
BOSCH

Electronic Automotive Handbook

1. Edition

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SI units

SI denotes "Système International d'Unités" (International System of Units). The system is laid down in ISO 31 and ISO 1000 (ISO: International Organization for Standardization) and for Germany in DIN 1301 (DIN: Deutsches Institut für Normung – German Institute for Standardization).

SI units comprise the seven base SI units and coherent units derived from these base SI units using a numerical factor of 1.

Base SI units

Base quantity and symbols	Base SI unit		
		Name	Symbol
Length	<i>l</i>	meter	m
Mass	<i>m</i>	kilogram	kg
Time	<i>t</i>	second	s
Electric current	<i>I</i>	ampere	A
Thermodynamic temperature	<i>T</i>	kelvin	K
Amount of substance	<i>n</i>	mole	mol
Luminous intensity	<i>I</i>	candela	cd

All other quantities and units are derived from the base quantities and base units. The international unit of force is thus obtained by applying Newton's Law:

force = mass x acceleration



$$F = m \cdot a$$

where $m = 1 \text{ kg}$ and $a = 1 \text{ m/s}^2$, thus $F = 1 \text{ kg} \cdot 1 \text{ m/s}^2 = 1 \text{ kg} \cdot \text{m/s}^2 = 1 \text{ N}$ (newton).

Definitions of the base SI units

1 meter is defined as the distance which light travels in a vacuum in 1/299,792,458 seconds (17th CGPM, 1983¹). The meter is therefore defined using the speed of light in a vacuum, $c = 299,792,458 \text{ m/s}$, and no longer by the wavelength of the radiation emitted by the krypton nuclide ⁸⁶Kr. The meter was originally defined as the forty-millionth part of a terrestrial meridian (standard meter, Paris, 1875).

1 kilogram is the mass of the international prototype kilogram (1st CGPM, 1889 and 3rd CGPM, 1901¹).

1 second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state

Actuators

Sections 

Quantities and units

Quantity		Unit
A	Pole face; piston surface area	mm ²
B	Magnetic induction or magnetic flux density	T
F	Force	N
I	Electric current	A
l	Length of conductor in field	mm
M	Torque	N · m
p	Pressure	Pa
Q	Volume rate of flow	l/min
Q_W	Heat flow	W
s	Distance, piston travel	mm
V	Volume	mm ³
V_{th}	Displaced volume per rotation	mm ³
α	Angle between current flow direction and magnetic lines of force	°
δ	Air-gap length	mm
μ_0	Permeability constant	
φ	Rotation angle	°

Actuators (final-control elements) form the junction between the electronic signal processor (data processing) and the actual process (mechanical motion). They convert the low-power signals conveying the positioning information into operating signals of an energy level adequate for process control. Signal converters are combined with amplifier elements to exploit the physical transformation principles governing the interrelationships between various forms of energy (electrical – mechanical – fluid – thermal).

Transistor actuator: Element with electronic circuitry for processing control signals. Includes auxiliary energy input and energy output stages.

Servo component: As above, but with the ability to process nonelectrical control signals.

Transistor actuator+ servo component = Final-control element.

Converter: Control component without control-signal processing, receives and transfers energy.

Actuator: Control chain comprising servo component and converter.

The term actuator is also employed as a general-purpose designation for servo components without converters on their own.

Actuator chain

1 Information, 2 Actuator, 3 Transformer, 4 Control element, 5 Losses, 6 External electrical energy, 7 External hydraulic energy.

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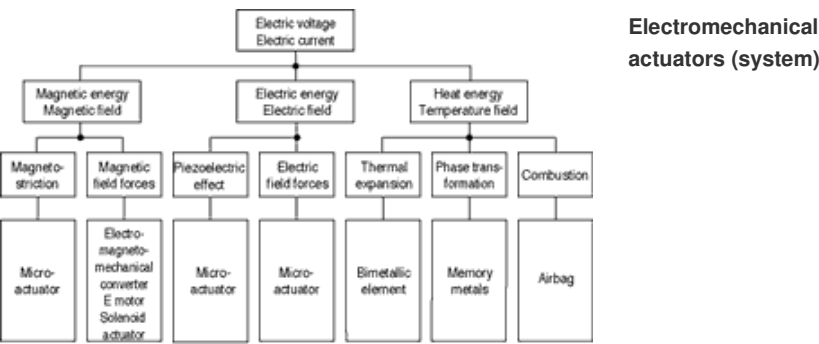
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Electromechanical actuators

This type of energy conversion represents one option for classifying electromechanical actuators. The energy emanating from the source is transformed into magnetic or electrical field energy, or converted to thermal energy. The individual force-generation principle is determined by these forms of energy, and bases upon either field forces or certain specific material characteristics. Magnetostrictive materials make it possible to design actuators for application in the micropositioning range. This category also includes piezoelectric actuators, which are built according to a multilayer design similar to ceramic capacitors and are potential actuators for fast-acting fuel injectors. Thermal actuators depend exclusively upon the exploitation of characteristics of specific materials.

Actuators in a motor vehicle are mostly electro-magneto-mechanical transformers and by extension electrical servomotors (see [Electrical machines](#)) and translational and rotational solenoid actuators. An exception is the pyrotechnical airbag system (see [Safety systems](#)). The solenoid actuators can themselves be the servo element, or they can assume a control function by governing a downstream force-amplification device (e.g. mechanical-hydraulic).

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Force generation in the magnetic field

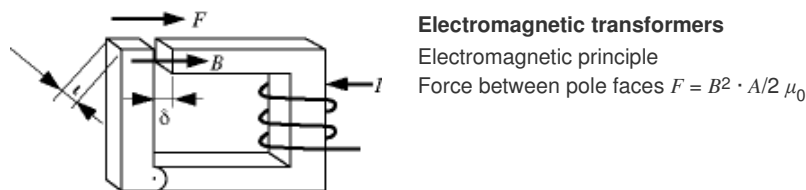
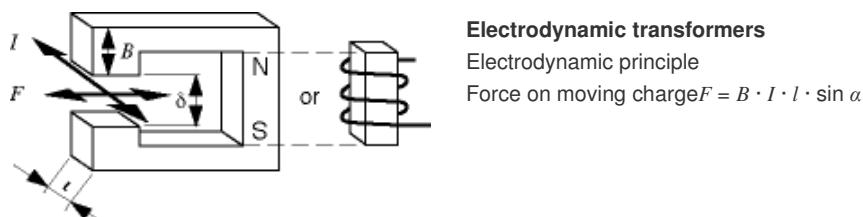
The distinction between the electrodynamic and the electromagnetic actuator principles stems from the manner in which forces are generated in the magnetic field. Common to both principles is the magnetic circuit with soft-magnetic material and the coil for excitation of the magnetic field. A major difference lies in the force

which can be extracted from the unit under technically-feasible conditions. Under identical conditions, the force produced through application of the electromagnetic principle is greater by a factor of 40. The electrical time constant for this type of actuator is comparable to the mechanical time constants. Both force-generation principles are applied in linear and rotary drive mechanisms.

Electrodynamic principle

Electrodynamic designs are based on the force exerted on mobile charges or charged conductors within a magnetic field (Lorentz force). An excitation coil or a permanent magnet generates a constant magnetic field. The electrical energy destined for conversion is applied to the moving armature coil (plunger or immersion coil). A high degree of actuator precision is achieved by designing the armature coil with low mass and low inductivity. The two accumulator elements (one on the fixed and one on the moving component) produce two active force directions via current-direction reversal in the armature and excitation coils.

The secondary field produced by the armature current flows in an open magnetic circuit, thereby diminishing the effects of saturation. Approximately speaking, the force (torque) exerted by an electrodynamic actuator over its setting range is proportional to current and independent of travel.



Electromagnetic principle

The electromagnetic principle exploits the mutual attraction displayed by soft ferrous materials in a magnetic field. The electromagnetic actuator is equipped with only one coil, which generates both the field energy and the energy to be transformed. In accordance with the operating principles, the excitation coil is equipped with an iron core to provide higher inductance. However, as the force is proportional to the square of the density of the magnetic flux, the unit is operative in only one direction. The electromagnetic actuator thus requires a return element (such as a mechanical spring or a magnetic return mechanism).

Dynamic response

The dynamic response of an electromechanical actuator, i.e. the activation and deactivation operations, is defined by the equation of mechanical motion, the

differential equation of electrical circuits and Maxwell's equations of dynamics. The current- and position-dependent force follows from Maxwell's equations.

The most basic electrical circuit consists of an inductor with an ohmic resistor. One means of enhancing the dynamic response is through over-excitation at the instant of activation, while deactivation can be accelerated with a Zener diode. In each case, increasing the dynamic response of the electrical circuit involves additional expenditure and increased losses in the actuator's triggering electronics.

Field diffusion is a delay effect which is difficult to influence in actuators with high dynamic response. Rapid switching operations are accompanied by high-frequency field fluctuations in the soft-magnetic material of the actuator's magnetic circuit. These fluctuations, in turn, induce eddy currents, which counteract their cause (build-up and decay of the magnetic field). The resultant delay in the build-up or reduction of forces can only be reduced by selecting appropriate materials with low electrical conductivity and permeability.

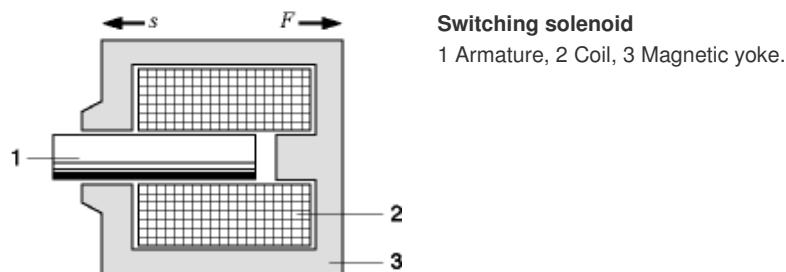
Design

Design selection is essentially determined by operating conditions (e.g., installation space, required force-travel curve and dynamic response).

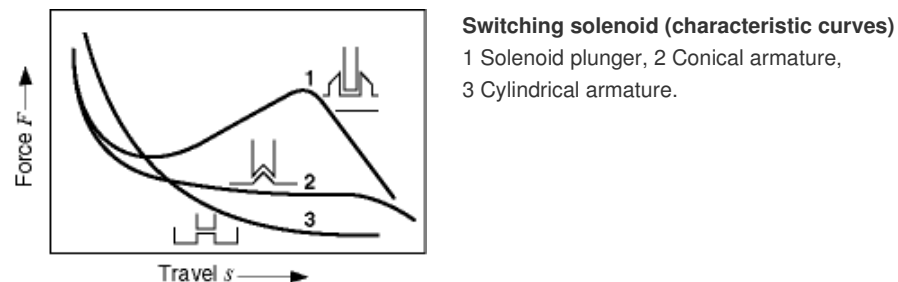
Electromagnetic actuators

A typical form for translational electromagnetic actuators is the switching solenoid with a force/travel curve which falls as a function of the square of positioning travel. The precise shape of the curve is determined by the type of working gap (e.g., conical or immersion armature).

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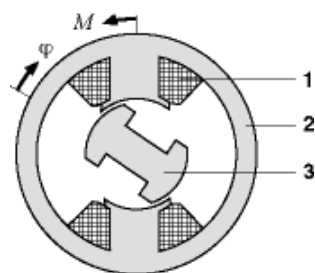
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Rotational electromagnetic actuators are characterized by a defined pole arrangement in stator and rotor. When current is applied to one of the coils, the rotor and stator poles respond with mutual attraction, and in doing so generate a torque.

The single-winding rotary actuator incorporates a pair of poles in each of the two main sections, as well as a coil in the stator. Its maximum positioning range is approx. 45°.

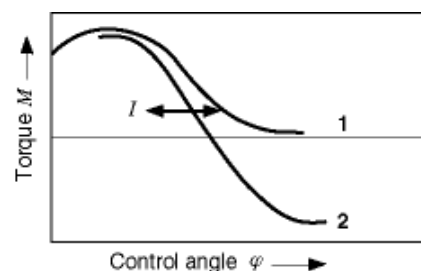
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Electromagnetic single-winding rotary actuator

1 Winding, 2 Stator, 3 Armature.

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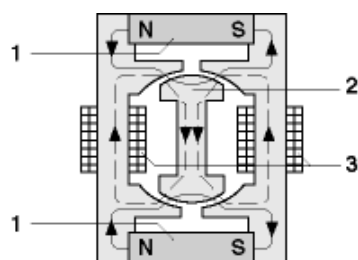


**Electromagnetic rotary actuator
(characteristic curves)**

1 Single-winding rotary actuator, 2 Torque motor.

The torque motor is a bidirectional electromagnetic rotary actuator featuring a stable working point and without counterforces. The rotor is maintained in a stable position by the excitation field of the permanent magnet in the stator. The magnetic field generated by one or two stator windings produces torque and provides unilateral compensation for the excitation field. This type of layout is suitable for applications in which substantial forces are required over small angles. The relationship between the applied current and the torque motor's force is roughly linear. The torque-motor principle is also employed in translational actuators.

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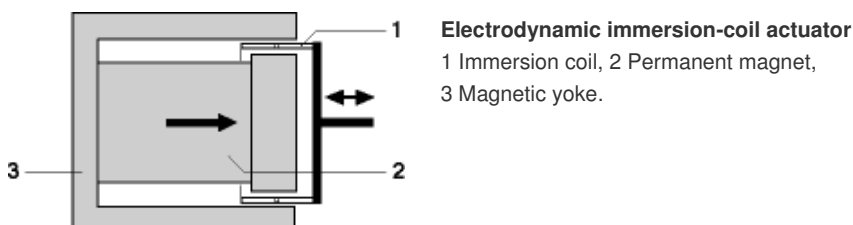
Torque motor

1 Magnets, 2 Armature, 3 Control windings.

Electrodynamic actuators

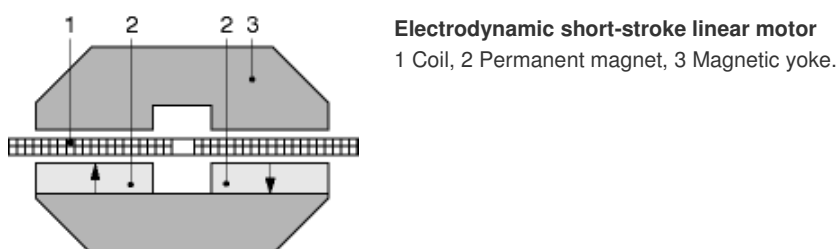
In a pot magnet (immersion-coil actuator), a cylindrical immersion coil (armature winding) is set in motion in a working gap. The positioning range is limited by the axial length of the armature winding and by the gap.

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The short-stroke linear motor is an actuator with a virtually round disk coil.

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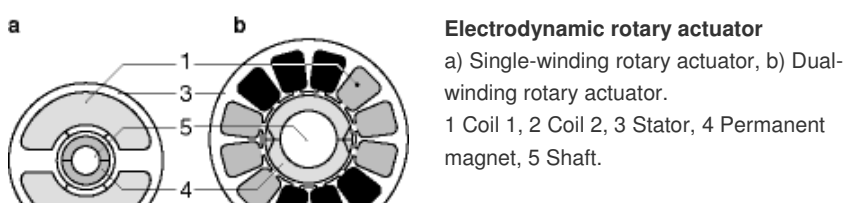


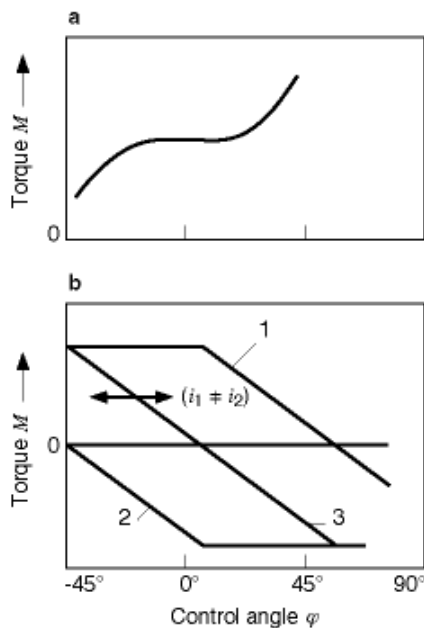
A distinction is made between single-winding and dual-winding rotary actuators.

Both types include a permanent magnet within the rotor and one or two stator windings. The rotor magnet is magnetized at both ends to produce magnetic flux in the rotary magnet's working gap, which combines with the armature current to produce a torque. Originating from the position illustrated, the positioning range is less than $\pm 45^\circ$. The positioning range of the single-winding rotary actuator also varies according to both the torque requirement and the angle range in which the necessary flux density can be provided.

The dual-winding rotary actuator can be described as a combination of two single-winding rotary actuators with a 90° peripheral offset and designed to produce opposed torque flows. A stable working point is achieved at the zero transition point on the resulting torque curve without auxiliary counteractive forces.

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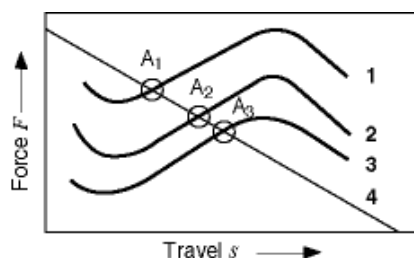
**Electrodynamic rotary actuator
(characteristic curves)**

a) Single-winding rotary actuator, b) Dual-winding rotary actuator. 1 Coil 1, 2 Coil 2, 3 Coil 1 and 2.

Applications

Electromechanical actuators are direct-action control elements, and without an intermediate ratio-conversion mechanism they convert the energy of the electrical control signal into a mechanical positioning factor/work. Typical applications include positioning of flaps, spools and valves. The described actuators are final-control elements without internal return mechanisms, i.e. without a stable working point. They are only capable of carrying out positioning operations from a stable initial position (working point) when a counterforce is applied (e.g., return spring and electrical control).

A solenoid plunger provides a stable static bias point when its force-travel curve is superimposed upon the characteristic response of a return spring. A variation of the coil current in the solenoid shifts the working point. Simple positioning is achieved by controlling the current. However, particular attention must be paid here to the nonlinearity of the force-current characteristic and the positioning system's sensitivity to interference factors (e.g. mechanical friction, pneumatic and hydraulic forces). The temperature sensitivity of the coil resistance results in positioning errors, making corrective current control necessary. A high-precision positioning system with good dynamic response must incorporate a position sensor and a controller.



**Working points (A) of a tractive
electromagnet**

1, 2, 3 Curves for different currents, 4 Curve for a return spring.

	Hydraulic actuators	Pneumatic actuators
Medium	– Fluid, mostly oil – Supply from tank, oil sump – Virtually incompressible – Self-lubricating – Viscosity heavily temperature-dependent	– Gas, mostly air – Supply from surrounding air – Compressible – Independent lubrication required – Viscosity fluctuations virtually irrelevant
Pressure range	to approx. 30 MPa (200 MPa for diesel fuel injectors)	to approx. 1 MPa or greater (approx. 0.05 MPa for vacuum actuators)
Line connections	Supply and return connection (possible leakage connection)	Pressure connection only, return directly to environment
Applications	Positioning applications with high load rigidity, demanding requirements for synchronization and positioning precision in closed-loop control system	Actuators with lower power requirement, positioning by mechanical stops, in open control loop

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Fluid-mechanical actuators

Hydraulic and pneumatic actuators utilize similar principles for the conversion and regulation of energy (see [Automotive hydraulics](#) and [Automotive pneumatics](#)). The table shows the differences in characteristics and applications.

In most applications, fluid-mechanical actuator drives are in the form of hydrostatic energy converters. These operate according to the displacement principle, converting the pressure energy of the fluid medium into mechanical work and vice versa.

In contrast, hydrodynamic transformers operate by converting flow energy (kinetic energy of the moving fluid) into mechanical work (example: [hydrodynamic coupling](#)).

Losses during energy conversion stem from leakage and friction. Fluid-thermal losses are caused by flow resistance, in which throttle action transforms the hydraulic energy into heat. A portion of this heat is dissipated into the environment, and some of it is absorbed and carried away by the fluid medium.

 Heat flow $Q_W = Q_1 \cdot p_1 - Q_2 \cdot p_2$

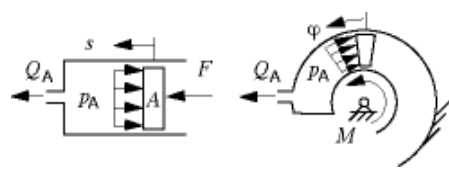
With incompressible fluids

 Heat flow $Q_W = Q_1 \cdot (p_1 - p_2)$

The flow develops into turbulence at restrictions. The flow rate of the fluid is then largely independent of viscosity. On the other hand, viscosity does play a role in the case of laminar flow in narrow pipes and apertures (see [Automotive hydraulics](#)).

Fluid-mechanical amplifiers control the transition of energy between fluid and mechanical states. The regulating mechanism must be designed for control with only a very small proportion of the energy required for the ultimate positioning operation.

Fluid-mechanical actuators



Linear actuator

$F = p_A \cdot A$

$s = Q_A / A$

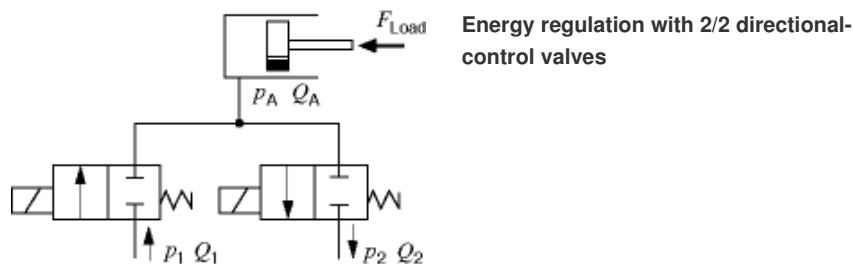
Rotary actuator

$M = (p_A \cdot V_{th}) / 2 \pi$

$\varphi = (Q_A / V_{th}) \cdot 2 \pi$

Switching valves open/close the orifice governing the flow to/from a fluid-mechanical energy converter. Provided that the control-element opens sufficiently, the throttling losses remain negligible. Pulse-width-modulated opening and closing can be applied to achieve quasicontinuous control of the fluid-mechanical conversion process with virtually no losses. In practice, however, pressure fluctuations and mechanical contact between the valve elements result in undesirable vibration and noise.

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Actuator performance data

The table below compares performance data for nine different actuator types.

It contains data based on components with lengths of 50 ...100 mm and diameters ranging from 20 ... 50 mm.

Comparisons between rotation motors and linear actuators are based on a conversion mechanism consisting of a mechanical spindle with nut (1 mm pitch). Spindle length and motor length are identical.

Performance data

No.	Actuator type	Expansion	Mechanical stress	Velocity m/s	Control-force	Mean control-	Efficiency
-----	---------------	-----------	-------------------	--------------	---------------	---------------	------------

		%	N/mm ²		density per stroke W/cm ³	force density mW/cm ³	%
1	Hydraulic cylinder	30	21	0.25	9	3020	92
2	Pneumatic cylinder	76	1	1	3.5	1180	88
3	DC Motor	70	0.0072)	63)	0.8	791	50
4	Ultrasonic motor	70	0.062)	0.353)	0.13	133	16
5	Piezoeffect actuator	0.09	30	24)	15.6	61	7
6	Memory wire	4	50	0.002	0.32	53	0.3
7	Valve solenoid1)	0.8	2.2	0.5	8	44	5
8	Magnetostriction actuator	0.09	22	1.5	1.6	5.4	5
9	Solenoid 5 % ED	21	0.1	0.16	0.12	4.1	5

1) Fuel cooled,

2) Shear stress in rotor gap/friction gap,

3) Rotor peripheral velocity,

4) Theoretical limit.

Expansion

Expansion is the stroke relative to the length of the inner actuator where energy is generated, e.g., piezoelectric-stack length, coil length, internal length of hydraulic cylinder. The effective stroke (70 % of specified spindle length) is assumed as the expansion for rotation motors.

Mechanical stress

Mechanical stress is the lift force relative to the force-generating area, e.g. cross-sectional area of piezoelectric devices, coil gap surface (end face or lateral surface), inner surface of hydraulic cylinder. The peripheral force at the rotor and the rotor lateral surface are used to calculate the shear stress in electric motors.

Velocity

The velocity is defined as the control-stroke travel divided by the control time. On rotating motors, it is the peripheral velocity of the rotor.

Mean control-force density

The mean control-force density is the thermally permissible control force relative to unit volume.

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 mW/cm^3

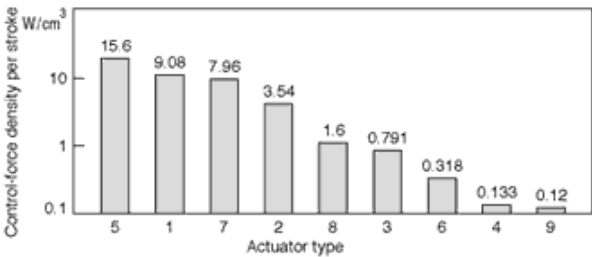
Mean control-force density of selected actuators

1 Hydraulic cylinder, 2 Pneumatic cylinder, 3 DC motor, 4 Ultrasonic motor, 5 Piezoeffect actuator, 6 Memory wire, 7 Valve solenoid actuator, 8 Magnetostriction actuator, 9 Solenoid actuator 5 % on-time.

Control-force density per stroke

The control-force density per stroke is the transitional maximum control force for one stroke relative to the unit volume. A spindle (1 mm pitch) with a length equal to the motor length is specified for motors.

 Enlarge picture



Control-force density per stroke of selected actuators

1 Hydraulic cylinder, 2 Pneumatic cylinder, 3 DC motor, 4 Ultrasonic motor, 5 Piezoeffect actuator, 6 Memory wire, 7 Valve solenoid actuator, 8 Magnetostriction actuator, 9 Solenoid actuator 5 % on-time.

Efficiency

The efficiency is the supplied energy divided by the energy transmitted to the actuator, not including losses associated with electronic or other control assemblies. Options for energy recycling (i.e., with piezoelectric actuators) are not considered.

Characteristics

Extremely high performance levels in the areas of expansion, mechanical stress and velocity make hydraulic actuators the preferred design for extended heavy-duty applications.

In electric motors, high peripheral velocities compensate for low magnetic-field forces, allowing these motors to provide high levels of force density in continuous operation.

Despite their limited expansion, piezoelectric actuators are capable of generating high force levels and are thus suitable for providing brief bursts of high energy.

Linear solenoids suffer from substantial thermal losses at the coil; with adequate

cooling they achieve moderate force-density ratings, comparable to those of solid-body actuators.

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