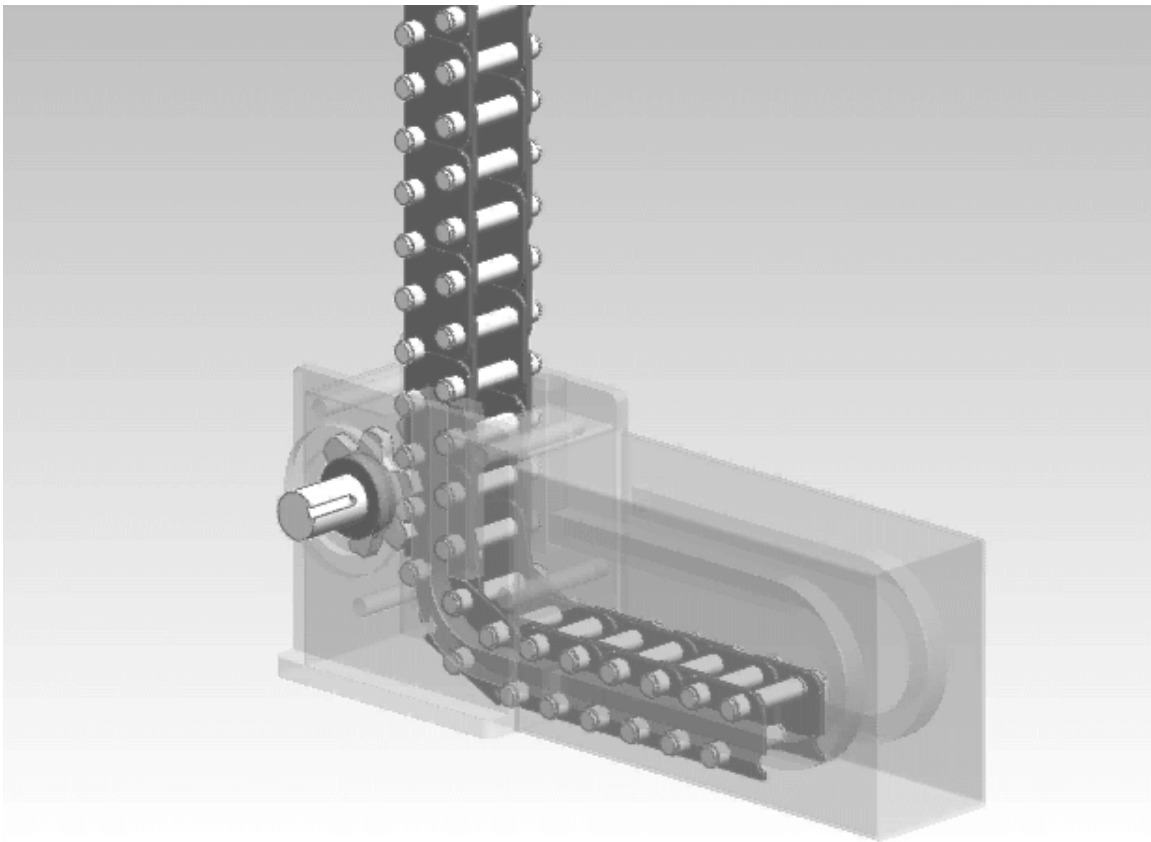
Materials

The pneumatic cylinders designed for educational use typically have transparent outer sleeves (often plexiglass), so students can see the piston moving inside.

The pneumatic cylinders designed for cleanroom applications often use lubricant-free Pyrex glass pistons sliding inside graphite sleeves.

Chapter 8

Rigid Chain Actuator



A **rigid chain actuator**, known variously as a **linear chain actuator**, **push-pull chain actuator**, **electric chain actuator** or **column-forming chain actuator**, is a specialized mechanical linear actuator used in window operating, push-pull material handling and lift applications. The actuator is a chain and pinion device that forms an articulated telescoping member to transmit traction and thrust. High-capacity rigid chain lifting columns (jacks) can move dynamic loads exceeding 10 tonnes (US 20,000 pounds) over more than 7 metres (20 feet) of travel.

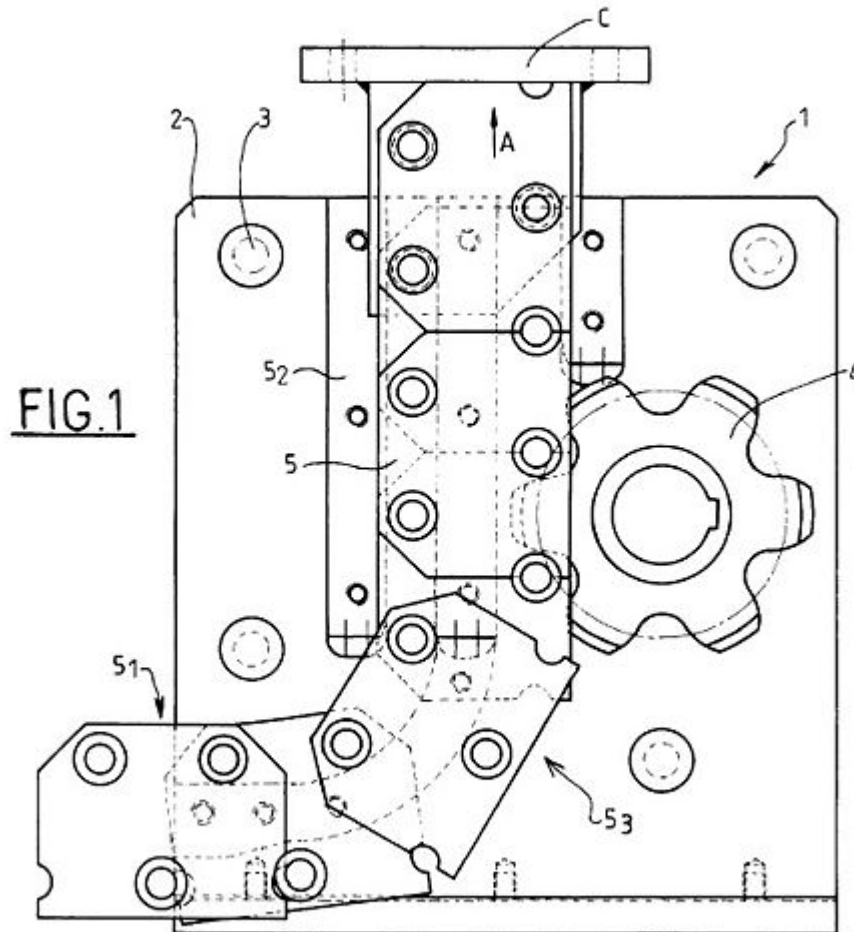
Principle of operation

U.S. Patent

May 1, 2001

Sheet 1 of 2

US 6,224,037 B1



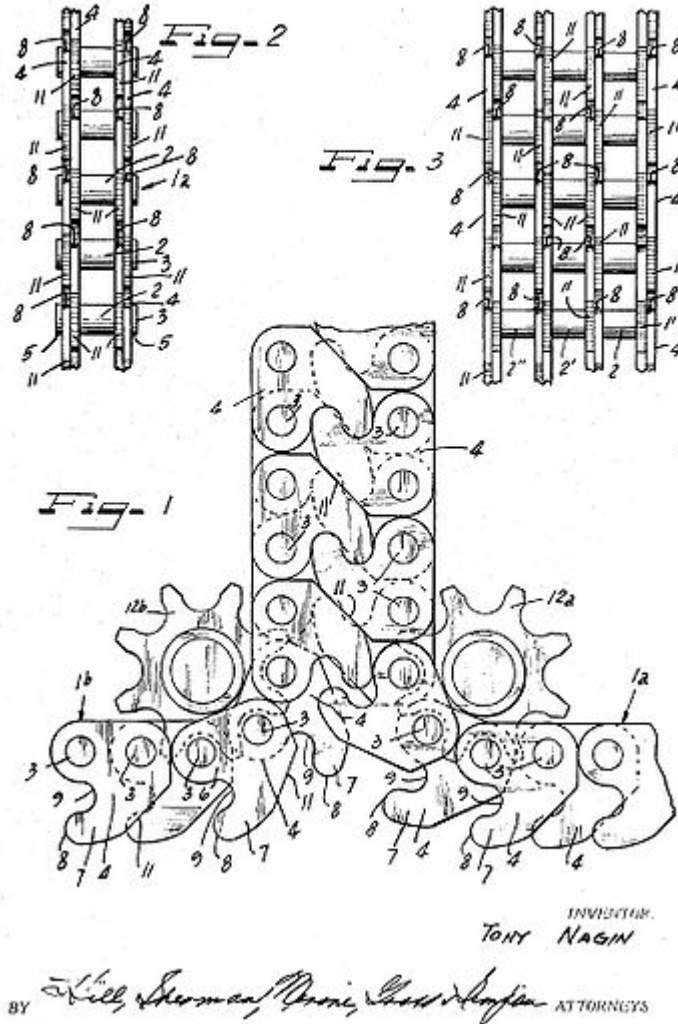
Patent Drawing for Serapid LinkLift Rigid Chain Actuator (2001).

Rigid chain actuators function as rack and pinion linear actuators that use articulated racks. Rigid chain actuators use limited-articulation chains, usually resembling a roller chain, that engage with pinions mounted on a drive shaft within a housing. The links of the actuating member, the “rigid chain”, are articulated in a manner that they deflect from a straight line to one side only. As the pinions spin, the links of the chain are rotated 90 degrees through the housing, which guides and locks the chain into a rigid linear form effective at resisting tension and compression (buckling). Because the actuating member can fold on itself, it can be stored relatively compactly in a storage magazine, either in an overlapping or coiled arrangement. Rigid chain actuators are generally driven by electric motors. Most rigid chains are manufactured from steel.

Use

PATENTED FEB 29 1972

3,645,146



Patent Drawing for Interlocking Rigid Chain Actuator (1972).

Modified roller chain has been used extensively in material handling equipment, but could only be used in push-pull applications when a continuous loop of chain was used (with the exception of chain encapsulated in a guide channel). The development of efficient rigid chain actuators broadened the use of chain actuation for industrial applications. Small scale rigid chain actuators are used as building hardware, incorporated into windows, door and hatches as motorized open/close mechanisms. Rigid chain actuators are also used as the lifting columns in performing arts facilities, incorporated in stage, orchestra and seating platform lift systems.

Increasingly rigid chain systems are being incorporated into scissor lift tables or platform lifts as the method of actuation, replacing hydraulic cylinders. They are also used for production line automation and die changing.

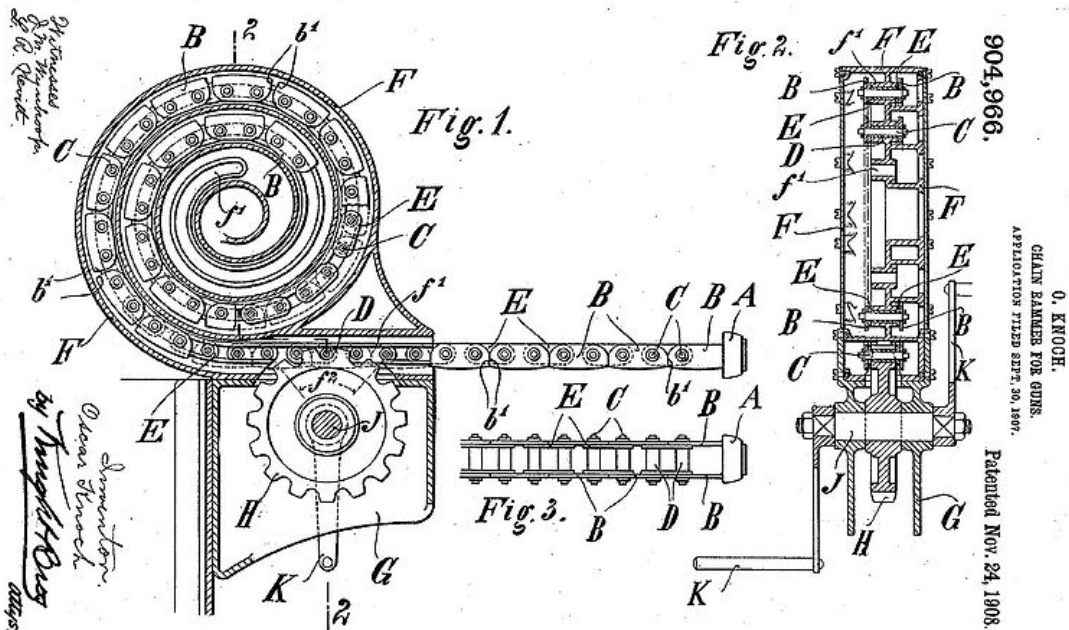
Types

The primary distinction between types of rigid chain actuator is whether the actuating member is formed from a single chain or from a pair of interlocking chains in a back-to-back arrangement, like a zipper. Interlocking chain actuators have the advantages over single-chain actuators of improved resistance to buckling and that the actuating member does not require lateral restraint at its leading end in order to resist a modicum of transverse loads on any edge of the member. For example, it may function as a relatively stable telescoping pole.

The design of the chain varies significantly depending on application and manufacturer. Variants have been designed to, among other things:

- Simplify manufacture
- Reduce friction and maintenance
- Limit size and weight
- Increase speed, travel, capacity, efficiency and stability

Development



Patent Drawing for Chain Rammer (1908).

Rigid chain actuators were developed from “chain rammers” that used a single “ram chain” thrust from a magazine to load heavy-caliber ordinance into the breech of a cannon. Robert Matthews received a US patent for his “Mechanical Rammer” in 1901 which used a roller on the leading end of the chain to guide it and allow thrust without deflection. Developed more than a century ago, his rammer still bears a strong resemblance to many modern rigid chain actuators. In 1908 Oscar Knoch was awarded a US patent for his “Chain Rammer for Guns”. By orienting the folding side of the chain upward his ram chain acted as a self-supporting telescoping beam with negligible sag. Used in this manner the need for a separate guide was eliminated.

An early conception of chain used as a telescoping column instead a horizontal rammer was by Eldridge E. Long, who as awarded a US patent for his “Lifting Jack” in 1933, which he believed was “particularly adapted for use upon automobiles”. It used a double chain configuration, each chain linking solid bearing blocks that were stacked to resist compressive loads. In 1951, Yaichi Hayakawa was awarded a US patent for his “Interlocking Chain Stanchion” which eliminated bearing blocks by integrated the compressive path of force into the interlocking links of two roller-like chains. The zipper action of back-to-back interlocking chains provided guideless chain travel regardless of orientation and path of travel.

It should be noted that in 1941, prior to the double chain configuration, Karl Bender received a US patent for "Compression Resistant Chain" using three interlocking chains. In addition to the back-to-back arrangement of the typical interlocking chain actuator, a third chain was interlocked between the other two at a right angle. Perhaps due to their relative complexity, triple-chain actuators are not common.

Chapter 9

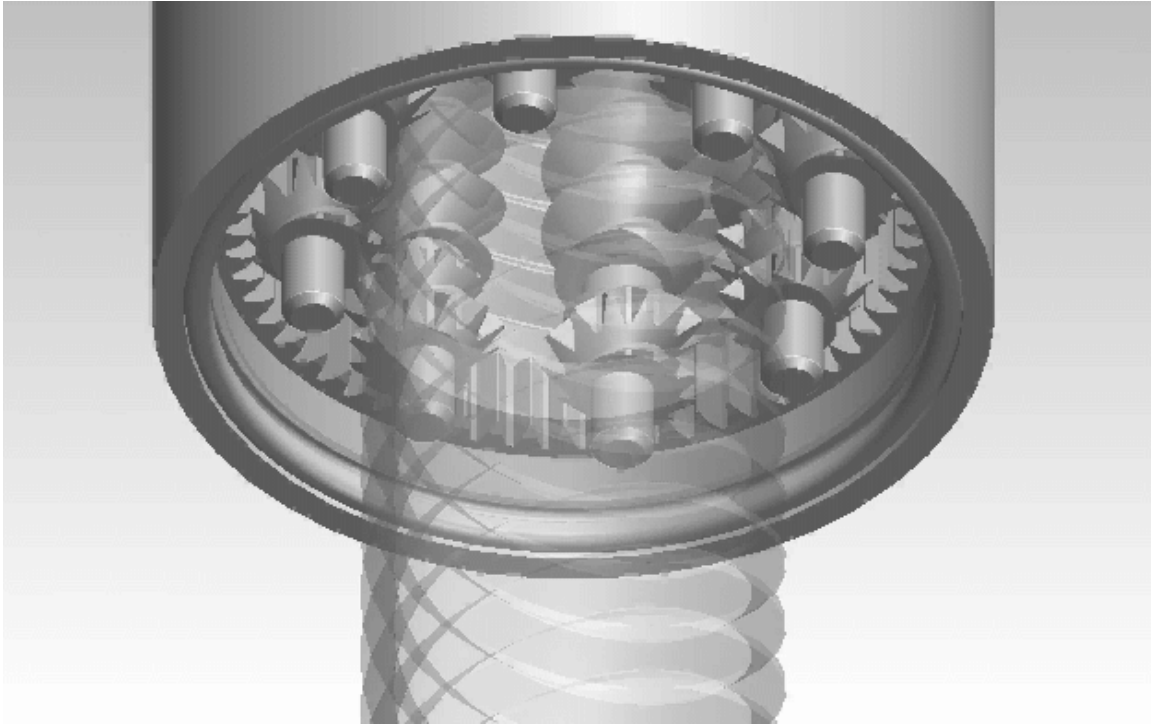
Roller Screw



A **roller screw**, also known as a **planetary roller screw** or **satellite roller screw**, is a low-friction precision mechanical device for converting rotational motion to linear motion, or vice versa. Planetary roller screws are most commonly used as the actuator mechanism in electro-mechanical linear actuators. Due to its complexity the roller screw is a relatively expensive actuator (as much as an order of magnitude more expensive than

ball screws), but may be suitable for high-precision, high-speed, heavy-load, long-life and heavy-use applications.

Principle of operation



Standard roller screw timing

A roller screw is a mechanical actuator similar to a ball screw that uses rollers as the load transfer elements between nut and screw instead of balls. The rollers are typically threaded but may also be grooved depending on roller screw type. Providing more bearing points than ball screws within a given volume, roller screws can be more compact for a given load capacity while providing similar efficiency (75%-90%) at low to moderate speeds, and maintain relatively high efficiency at high speeds. Roller screws can surpass ball screws in regard to positioning precision, load rating, rigidity, speed, acceleration, and lifetime. Standard roller screw actuators can achieve dynamic load ratings above 130 tons of force (exceeded in single-unit actuator capacity only by hydraulic cylinders).

The three main elements of a typical planetary roller screw are the screw shaft, nut and planetary roller. The screw, a shaft with a multi-start V-shaped thread, provides a helical raceway for multiple rollers radially arrayed around the screw and encapsulated by a threaded nut. The thread of the screw is typically identical to the internal thread of the nut. The rollers spin in contact with, and serve as low-friction transmission elements between screw and nut. The rollers typically have a single-start thread with convex flanks that limit friction at the rollers' contacts with screw and nut. The rollers typically orbit the screw as they spin (in the manner of planet gears to sun gear), and are thus known as

planetary, or satellite, rollers. As with a lead screw or ball screw, rotation of the nut results in screw travel, and rotation of the screw results in nut travel.

For a given screw diameter and quantity of thread starts more rollers corresponds to higher static load capacity, but not necessarily to a higher dynamic load capacity. Preloaded split nuts and double nuts are available to eliminate backlash.

Planetary roller screw types

Carl Bruno Strandgren developed some of the earliest effective forms of roller screws and was awarded US patents for such a “Screw-Threaded Mechanism” in 1954, and “Nut and Screw Devices” and the "Roller Screw" in 1965.

Roller screw types are defined by the motion of the rollers relative to the nut and screw. The four commercially available types of roller screw are *standard*, *inverted*, *recirculating*, and *bearing ring*.

Differential roller screws, typically variants of the standard and recirculating types, are also commercially available. Differential roller screws modify the rotational speed ratios between the rollers and the screw by varying the flank angles and contact points of the threads or grooves. In that way differential roller screws change the effective lead of the screw. William J. Roantree received a US patent for the "Differential Roller Nut" in 1968.

Standard planetary roller screw

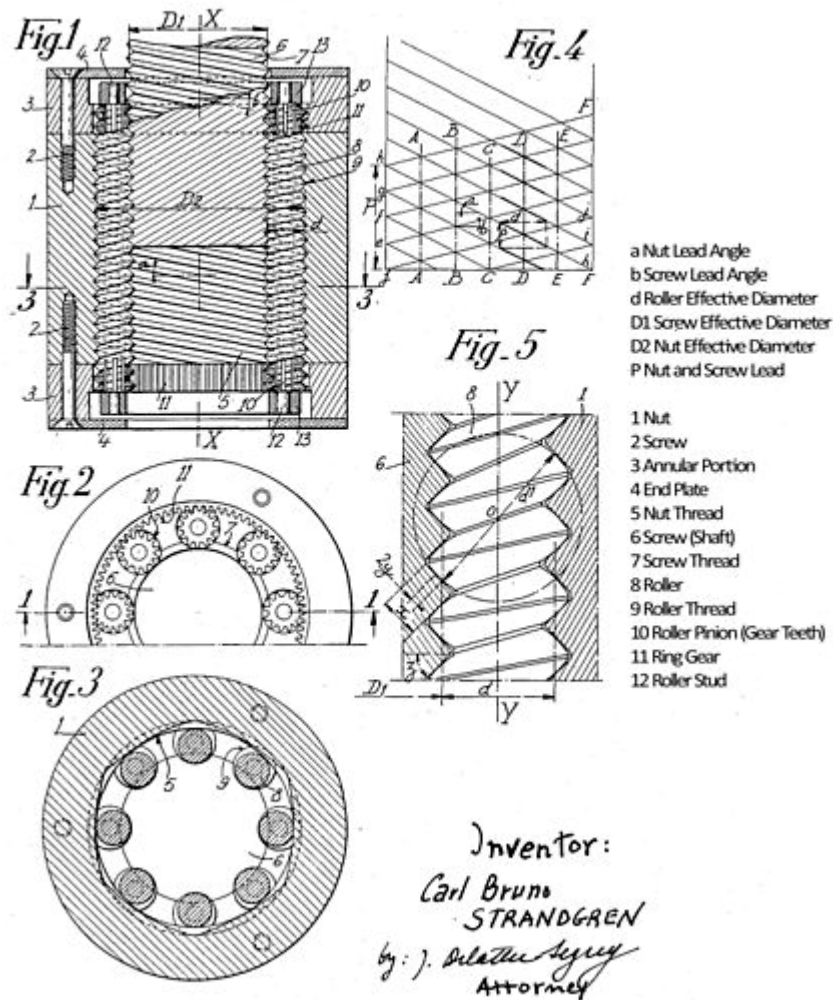
July 13, 1954

C. B. STRANDGREN
SCREW-THREADED MECHANISM

2,683,379

Filed July 7, 1950

2 Sheets-Sheet 1



Patent drawing for standard roller screw (1954), with legend.

The standard planetary roller screw is also known as the non-recirculating roller screw. The lack of axial movement of the roller relative to the nut, and the gearing of rollers to nut, are definitive of the standard type of roller screw.

The nut and screw have identical multiple-start threads. The rollers have a single-start thread with an angle matching the nut thread. The matched thread angle prevents axial movement between the nut and the roller as the rollers spin. The nut assembly includes spacer rings and ring gears that position and guide the rollers. The spacer rings, which rotate within the ring gears, have equidistant holes that act as rotary bearings for the smooth pivot ends (studs) of the rollers. The ring gears time the spinning and orbit of the

rollers about the screw axis by engaging gear teeth near the ends of the rollers. The spacer rings rotate on axis with the screw in unison with the orbit of the rollers. The spacer rings float relative to the nut, axially secured by retaining rings, because they spin around the screw at a lower frequency (angular velocity) than the nut.

Configuration

Standard roller screws are typically identified by screw diameter (typically ranging from 3.5mm – 200mm) and lead (1mm – 42mm). The threading of the screw (3 – 6 starts) is either rolled (lower capacity) or ground (higher capacity). The diameters of the nut and rollers (7 – 14 in quantity) are simple functions of the screw diameter and lead.

Where:

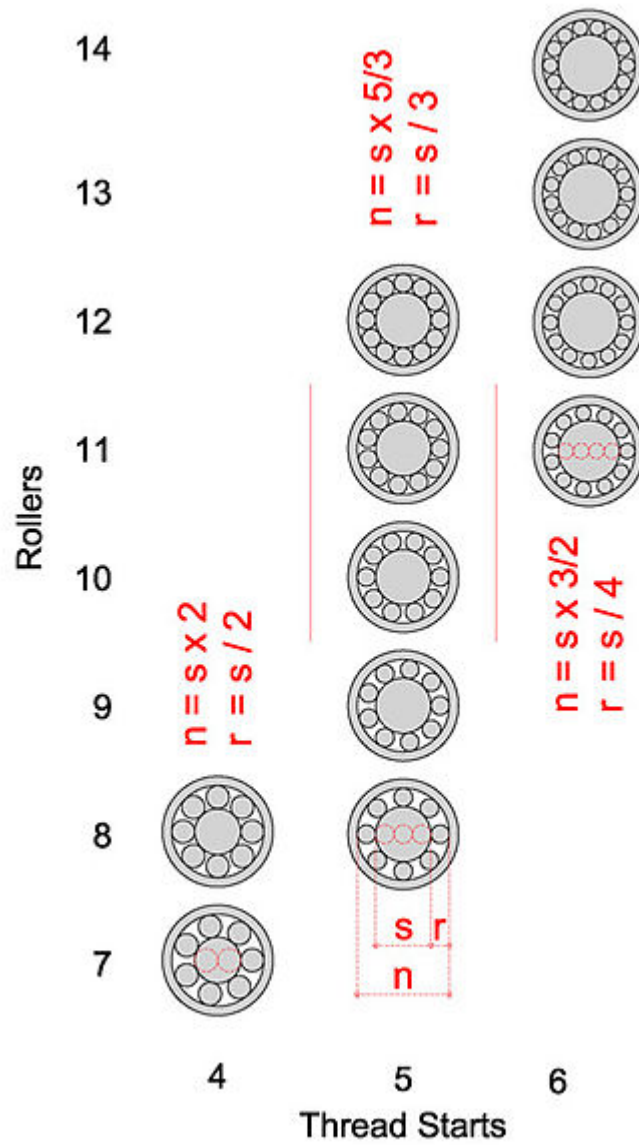
s_d = effective screw diameter * t = thread starts on nut and screw

r_d = effective roller diameter l = screw lead

n_d = effective nut inside diameter p = roller thread pitch

* effective diameter is also known as pitch diameter

The following relationships apply to standard and inverted roller screws:



Common configurations of standard roller screws

$$n_d = \frac{s_d \cdot t}{t - 2} \quad \therefore \quad \begin{array}{l} \text{nut to screw gear ratio} \\ (n_d : s_d) = 1 : (t / (t - 2)) \end{array}$$

$$r_d = \frac{s_d}{t - 2} \quad \therefore \quad \begin{array}{l} \text{roller to screw gear ratio} \\ (r_d : s_d) = 1 : (t - 2) \end{array}$$

$$r_d = \frac{n_d}{t} \quad \therefore \begin{array}{l} \text{roller to nut gear ratio} \\ (r_d : n_d) = 1 : t \end{array}$$

$$r_d = \frac{n_d - s_d}{2}$$

$$p = \frac{l}{t} \quad \therefore \begin{array}{l} \text{ratio of roller thread pitch to} \\ \text{screw lead } (p : l) = 1 : t \end{array}$$

For example, if

Screw: 30mm diameter, 20mm lead, 5 start thread

then

Rollers: 10mm diameter rollers, 4mm thread pitch
Nut: 50mm effective diameter.

Inverted roller screw

The inverted planetary roller screw is also known as the reverse roller screw. The lack of axial movement of the roller relative to the screw, and the gearing of rollers to screw, are definitive of the inverted type of planetary roller screw. This type of roller screw was developed simultaneously with the standard roller screw.

Inverted roller screws operate on the same principles of standard roller screws except that the function of the nut and screw is reversed in relation to the rollers. The rollers move axially within the nut, which is elongated to accommodate the full extent of screw shaft travel. The threaded portion of the screw shaft is limited to the threaded length of the rollers. The non-threaded portion of the screw shaft can be a smooth or non-cylindrical shape. The ring gear is replaced by gear teeth above and below the threaded portion of the screw shaft.

Aside from the inversion of the relationship of rollers to nut and screw, the configuration and relationships of inverted roller screws match those of standard roller screws.

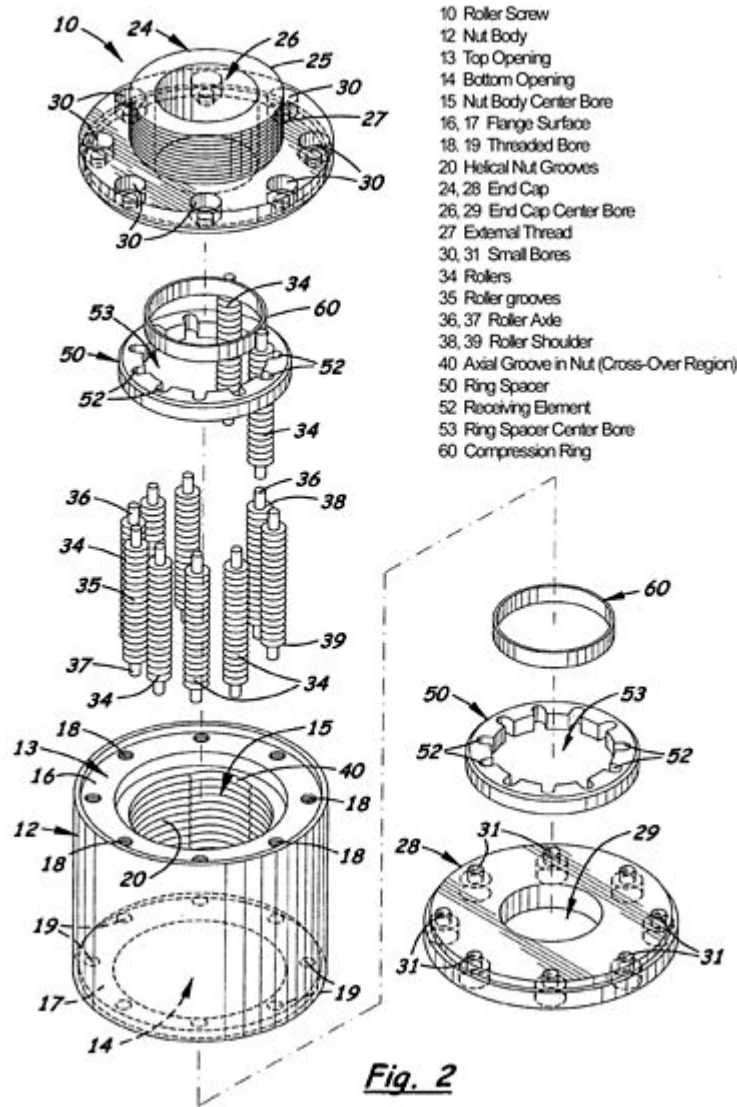
Recirculating roller screw

U.S. Patent

May 16, 2006

Sheet 2 of 10

US 7,044,017 B2



Cage-less recirculating roller screw patent drawing (2006), with legend.

The recirculating type of planetary roller screw is also known as a recycling roller screw. A recirculating roller screw can provide a very high degree of positional accuracy by using minimal thread leads. The rollers of a recirculating roller screw move axially within the nut until being reset after one orbit about the screw. Recirculating roller screws do not employ ring gears. Carl Bruno Strandgren was awarded a US Patent for the recirculating roller screw in 1965.

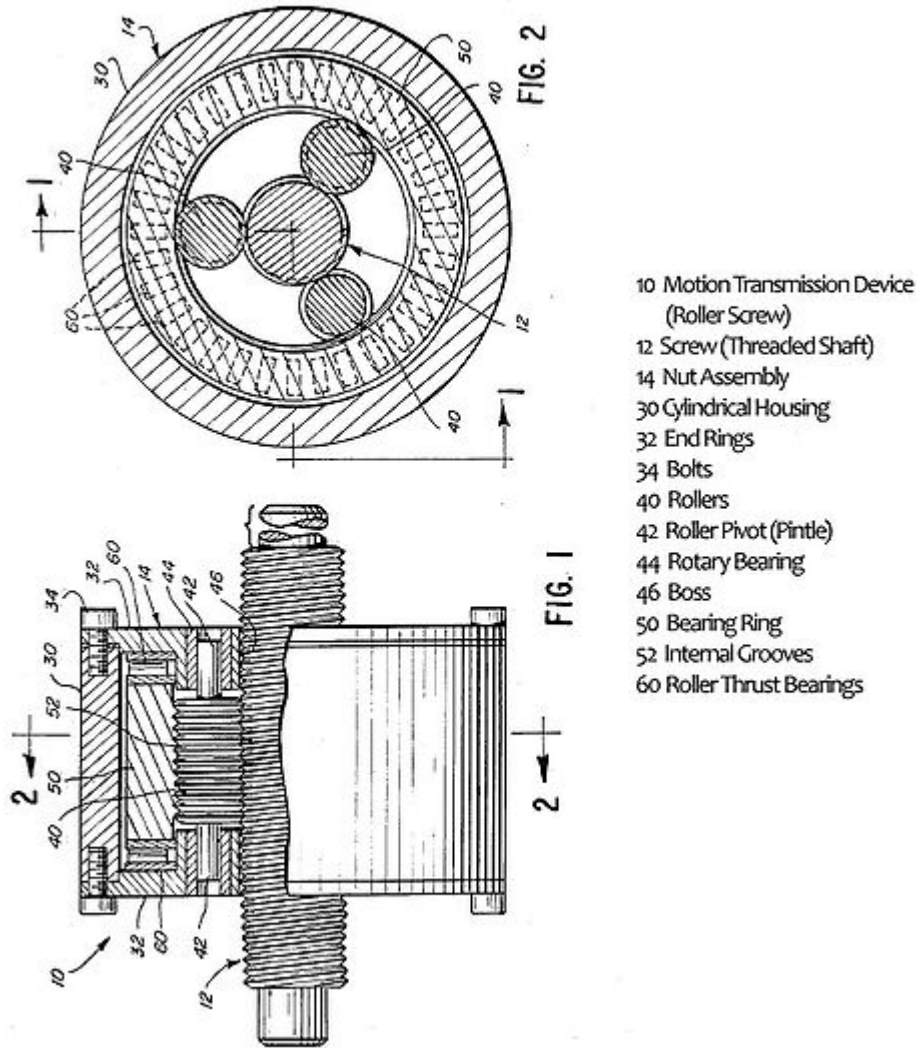
The screw and nut may have very fine identical single- or two-start threads. Recirculating rollers are grooved (instead of threaded) so they move axially during spinning engagement with the threads of the nut and screw, shifting up or down by one lead of

thread after completing an orbit around the screw. The nut assembly typically includes a slotted cage and cam rings. The cage captivates the rollers in elongated slots, equally spacing the rollers while permitting rotation and axial motion of the rollers. The cam rings have opposing cams aligned with an axial groove in the wall of the nut. After a roller completes an orbit about the nut it is released into the groove, disengages from nut and screw, and is pushed between the cams to the axial midpoint of the nut assembly (shifting by a distance equal to the lead of the screw). Returned to its starting position, and reengaged to nut and screw, the roller may then orbit the screw once again.

In 2006, Charles C. Cornelius and Shawn P. Lawlor received a patent for a cage-less recirculating roller screw system. As with the traditional recirculating roller screw system, rollers disengage from the screw when they come upon an axial groove in the wall of the nut. The system differs in that the rollers are continually engaged by the nut, and the axial groove of the nut is threaded. Non-helical threads in the axial groove of the nut return the roller to its axial starting position (after completion of an orbit). Non-circular compression rings, or cam rings, at opposite ends of the rollers (roller axles) apply constant pressure between rollers and nut, synchronizing roller rotation and thrusting the rollers into the nut's axial groove. Lacking ring gears and roller cage, cage-less recirculating roller screws can be relatively efficient and, as a result, permit higher dynamic capacities for some screw shaft diameters.

Bearing ring roller screw

U.S. Patent Mar. 18, 1986 Sheet 1 of 3 4,576,057



Patent Drawing for Spiracon Roller Screw (1986), with legend.

In 1986 Oliver Saari was awarded a patent for a bearing ring roller screw, commonly referred to by its trademark, Spiracon. This type matches the orbit of the rollers to the rotation of the nut assembly. The actuator contains more load transfer elements than the other types, a bearing ring and thrust bearings, but manufacture of component parts is relatively simple (e.g. gearing teeth may be eliminated).

In the other roller screw types above, loads are transferred from the nut through the rollers to the screw (or in the reverse order). In this type of actuator, thrust bearings and a freely-rotating internally-grooved bearing ring transfer loads between the rollers and the nut.

The screw has a multi-start thread. The rollers and encapsulating rotating ring are identically grooved, not threaded, so there is no axial movement between the two. The nut assembly includes a cylindrical housing capped by non-rotating spacer rings. The spacer rings have equidistant holes that act as rotary bearings for the smooth pivot ends (studs) of the rollers. Roller-type thrust bearings between the spacer rings and bearing ring permit free rotation of the bearing ring while transferring the axial load between the two.

The rollers act as the “threads” of the nut assembly, causing axial movement of the rotating screw due to their orbital restraint. Screw rotation spins the rollers, which spin the bearing ring, dissipating the load-induced friction along the way.

Timothy A. Erhart was awarded a US patent in 1996 for a linear actuator effectively incorporating an inverted bearing ring roller screw. The screw shaft is grooved the length of and to match the grooved rollers, which travel with the shaft. The bearing ring is elongated and internally threaded for the length of screw shaft travel. The nut assembly housing and sealed end ring forms the exterior of the actuator assembly.

Chapter 10

Rotary Actuator



Electric rotary valve actuator controlling a butterfly valve

A **rotary actuator** is an actuator that produces a rotary motion or torque.

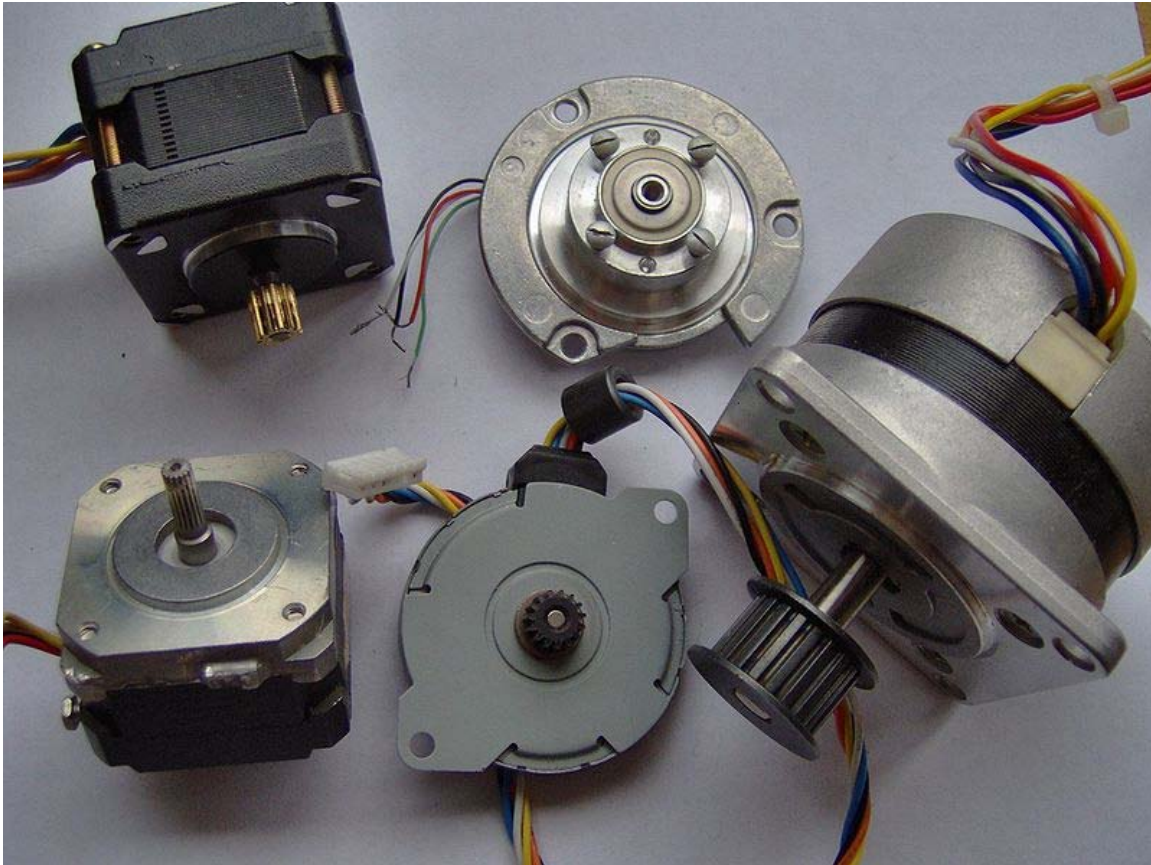
The simplest actuator is purely mechanical, where linear motion in one direction gives rise to rotation. The most common actuators though are electrically powered. Other actuators may be powered by pneumatic or hydraulic power, or may use energy stored internally through springs.

The motion produced by an actuator may be either continuous rotation, as for an electric motor, or movement to a fixed angular position as for servos and stepper motors. A further form, the torque motor, does not necessarily produce any rotation but merely generates a precise torque which then either causes rotation, or is balanced by some opposing torque.

Actuator power sources

Electric actuators

Stepper motors



The variety of stepper motors

Stepper motors are a form of electric motor that has the ability to move in discrete steps of a fixed size. This can be used either to produce continuous rotation at a controlled speed or to move by a controlled angular amount. If the stepper is combined with either a

position encoder or at least a single datum sensor at the zero position, it is possible to move the motor to any angular position and so to act as a rotary actuator.

Servomotors



Dismantled radio control servo

A servo or servomotor is a packaged combination of several components: a motor (usually electric, although fluid power motors may also be used), a gear train to reduce the many rotations of the motor to a higher torque rotation, a position encoder that identifies the position of the output shaft and an inbuilt control system. The input control signal to the servo indicates the desired output position. Any difference between the position commanded and the position of the encoder gives rise to an error signal that

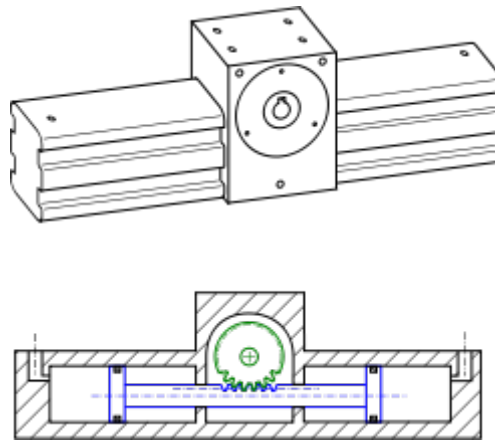
causes the motor and geartrain to rotate until the encoder reflects a position matching that commanded.

This type of servo is widely used for radio-controlled models.

Other types

A recent, and novel, form of ultra-lightweight actuator uses memory wire. As a current is applied, the wire is heated above its transition temperature and so changes shape, applying a torque to the output shaft. When power is removed, the wire cools and returns to its earlier shape.

Fluid power actuators



Hydraulic or pneumatic rotary actuator, using a rack and pinion

Both hydraulic and pneumatic power may be used to drive an actuator, usually the larger and more powerful types. As their internal construction is generally similar (in principle, if not in size) they are often considered together as *fluid power* actuators. Fluid power actuators are of two common forms: those where a linear piston and cylinder mechanism is geared to produce rotation (*illustrated*), and those where a rotating asymmetrical vane swings through a cylinder of two different radii. The differential pressure between the two sides of the vane gives rise to an unbalanced force and thus a torque on the output shaft. Vane actuators require a number of sliding seals and the joints between these seals have tended to cause more problems with leakage than for the piston and cylinder type.

Vacuum actuators

Where a supply of vacuum is available, but not pneumatic power, rotary actuators have even been made to work from vacuum power. The only common instance of these was for early automatic windscreen wipers on cars up until around 1960. These used the manifold vacuum of a petrol engine to work a quarter-turn oscillating vane actuator. Such windscreen wipers worked adequately when the engine was running under light load, but

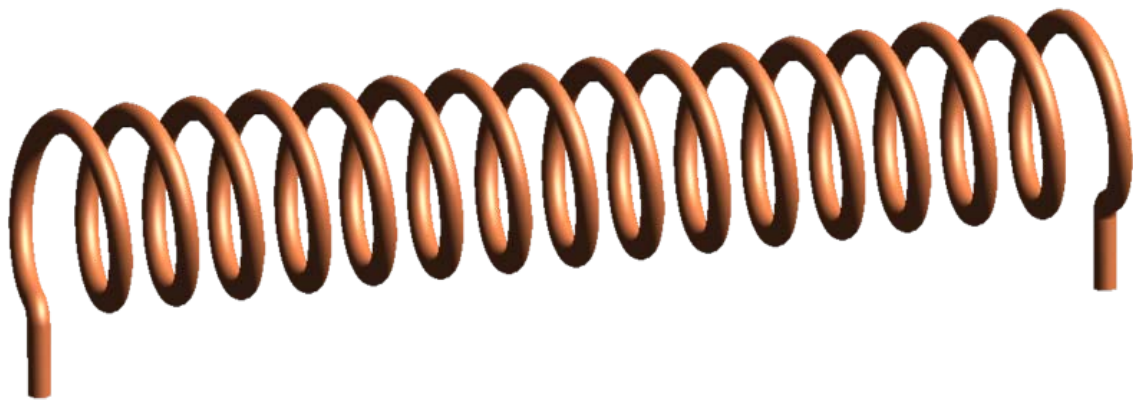
they were notorious that when working hard at top speed or climbing a hill, the manifold vacuum was reduced and the wipers slowed to a crawl.

Applications

Rotary actuators are used in a vast range of applications. These require actuators of all sizes, power and operating speed. These can range from zero power actuators that are only used as display devices, such as air core gauges. Others include valve actuators that operate pipeline and process valves in the petrochemical industry, through to actuators for large civil engineering projects such as sluice gates and dams.

Chapter 11

Solenoid



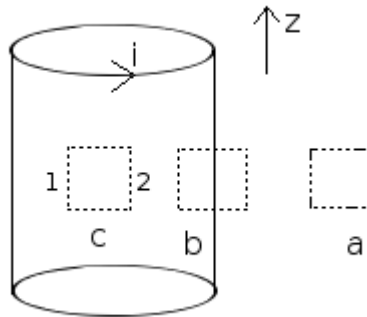
Solenoid

A **solenoid** is a coil wound into a tightly packed helix. In physics, the term **solenoid** refers to a long, thin loop of wire, often wrapped around a metallic core, which produces a magnetic field when an electric current is passed through it. Solenoids are important because they can create controlled magnetic fields and can be used as electromagnets. The term *solenoid* refers specifically to a magnet designed to produce a uniform magnetic field in a volume of space (where some experiment might be carried out).

In engineering, the term **solenoid** may also refer to a variety of transducer devices that convert energy into linear motion. The term is also often used to refer to a solenoid valve, which is an integrated device containing an electromechanical solenoid which actuates either a pneumatic or hydraulic valve, or a solenoid switch, which is a specific type of relay that internally uses an electromechanical solenoid to operate an electrical switch; for example, an automobile starter solenoid, or a linear solenoid, which is an electromechanical solenoid.

Magnetic field of a solenoid

Inside



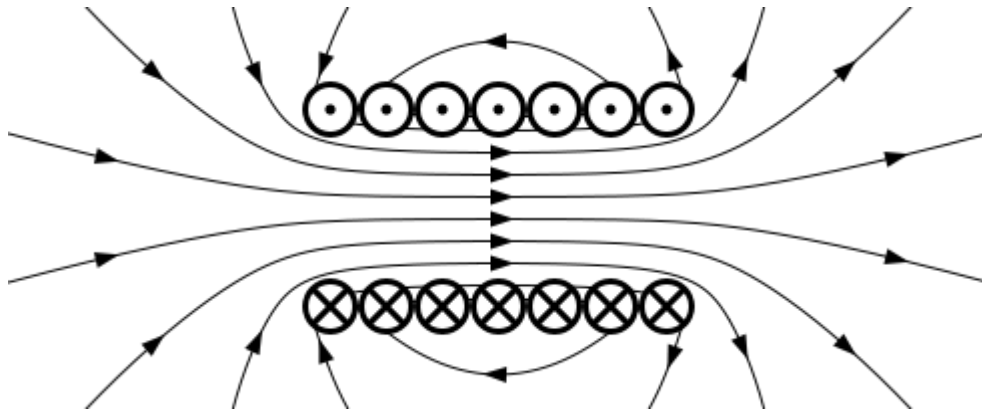
A solenoid with 3 Ampèrian loops: *a*, *b* and *c*.

In short: the magnetic field inside an infinitely long solenoid is homogeneous and its strength does not depend on the distance from the axis.

This is a derivation of the magnetic flux density around a solenoid that is long enough so that fringe effects can be ignored. In the diagram to the right, we immediately know that the flux density vector points in the positive z direction inside the solenoid, and in the negative z direction outside the solenoid. We see this by applying the right hand grip rule for the field around a wire. If we wrap our right hand around a wire with the thumb pointing in the direction of the current, the curl of the fingers shows how the field behaves. Since we are dealing with a long solenoid, all of the components of the magnetic field not pointing upwards cancel out by symmetry. Outside, a similar cancellation occurs, and the field is only pointing downwards.

Now consider the imaginary loop *c* that is located inside the solenoid. By Ampère's law, we know that the line integral of \mathbf{B} (the magnetic flux density vector) around this loop is zero, since it encloses no electrical currents (it can be also assumed that the circuital electric field passing through the loop is constant under such conditions: a constant or constantly changing current through the solenoid). We have shown above that the field is pointing upwards inside the solenoid, so the horizontal portions of loop *c* doesn't contribute anything to the integral. Thus the integral of the up side 1 is equal to the integral of the down side 2. Since we can arbitrarily change the dimensions of the loop and get the same result, the only physical explanation is that the integrands are actually equal, that is, the magnetic field inside the solenoid is radially uniform. Note, though, that nothing prohibits it from varying longitudinally, which in fact it does.

Outside



Magnetic field created by a solenoid (cross-sectional view) described using field lines.

A similar argument can be applied to the loop *a* to conclude that the field outside the solenoid is radially uniform or constant. This last result, which holds strictly true only near the centre of the solenoid where the field lines are parallel to its length, is important inasmuch as it shows that the flux density outside is practically zero since the radii of the field outside the solenoid will tend to infinity.

An intuitive argument can also be used to show that the flux density outside the solenoid is actually zero. Magnetic field lines only exist as loops, they cannot diverge from or converge to a point like electric field lines can. The magnetic field lines follow the longitudinal path of the solenoid inside, so they must go in the opposite direction outside of the solenoid so that the lines can form a loop. However, the volume outside the solenoid is much greater than the volume inside, so the density of magnetic field lines outside is greatly reduced. Now recall that the field outside is constant. In order for the total number of field lines to be conserved, the field outside must go to zero as the solenoid gets longer.

Quantitative description

Now we can consider the imaginary loop *b*. Take the line integral of \mathbf{B} around the loop, with the length of the loop *l*. The horizontal components vanish, and the field outside is practically zero, so Ampère's Law gives us:

$$Bl = \mu_0 Ni$$

where μ_0 is the magnetic constant, *N* the number of turns, *i* the current. From this we get:

$$B = \mu_0 \frac{Ni}{l}.$$

This equation is for a solenoid with no core. The inclusion of a ferromagnetic core, such as iron, increases the magnitude of the magnetic flux density in the solenoid. This is expressed by the formula

$$B = \mu_0 \mu_r \frac{Ni}{l} = \mu \frac{Ni}{l}$$

where μ_r is the relative permeability and μ ($\mu_0 \mu_r$) the permeability of the material that the core is made of.

Inductance of a solenoid

As shown above, the magnetic flux density B within the coil is practically constant and is given by

$$B = \mu_0 \frac{Ni}{l}$$

where μ_0 is the magnetic constant, N the number of turns, i the current and l the length of the coil. Ignoring end effects, the total magnetic flux through the coil is obtained by multiplying the flux density B by the cross-section area A :

$$\Phi = \mu_0 \frac{NiA}{l},$$

When this is combined with the definition of inductance,

$$L = \frac{N\Phi}{i}$$

it follows that the inductance of a solenoid is given by:

$$L = \mu_0 \frac{N^2 A}{l}.$$

A table of inductance for short solenoids of various diameter to length ratios has been calculated by Dellinger, Whitmore, and Ould.

This, and the inductance of more complicated shapes, can be derived from Maxwell's equations. For rigid air-core coils, inductance is a function of coil geometry and number of turns, and is independent of current.

Similar analysis applies to a solenoid with a magnetic core, but only if the length of the coil is much greater than the product of the relative permeability of the magnetic core and the diameter. That limits the simple analysis to low-permeability cores, or extremely long

thin solenoids. The presence of a core can be taken into account in the above equations by replacing the magnetic constant μ_0 with μ or $\mu_0\mu_r$, where μ represents permeability and μ_r relative permeability. Note that since the permeability of ferromagnetic materials changes with applied magnetic flux, the inductance of a coil with a ferromagnetic core will generally vary with current.

Applications

Electromechanical solenoids

28. The Commercial Solenoid.—The solenoid is used in practice for tripping circuit breakers (Par. 237), for operating contactors in automatic motor starters (Par. 219), for operating voltage regulating devices (Par. 207), for arc lamp feeds (Chap. XIII, Vol. II), for operating valves, and for numerous other purposes. In practically all instances a soft iron (or steel) plunger

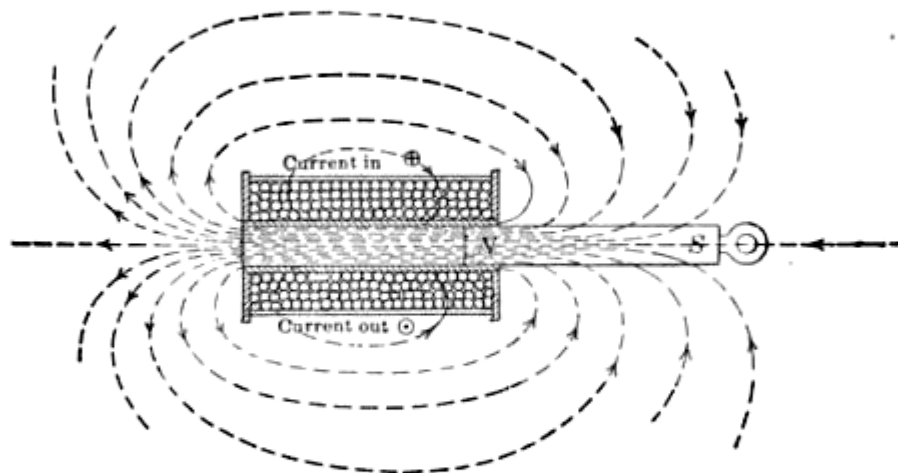


FIG. 30.—Simple solenoid and plunger.

er or armature is necessary to obtain the tractive pull required of the solenoid. The operation of a solenoid and plunger is indicated in Fig. 30. The flux due to the solenoid produces magnetic poles on the plunger. The pole nearer the plunger will be of such sign that it will be urged along the lines of force, (see Par. 11) and in such a direction as to be drawn within the solenoid.

A 1920 explanation of a commercial solenoid used as an electromechanical actuator

Electromechanical solenoids consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature). The coil is shaped such that

the armature can be moved in and out of the center, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve). Although typically weak over anything but very short distances, solenoids may be controlled directly by a controller circuit, and thus have very low reaction times.

The force applied to the armature is proportional to the change in inductance of the coil with respect to the change in position of the armature, and the current flowing through the coil. The force applied to the armature will always move the armature in a direction that increases the coil's inductance.

Electromechanical solenoids are commonly seen in electronic paintball markers, pinball machines, dot matrix printers and fuel injectors.

Rotary solenoid

The rotary solenoid is an electromechanical device used to rotate a ratcheting mechanism when power is applied. These were used in the 1950s for rotary snap-switch automation in electromechanical controls. Repeated actuation of the rotary solenoid advances the snap-switch forward one position. Two rotary actuators on opposite ends of the rotary snap-switch shaft, can advance or reverse the switch position.

The rotary solenoid has a similar appearance to a linear solenoid, except that the core is mounted in the center of a large flat disk, with two or three inclined grooves cut into the underside of the disk. These grooves align with slots on the solenoid body, with ball bearings in the grooves.

When the solenoid is activated, the core is drawn into the coil, and the disk rotates on the ball bearings in the grooves as it moves towards the coil body. When power is removed, a spring on the disk rotates it back to its starting position, also pulling the core out of the coil.

The rotary solenoid was invented in 1944 by George H. Leland, of Dayton, Ohio, to provide a more reliable and shock/vibration tolerant release mechanism for air-dropped bombs. Previously used linear (axial) solenoids were prone to inadvertent releases. U.S. Patent number 2,496,880 describes the electromagnet and inclined raceways that are the basis of the invention. Leland's engineer, Earl W. Kerman, was instrumental in developing a compatible bomb release shackle that incorporated the rotary solenoid. Bomb shackles of this type are found in a B-29 aircraft fuselage on display at the National Museum of the USAF in Dayton, Ohio.

Rotary voice coil

This is a rotational version of a solenoid. Typically the fixed magnet is on the outside, and the coil part moves in an arc controlled by the current flow through the coils. Rotary voice coils are widely employed in devices such as disk drives.

Pneumatic solenoid valves

A pneumatic solenoid valve is a switch for routing air to any pneumatic device, usually an actuator, allowing a relatively small signal to control a large device. It is also the interface between electronic controllers and pneumatic systems.

Hydraulic solenoid valves

Hydraulic solenoid valves are in general similar to pneumatic solenoid valves except that they control the flow of hydraulic fluid (oil), often at around 3000 psi (210 bar, 21 MPa, 21 MN/m²). Hydraulic machinery uses solenoids to control the flow of oil to rams or actuators to (for instance) bend sheets of titanium in aerospace manufacturing. Solenoid-controlled valves are often used in irrigation systems, where a relatively weak solenoid opens and closes a small pilot valve, which in turn activates the main valve by applying fluid pressure to a piston or diaphragm that is mechanically coupled to the main valve. Solenoids are also in everyday household items such as washing machines to control the flow and amount of water into the drum.

Transmission solenoids control fluid flow through an automatic transmission and are typically installed in the transmission valve body.

Automobile starter solenoid

In a car or truck, the starter solenoid is part of an automobile starting system. The starter solenoid receives a large electric current from the car battery and a small electric current from the ignition switch. When the ignition switch is turned on (i.e. when the key is turned to start the car), the small electric current forces the starter solenoid to close a pair of heavy contacts, thus relaying the large electric current to the starter motor.

Starter solenoids can also be built into the starter itself, often visible on the outside of the starter. If a starter solenoid receives insufficient power from the battery, it will fail to start the motor, and may produce a rapid 'clicking' or 'clacking' sound. This can be caused by a low or dead battery, by corroded or loose connections in the cable, or by a broken or damaged positive (red) cable from the battery. Any of these will result in some power to the solenoid, but not enough to hold the heavy contacts closed, so the starter motor itself never spins, and the engine does not start.

Chapter 12

Valve Actuator



Electric actuator on a valve in a power plant

Actuators are used for the automation of industrial valves and can be found in all kinds of technical process plants: they are used in wastewater treatment plants, power plants and even refineries. This is where they play a major part in automating process control. The valves to be automated vary both in design and dimension. The diameters of the valves range from a few inches to a few metres.

Depending on their type of supply, the actuators may be classified as pneumatic, hydraulic, or **electric actuators**.

Classification of actuators according to their movement

Travel means the distance the closing element within the valve has to cover to completely open or close that valve. Typical closing elements include butterfly, globe or gate valve discs. These three closing elements stand for the three basic movements required for covering the travel. The butterfly valve disc is operated by a 90° swivel movement from end position OPEN to CLOSED, the globe valve disc is operated by a rather short linear movement (stroke) while the gate valve disc movement covers the full diameter of the valve. Each movement type requires a specific actuator type.



Electric multi-turn actuator on a gate valve

Multi-turn actuators

Multi-turn actuators are required for the automation of multi-turn valves. One of the major representatives of this type is the gate valve. The basic requirements on multi-turn actuators are described in the standard EN ISO 5210 as follows:

"A multi-turn actuator is an actuator which transmits to the valve a torque for at least one full revolution. It is capable of withstanding thrust."

A valve stem is mounted to the gate valve disc. The multi-turn actuator moves the gate valve disc from OPEN to CLOSED and vice versa via a stem nut. To cover the complete valve travel, the so-called valve stroke, the actuator has to perform – depending on the valve – a few or several hundred rotations. Due to their design, the stroke of electric actuators, contrary to that of their pneumatic counterparts, has no limits. Therefore, gate valves are exclusively automated by means of electric multi-turn actuators.

The multi-turn actuator has to be able to withstand the weight of the gate valve disc by means of the valve attachment, the interface to the valve. This is expressed in the second sentence of the definition.

Gate valves may have a diameter of approx. 4 inches to several meters. The torque requirement for multi-turn solutions ranges from approx. 10 N m to 30,000 N m.



Electric part-turn actuator on a butterfly valve

Part-turn actuators

Part-turn actuators are required for the automation of part-turn valves. Major representatives of this type are butterfly valves and ball valves. The basic requirements on part-turn actuators are described in the standard EN ISO 5211 as follows:

"A part-turn actuator is an actuator which transmits a torque to the valve for less than one full revolution. It need not be capable of withstanding thrust."

Less than one full revolution usually means a swivel movement of 90°; however, there are some valve types requiring a different swing angle, such as two-way valves. The

closing elements in part-turn actuators are always supported by the valve housing, i.e. the weight of the closing element does not act upon the part-turn actuator. This is expressed in the second sentence of the definition.

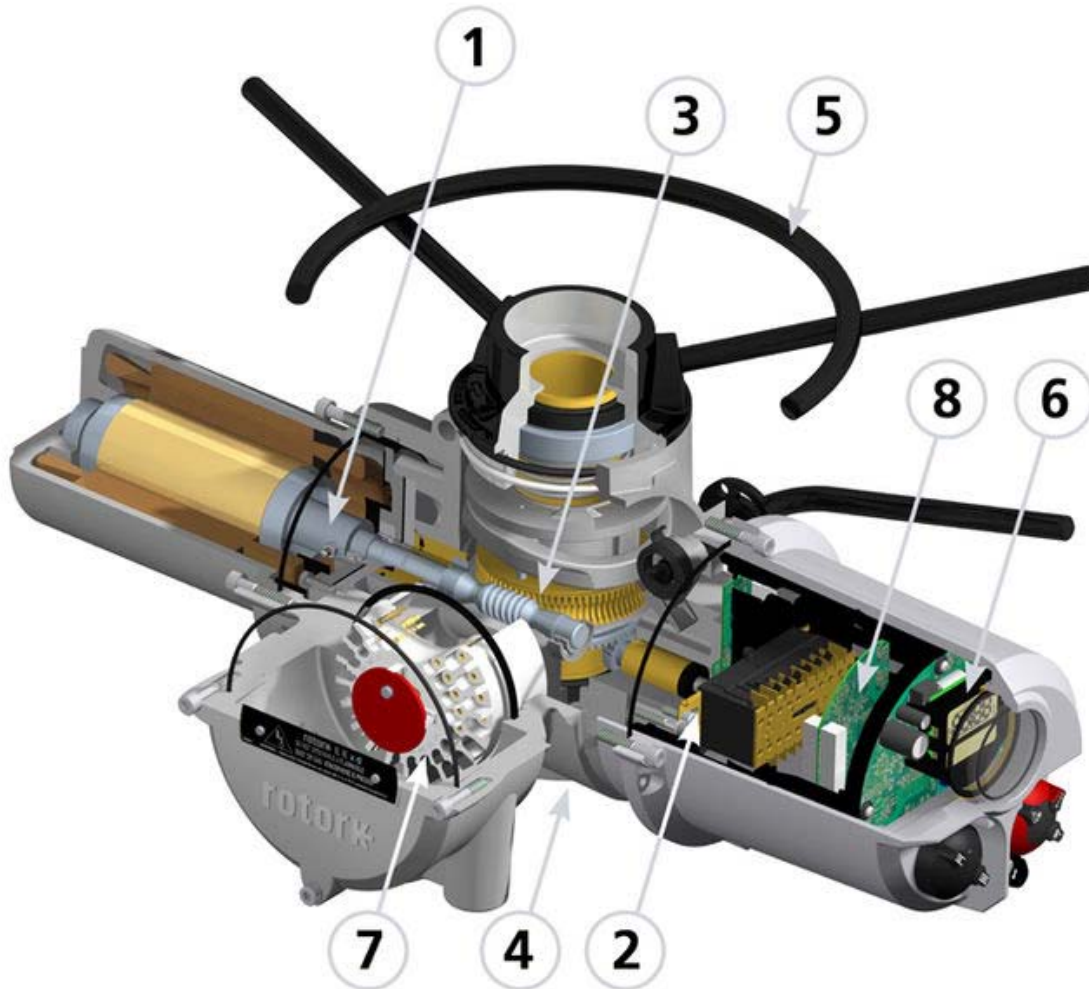
Part-turn valves diameters range from a few inches to several metres. The torque requirement for operating the closing element has a comparable range from approximately 10 N m to several 100,000 N m. Electric actuators are unrivalled for large-diameter valves with high torque requirements.

Linear actuators

Currently there is no international standard describing linear actuators or linear thrust units. A typical representative of the valves to be automated is the control valve. Just like the plug in the bathtub is pressed into the drain, the plug is pressed into the plug seat by a stroke movement. The pressure of the medium acts upon the plug while the thrust unit has to provide the same amount of thrust to be able to hold and move the plug against this pressure.

Most of the linear actuators used are pneumatic diaphragm actuators. They are characterised by a simple design principle and are therefore cost-effective. A compressed air supply is a prerequisite for their use. In case this is not possible, the use of thrust units is recommended which can easily be supplied with power.

Design



Electric multi-turn actuator with controls

Motor (1)

Robust asynchronous three-phase AC motors are mostly used as the driving force, for some applications also single-phase AC or DC motors are used. These motors are specially adapted for valve automation as they provide higher torques from standstill than comparable conventional motors, a necessary requirement to unseat sticky valves. The actuators are expected to operate under extreme ambient conditions, however they are generally not used for continuous operation since the motor heat buildup can be excessive.

Limit and torque sensors (2)

The limit switching measures the travel and signals when an end position has been reached, the torque switching measures the torque present in the valve. When exceeding a

set limit, this is signalled in the same way. Actuators are often equipped with a remote position transmitter which indicates the valve position as continuous current or voltage signal .

Gearing (3)

Often a worm gearing is used to reduce the high output speed of the electric motor. This enables a high reduction ratio within the gear stage, leading to a low efficiency which is desired for the actuators. The gearing is therefore self-locking i.e. it prevents accidental and undesired changes of the valve position by acting upon the valve's closing element. This is of major importance for multi-turn actuators which are axially loaded with the weight of the gate valve disc.

Valve attachment (4)

The valve attachment consists of two elements. First: The flange used to firmly connect the actuator to the counterpart on the valve side. The higher the torque to be transmitted, the larger the flange required.

Second: The output drive type used to transmit the torque or the thrust from the actuator to the valve shaft. Just like there is a multitude of valves there is also a multitude of valve attachments.

Dimensions and design of valve mounting flange and valve attachments are stipulated in the standards EN ISO 5210 for multi-turn actuators or EN ISO 5211 for part-turn actuators. The design of valve attachments for linear actuators is generally based on DIN 3358.

Manual operation (5)

In their basic version most electric actuators are equipped with a handwheel for operating the actuators during commissioning or power failure. The handwheel does not move during motor operation.

Actuator controls (6)

Both actuator signals and operation commands of the DCS are processed within the actuator controls. This task can in principle be assumed by external controls, e.g. a PLC. Modern actuators include integral controls which process signals locally without any delay. The controls also include the switchgear required to control the electric motor. This can either be reversing contactors or thyristors which, being an electric component, are not subject to mechanic wear. Controls use the switchgear to switch the electric motor on or off depending on the signals or commands present. Another task of the actuator controls is to provide the DCS with feedback signals, e.g. when reaching a valve end position.

Electrical connection (7)

The supply cables of the motor and the signal cables for transmitting the commands to the actuator and sending feedback signals on the actuator status are connected to the electrical connection. The electrical connection can be designed as a separately sealed terminal bung or plug/socket connector. For maintenance purposes, the wiring should be easily disconnected and reconnected.

Fieldbus connection (8)

Fieldbus technology is increasingly used for data transmission in process automation applications. Electric actuators can therefore be equipped with all common fieldbus interfaces used in process automation. Special connections are required for the connection of fieldbus data cables..

Functions

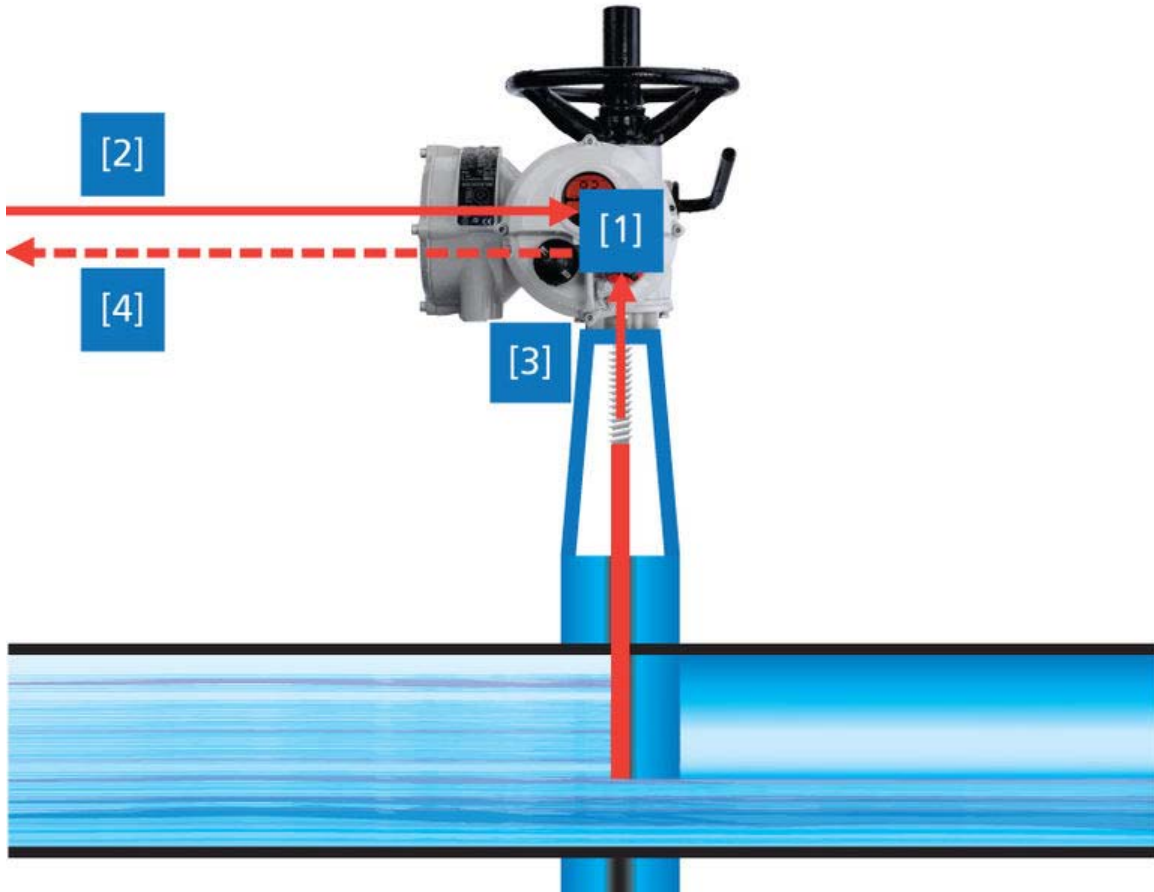
Automatic switching off in the end positions

After receiving an operation command, the actuator moves the valve in direction OPEN or CLOSE. When reaching the end position, an automatic switch-off procedure is started. Two fundamentally different switch-off mechanisms can be used. The controls switch off the actuator as soon as the set tripping point has been reached. This is called limit seating. However there are valve types for which the closing element has to be moved in the end position at a defined force or a defined torque to ensure that the valve seals tightly. This is called torque seating. The controls are programmed as to ensure that the actuator is switched off when exceeding the set torque limit. The end position signal of the limit switching is used for signalling the end position.

Safety functions

The torque switching is not only used for torque seating in the end position, but it also serves as overload protection over the whole travel and protects the valve against excessive torque. If excessive torque acts upon the closing element in an intermediate position, e.g. due to a trapped object, the torque switching will trip when reaching the set tripping torque. In this situation the end position is not signalled by the limit switching. The controls can therefore distinguish between normal operation torque switch tripping in one of the end positions and switching off in an intermediate position due to excessive torque.

Temperature sensors are required to protect the motor against overheating. For some applications by other manufacturers, the increase of the motor current is also monitored. Thermoswitches or PTC thermistors which are embedded in the motor windings mostly reliably fulfil this task. They trip when the temperature limit has been exceeded and the controls switch off the motor.



The positioner is supplied with a setpoint and an actual value. The motor is controlled until the actual value is identical to the setpoint. The DCS generally needs a feedback signal

Process control functions

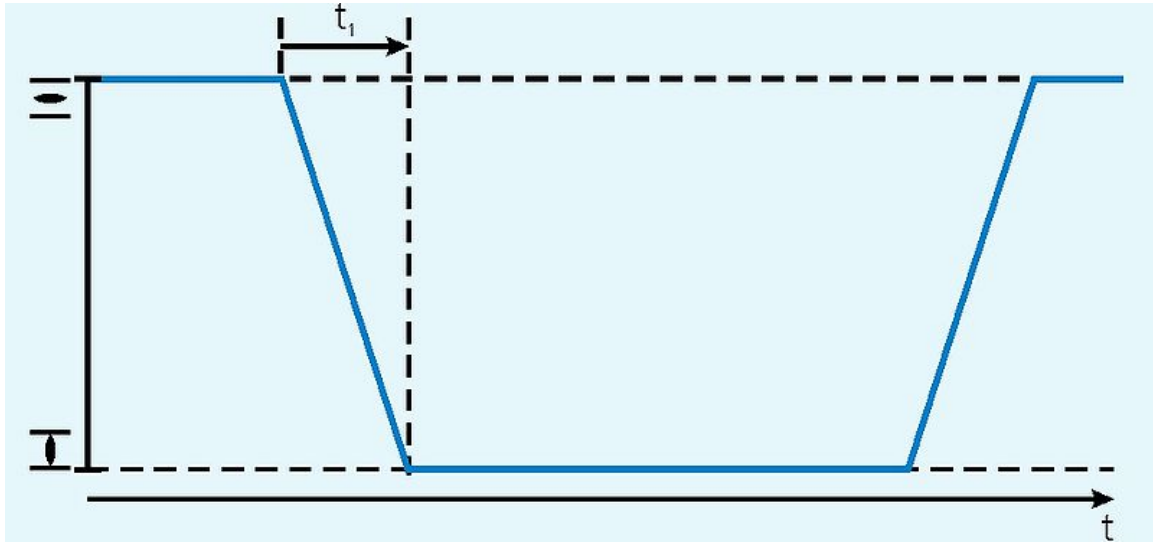
Due to increasing decentralisation in automation technology and the introduction of micro processors, more and more functions have been transferred from the DCS to the field devices. The data volume to be transmitted was reduced accordingly, in particular by the introduction of fieldbus technology. Electric actuators whose functions have been considerably expanded are also affected by this development. The simplest example is the position control. Modern positioners are equipped with self-adaptation i.e. the positioning behaviour is monitored and continuously optimised via controller parameters.

Meanwhile, electric actuators are equipped with fully-fledged process controllers (PID controllers). Especially for remote installations, e.g. the flow control to an elevated tank, the actuator can assume the tasks of a PLC which otherwise would have to be additionally installed.

Diagnosis

The diagnostic function covers two aspects. Modern actuators have extensive diagnostic functions which help to identify the cause of a failure. The second function is the logging of operating data. The evaluation of the data allows to draw conclusions on the previous course of operation. Working on this basis, the operation can be optimised by changing the parameters and the wear of both actuator and valve be reduced.

Duty types



Typical time period in open-close duty. t_1 is the operating time and may not exceed the maximum permissible running time



Typical time period in modulating duty.

Open-close duty

If valves are used as shut-off valves, the valve is either opened or closed. Intermediate positions are not approached. The valve is rarely operated, the interval between operations may be a few minutes or even several months.

The 'Short-time duty S2' operation mode of the electric motor in accordance with the IEC 34-1 standard indicates that the actuator is suitable for this kind of applications. Another characteristic of this duty type is the maximum permissible running time without interruption. A typical time for actuators is 15 min.

Positioning duty

Defined intermediate positions are approached for setting a static flow through a pipeline. The same running time limits as in open-close duty apply.

Modulating duty

The most distinctive feature of a closed-loop application is that changing conditions require frequent adjustment of the MOV e.g. to set a certain flow rate. Sensitive closed-loop applications require adjustments within intervals of a few seconds. The demands on the actuator are higher than in open-close or positioning duty. Both mechanics and motor have to be designed as to be able to withstand the high number of starts without any deterioration in control accuracy.

The duty type of the electric motors suitable for this application is called *intermittent duty S4* or *intermittent duty S5*. The running time is limited by the relative on-time; for modulating actuators this is usually 25 %.



Actuators are used in Siberia



Sahara

Service conditions

Electric actuators are used worldwide, in all climate zones, in all kinds of industrial plants under special local ambient conditions. The applications are often safety related, therefore the plant operators put high demands on the reliability of the devices. Failure of an actuator may cause accidents in process-controlled plants and toxic substances may leak into the environment.

Process-controlled plants are often operated for several decades which justifies the higher demands put on the lifetime of the devices.

For this reason, actuators are always designed in high enclosure protection. The manufacturers put a lot of work and knowledge into corrosion protection.

Enclosure protection

The enclosure protection types are defined according to the so-called IP codes of EN 60529. The basic version of most electric actuators is already designed in the second highest enclosure protection IP 67. This means they are protected against the ingress of dust and water during immersion (30 min at a max. head of water of 1 m). Most actuator

manufacturers also supply devices in enclosure protection IP 68 which provide protection against submersion up to a max. head of water of 6 m.

Ambient temperatures

In Siberia, temperatures up to $-60\text{ }^{\circ}\text{C}$ may occur, in technical process plants, $+100\text{ }^{\circ}\text{C}$ may be exceeded. Using the proper lubricant is crucial for full operability under these conditions. Greases which may be used at room temperature will become too solid at low temperatures so that the actuator cannot overcome the resistance within the device. At high temperatures, these greases will liquify and lose their lubricating power. When sizing the actuator, the ambient temperature and the selection of the correct lubricant are of major importance.

Explosion protection

Electric actuators are used in applications where potentially explosive atmospheres may occur. This includes among others refineries, pipelines, oil and gas exploration or even mining. In case potentially explosive gas-air-mixtures or gas-dust-mixtures occur, the actuator may not act as ignition source. Basically, hot surfaces on the actuator as well as ignition sparks created by the actuator have to be avoided. This can be achieved by a flameproof enclosure, for example; i.e. the housing is designed as to prevent ignition sparks from leaving the housing even in case of an explosion inside.

Actuators designed for these applications, being explosion-proof devices, have to be qualified by a test authority (notified body). There is no such thing as a worldwide uniform standard: depending on the country where the actuators are used, different directives and regulations have to be observed. Within the European Union, ATEX 94/9/EC applies, in US, the NEC (approval by FM) or the CEC in Canada (approval by the CSA). Explosion-proof actuators have to meet the design requirements of these directives and regulations.

Additional uses

Small electric actuators can be used in a wide variety of assembly, packaging and testing applications. Such actuators can be linear, rotary, or a combination of the two, and can be combined to perform work in three dimensions. Such actuators are often used to replace pneumatic cylinders.