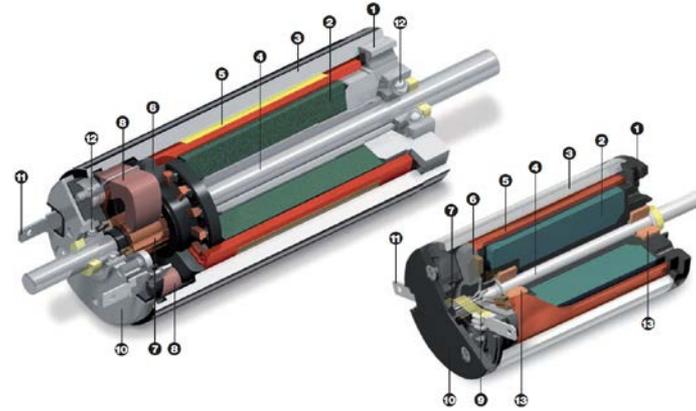


IGM
Direktor: Univ.-Prof. Dr.-Ing. B. Corves
RWTH AACHEN
RHEINISCH-WESTFÄLISCHE HOCHSCHULE AACHEN

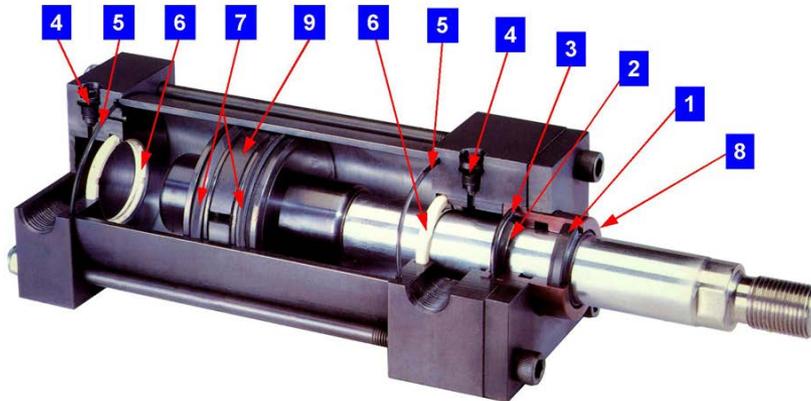
Mechanism and Drive Synthesis Lecture (Part I)

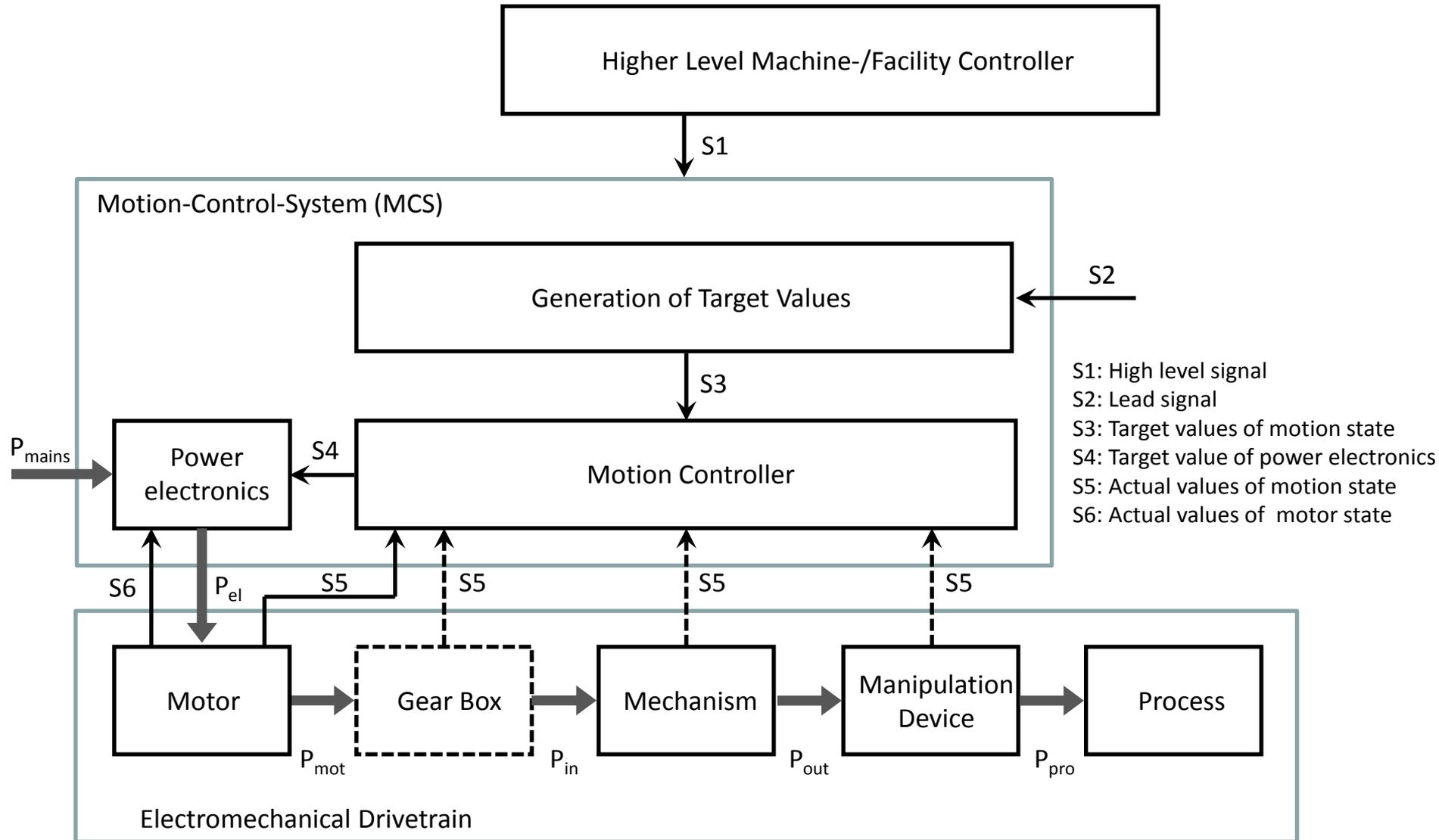
TrISToMM 2015, Izmir, Sunday, June 14th

▶ **1 Drive Systems**



- 1.1 Rotational Electrical Drives
- 1.2 Linear Electrical Drives
- 1.3 Linear Pneumatic Drives





- **What maximum power is required?** $P=F \cdot v$ or $P=T \cdot \omega$
- **What maximum force/torque is required?** F_{\max} or T_{\max} ?
- **What maximum RPM is required?** n_{\max} ?
- **Variable RPM?** $n = f(t)$
- **RPM Control?** Precision? Control Concept?
- **Position Control?** Precision? Control Concept?
- **Which supply voltage is available?** 220 V, 380 V, ...
- **Which acceleration capability is required?** $M=J \cdot \ddot{\varphi}$? ?
- **What precision is required?**
- ...

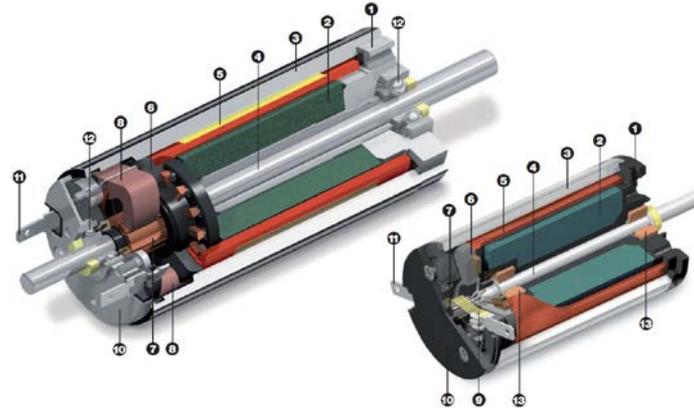
| Motor Type | Load dependant RPM | Frequency dependant RPM | Mechanical Commutation | Electronic Commutation | Life time relatively high | Expensive motor concept | Robust motor concept | Good motor acoustics | Expensive current controller | High RPM possible | Suitable for high power output |
|---|--------------------|-------------------------|------------------------|------------------------|---------------------------|-------------------------|----------------------|----------------------|------------------------------|-------------------|--------------------------------|
| stepper motor | | ✗ | | | ✗ | ✗ | ✗ | | | | |
| switched reluctance motor | | ✗ | | | ✗ | ✗ | ✗ | ✗ | | | |
| Three-phase synchronous motor | | ✗ | | | ✗ | ✗ | ✗ | ✗ | | | ✗ |
| Three-phase asynchronous motor | ✗ | | | | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| AC motor capacitor with double-stranded auxiliary branch and squirrel-cage rotor | ✗ | | | | ✗ | ✗ | ✗ | | | | |
| AC motor capacitor with three strands auxiliary branch and squirrel-cage rotor | ✗ | | | | ✗ | ✗ | ✗ | | | | |
| AC motor capacitor with double-stranded auxiliary branch and permanent magnet rotor | | ✗ | | | ✗ | ✗ | ✗ | | | | |
| AC motor capacitor with three strands auxiliary branch and permanent magnet rotor | | ✗ | | | ✗ | ✗ | ✗ | | | | |
| Universal motor | ✗ | | | | | | | | | ✗ | |
| Elektronic motor | ✗ | | | ✗ | ✗ | ✗ | ✗ | ✗ | | ✗ | |
| DC series motor | ✗ | | ✗ | | | | | | | ✗ | ✗ |
| DC shunt motor | ✗ | | ✗ | | | | | | | ✗ | ✗ |
| Permanent magnet DC motor | ✗ | | ✗ | | | | | | | ✗ | |

Especially for high power requirements

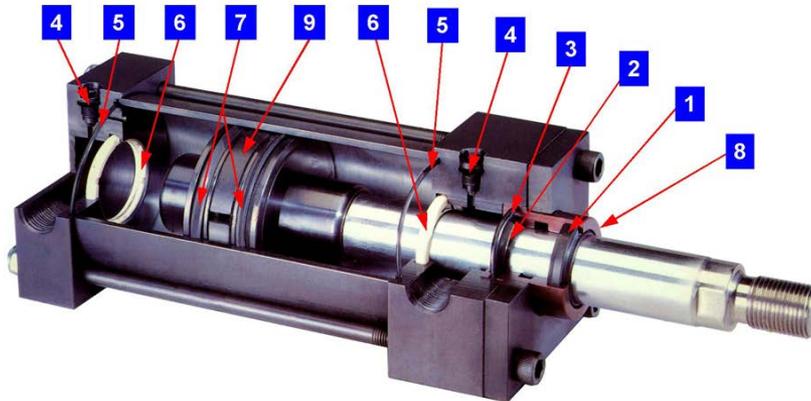
Low-noise operation, robust construction and high durability for high performance

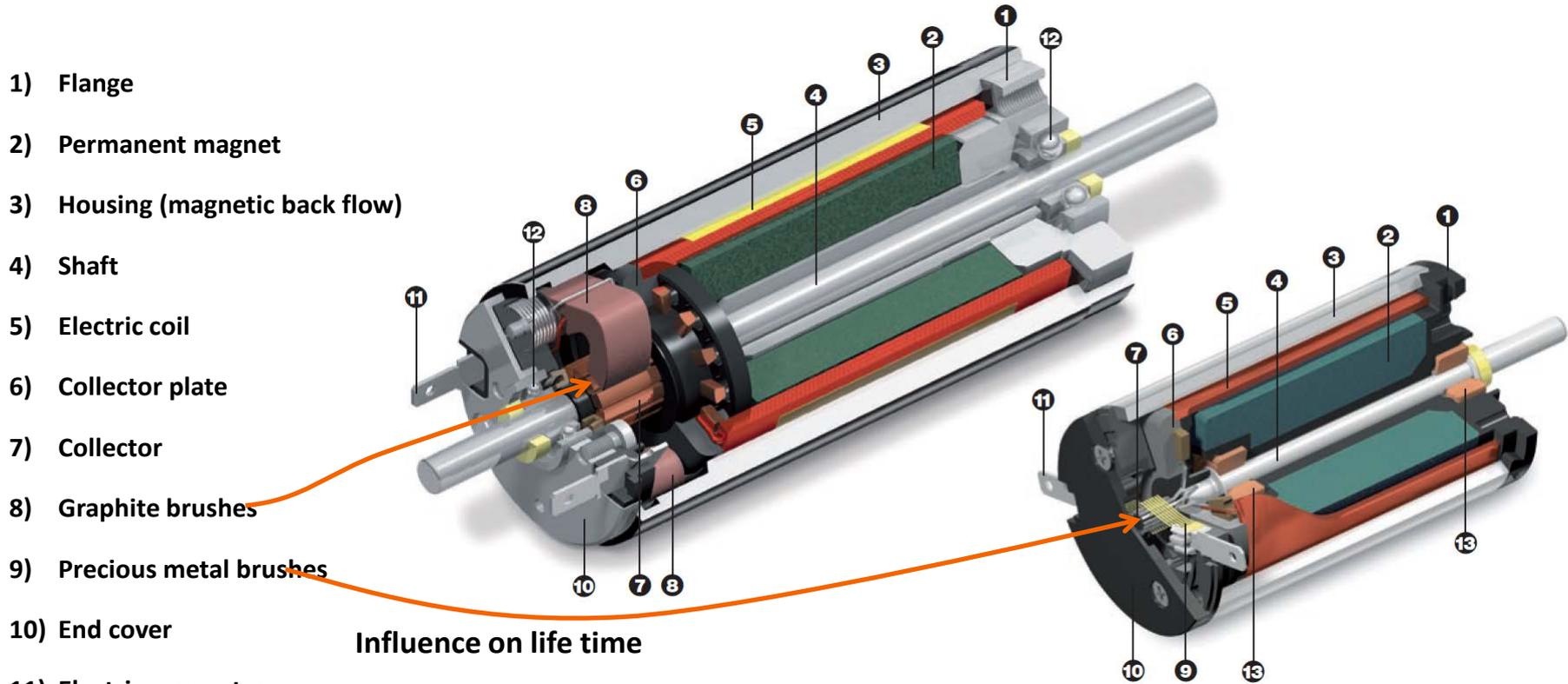
Mechanical commutation leads to rough performance and high wear with limited life time

▶ 1 Drive Systems



- ▶ 1.1 Rotational Electrical Drives
- 1.2 Linear Electrical Drives
- 1.3 Linear Pneumatic Drives





- 1) Flange
- 2) Permanent magnet
- 3) Housing (magnetic back flow)
- 4) Shaft
- 5) Electric coil
- 6) Collector plate
- 7) Collector
- 8) Graphite brushes
- 9) Precious metal brushes
- 10) End cover
- 11) Electric connectors
- 12) Ball bearings
- 13) Sintered journal bearings

Influence on life time

- Electric loading
- RPM
- Operation mode
- Environmental influence
- Brush design

Graphite brushes

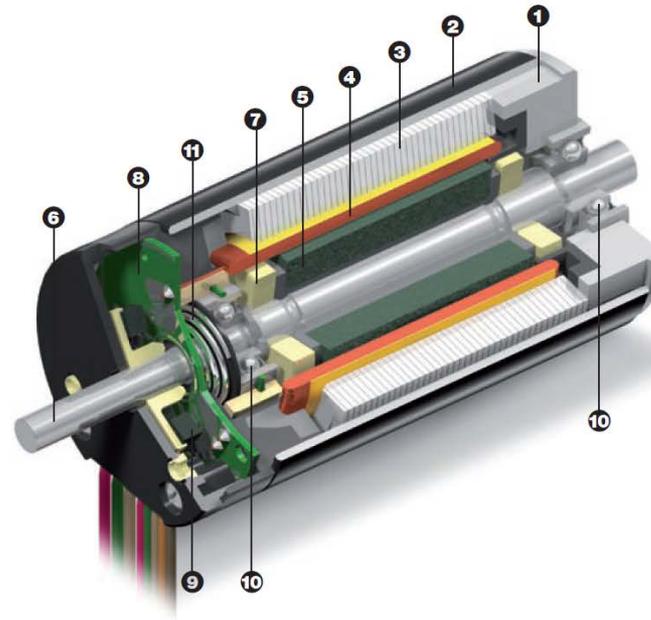
- In large Motors
- For high current loads
- For Start-Stop-operation
- For reverse operation

Precious metal brushes

- In smaller Motors
- For low current loads
- For continuous operation
- For battery operation

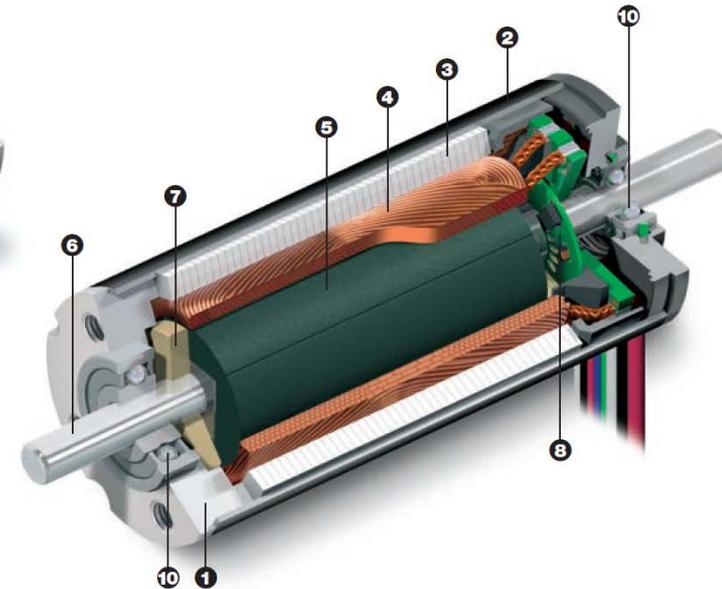
Source: maxon motor, Sachseln, OW, CH

- 1) Flange
- 2) Housing
- 3) Stator
- 4) Electric coil
- 5) Permanent magnet
- 6) Shaft
- 7) Balancing disks
- 8) Print with hall-sensors
- 9) Control magnet
- 10) Pre-stressed ball bearings
- 11) Pre-stressing spring



Block commutation with Hall sensors

- Relatively simple and cost efficient electronics
- Torque ripples
- Controlled start-up
- High start-up torque and accelerations even for Start-Stop
- For high dynamic servo drives



Sine commutation

- More expensive electronics
- No torque ripples
- Very smooth RPM characteristics
- Higher continuous torque then for block commutation

Sensorless block commutation

- Torque ripples
- No defined start-up
- Not suitable for low RPM
- Especially for continuous operation with higher RPM

Source: maxon motor, Sachseln, OW, CH

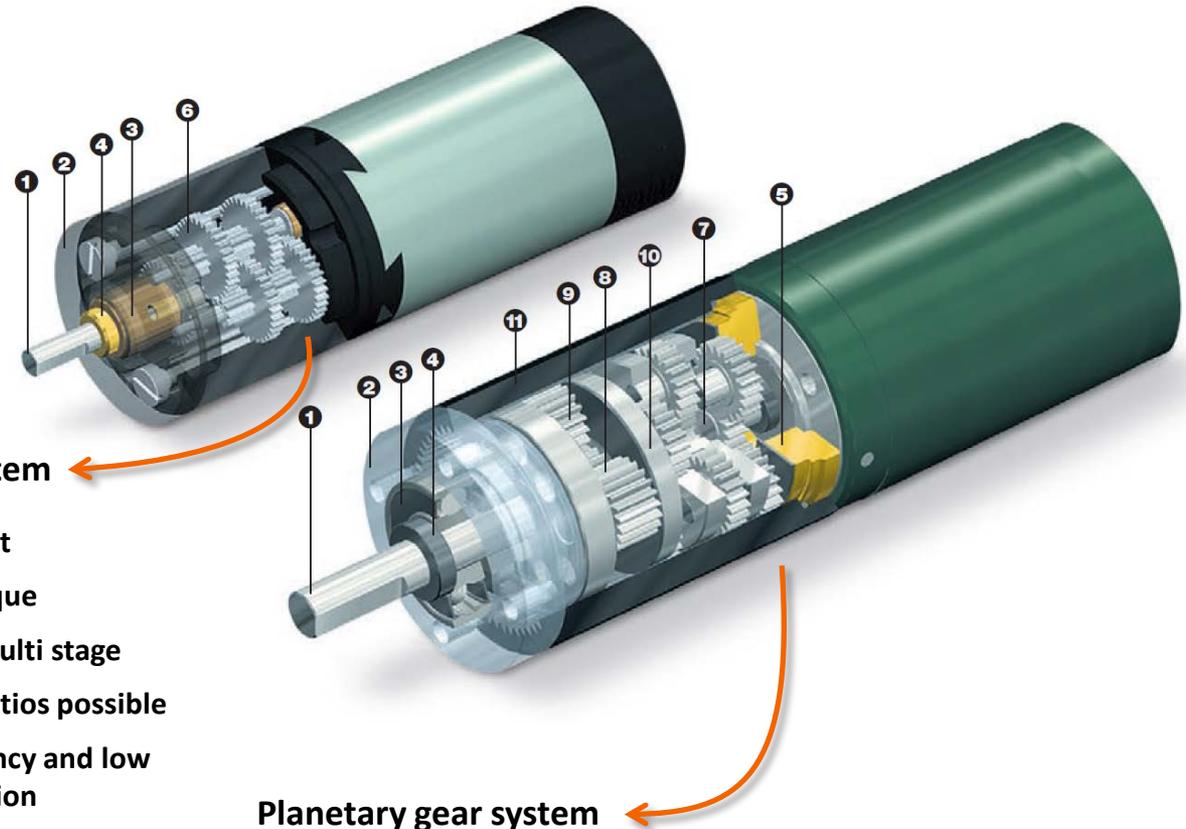
- 1) Output shaft
- 2) Mounting flange
- 3) Shaft bearing
- 4) Axial bearing
- 5) Gear-motor connection plate
- 6) Gears
- 7) Pinion
- 8) Planetary gears
- 9) Sun gear
- 10) Planetary carrier
- 11) Annulus gear

Spur-gear system

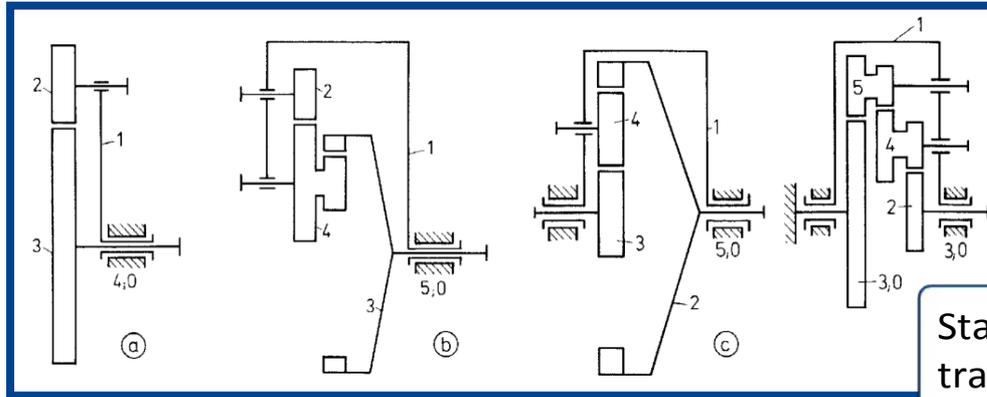
- cost efficient
- For low torque
- Two oder multi stage
- High gear ratios possible
- High efficiency and low noise emission

Planetary gear system

- For high torque
- High power density
- Two oder multi stage
- High gear ratios with low space requirements
- For high dynamic servo drives



Source: maxon motor, Sachseln, OW, CH



Stationary transmission ratio:

$$i_0 = i_{31/21} = \frac{\omega_{31}}{\omega_{21}}$$

Angular velocity of orbital gear 2:

$$\omega_{20z} = \omega_{10z} + \omega_{21z} \Rightarrow \omega_{21z} = \omega_{20z} - \omega_{10z}$$

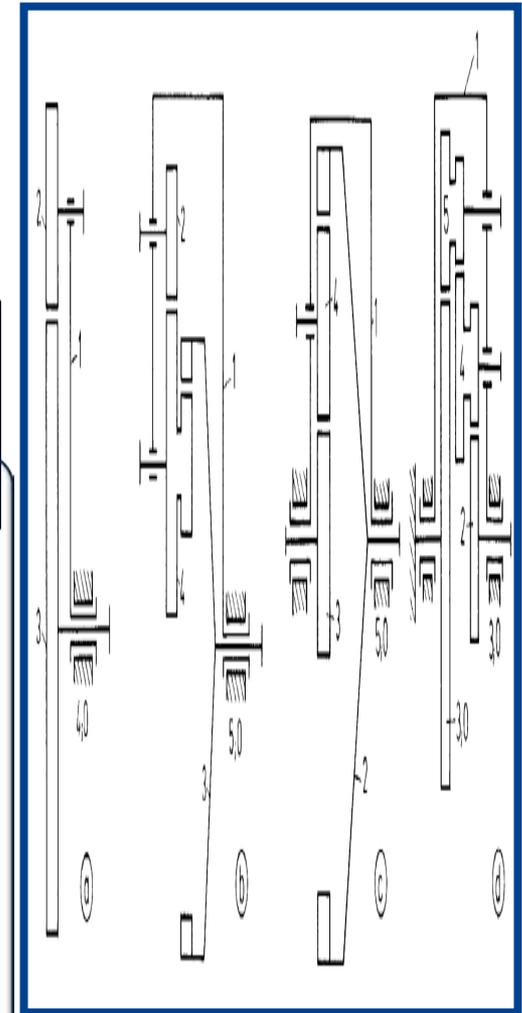
Angular velocity of sun gear 3:

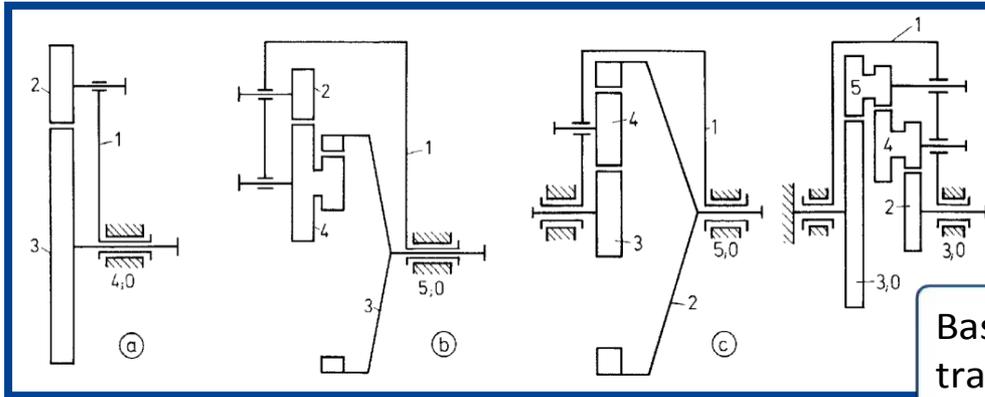
$$\omega_{30z} = \omega_{10z} + \omega_{31z}$$

With the base transmission ratio $i_{31/21}$ and thus $\omega_{31z} = i_{31/21} \cdot \omega_{21z}$

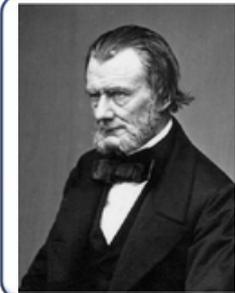
the **Basic Equation** according to **Willis** can be derived:

$$\omega_{30z} = \omega_{10z} + i_{31/21}(\omega_{20z} - \omega_{10z}) \text{ resp. } \omega_{30z} = i_{31/21}\omega_{20z} + (1 - i_{31/21})\omega_{10z}$$





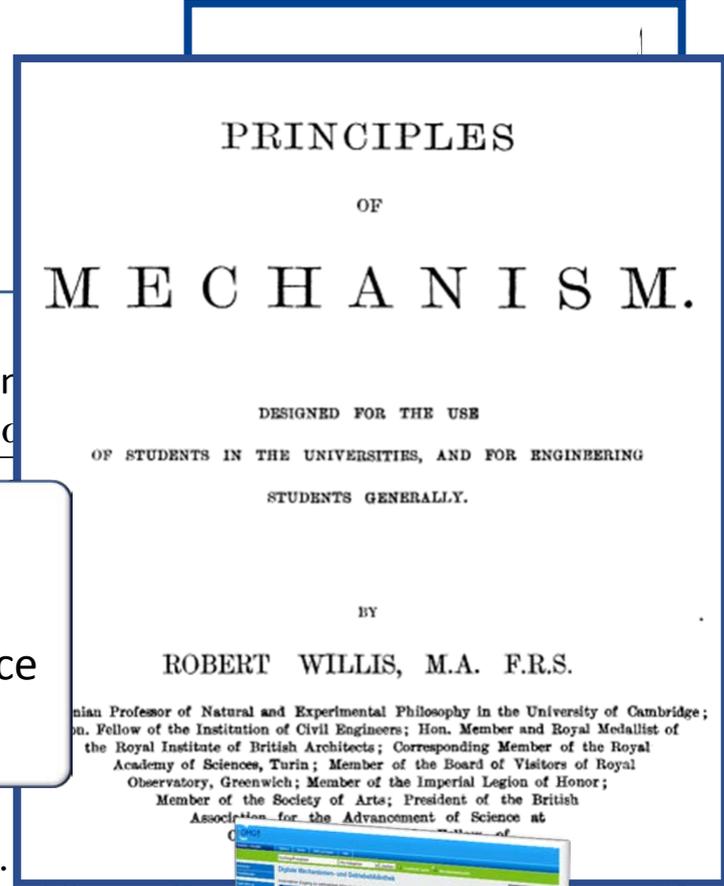
Base transmission ratio
 $i_0 = i_{31/21} = \dots$



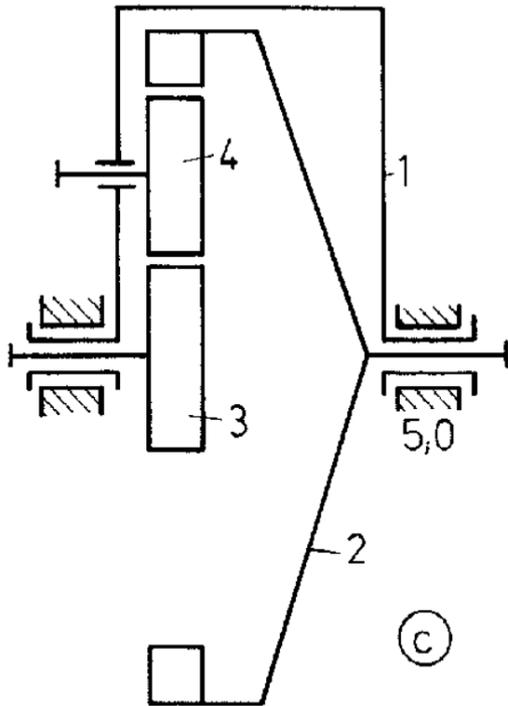
Robert Willis (1800 - 1875)
 English mathematician and architect,
 Professor of natural- und experimental science
 at Cambridge University

With the base transmission ratio $i_{31/21}$ and thus $\omega_{31z} = i_{31/21} \cdot \omega_{21z}$
 the **Basic Equation** according to **Willis** can be derived:

$$\omega_{30z} = \omega_{10z} + i_{31/21}(\omega_{20z} - \omega_{10z}) \text{ resp. } \omega_{30z} = i_{31/21}\omega_{20z} + (1 - i_{31/21})\omega_{10z}$$



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Basic equation according to Willis

$$\omega_{30z} = i_{31/21}\omega_{20z} + (1 - i_{31/21})\omega_{10z} \quad \text{with } i_{31/21} = \frac{r_2}{r_3} < -1$$

| In-put | Out-put | grounded | Willis | Transmission ratio |
|--------|---------|----------|---|--|
| 3 | 2 | 1 | $\omega_{30z} = i_{31/21}\omega_{20z}$ | $i = \frac{1}{i_{31/21}}$ |
| 3 | 1 | 2 | $\omega_{30z} = (1 - i_{31/21})\omega_{10z}$ | $i = \frac{1}{1 - i_{31/21}}$ |
| 2 | 3 | 1 | $\omega_{30z} = i_{31/21}\omega_{20z}$ | $i = i_{31/21}$ |
| 2 | 1 | 3 | $0 = i_{31/21}\omega_{20z} + (1 - i_{31/21})\omega_{10z}$ | $i = \frac{-i_{31/21}}{1 - i_{31/21}}$ |
| 1 | 3 | 2 | $\omega_{30z} = (1 - i_{31/21})\omega_{10z}$ | $i = 1 - i_{31/21}$ |
| 1 | 2 | 3 | $0 = i_{31/21}\omega_{20z} + (1 - i_{31/21})\omega_{10z}$ | $i = \frac{1 - i_{31/21}}{-i_{31/21}}$ |

Frühere Ausgaben: 08.78, 01.10 Entwurf, deutsch
 Former editions: 08/78, 01/10 Draft, in German only

| | | | | | |
|---|--------------|--|-------------|--|--|
| ICS 01.040.21, 21.200 | | VDI-RICHTLINIEN | | Oktober 2012 October 2012 | |
| VEREIN DEUTSCHER INGENIEURE | | Planetengetriebe Begriffe, Symbole, Berechnungsgrundlagen Planetary gear drives Definitions, symbols, designs, calculations | | VDI 2157 Ausg. deutsch/englisch Issue German/English | |
| Die deutsche Version dieser Richtlinie ist verbindlich. | | The German version of this guideline shall be taken as authoritative. No guarantee can be given with respect to the English translation. | | | |
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| 2 Normative Verweise | 3 | 2 Normative references | 3 | | |
| 3 Begriffe | 3 | 3 Terms and definitions | 3 | | |
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| 3.2 Besondere Begriffe bei Planetengetrieben | 6 | 3.2 Special terms and definitions used with planetary transmissions | 6 | | |
| 4 Formelzeichen, Abkürzungen und Indizes | 8 | 4 Symbols, abbreviations and indices | 8 | | |
| 5 Berechnungsgrundlagen | 11 | 5 Basic principles of calculations | 11 | | |
| 5.1 Standgetriebe | 11 | 5.1 Stationary transmission | 11 | | |
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| VDI-Handbuch Getriebetechnik II: Gleichförmig übersetzte Getriebe | | | | | |

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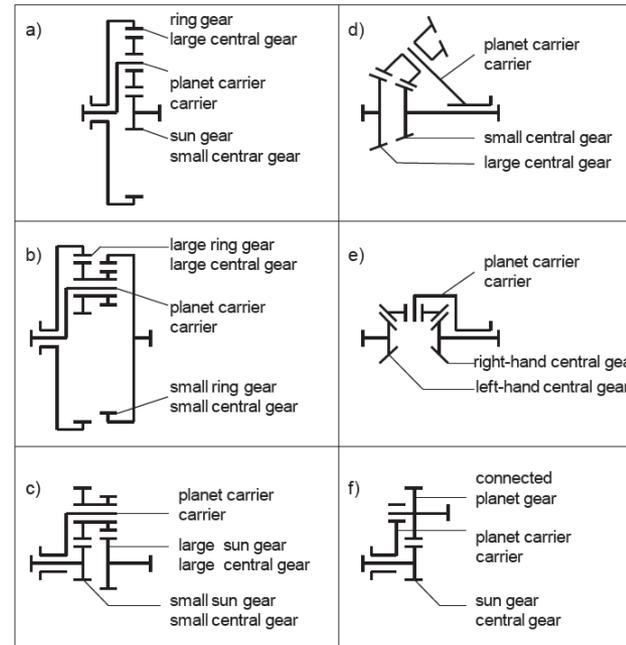


Figure 1. Designations of the externally connected gears and carrier

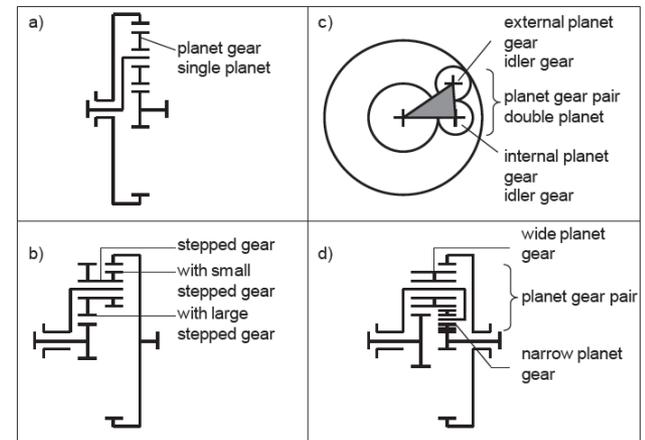
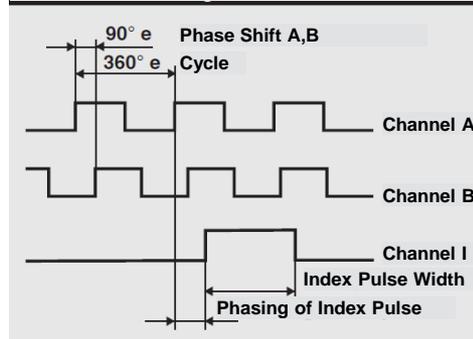


Figure 2. Designations of the planet gears

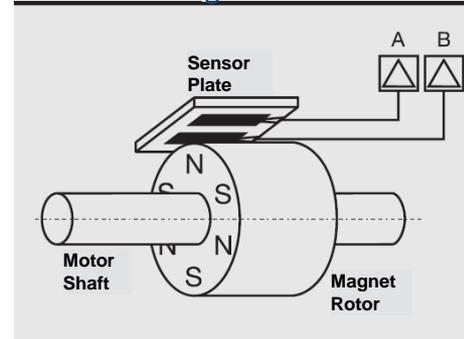
Digital incremental encoder

- Relative position signal
- Rotation direction detection
- Standard solution for many applications

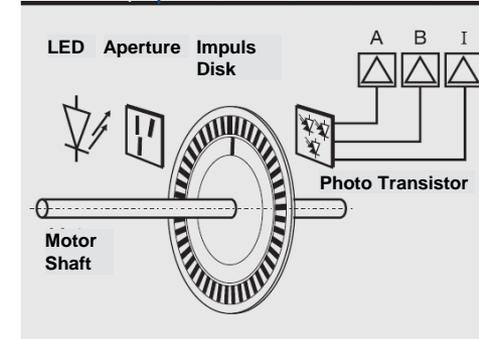
Output signals of a digital encoder



Schematic design of a magnetic encoder



Schematic design of an opto-electronic encoder



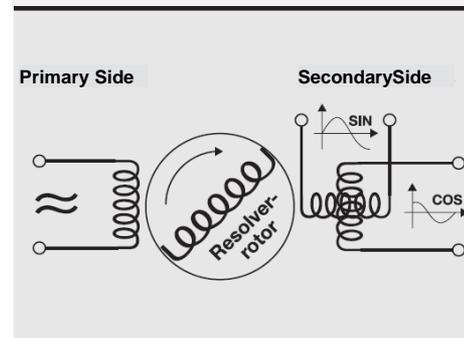
DC Tacho

- Analog RPM-signal
- Rotation direction detection
- Unsuitable for positioning demands

Resolver

- Analog rotor position signal
- Analog RPM signal
- Complex evaluation electronics required
- Special solution for EC-motors

Schematic design of a resolver



Source: maxon motor, Sachseln, OW, CH

Power balance

$$P_{el} = P_{mech} + P_{loss} \Rightarrow P_{mech} = P_{el} - P_{loss}$$

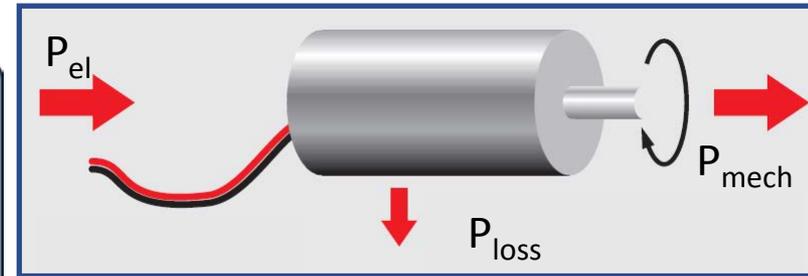
Elektrical Power: $P_{el} = U \cdot I$

Mechanical Power: $P_{mech} = \omega \cdot M = 2\pi \cdot n \cdot M$

Power Loss $P_{loss} = P_{loss,el} + P_{loss,mech}$

Elektrical Power Loss $P_{loss,el} = U_{ind} \cdot I_0^2$

Mechanical Power Loss $P_{loss,mech} = \omega \cdot M_R = \omega \cdot k_M \cdot I_0$



Elektromechanical Parameters

Idle current $I_0 [A]$

Torque constant $k_M \left[\frac{Nm}{A} \right]$

This constant allows to calculate the torque for a given current value

$$M_R = k_M \cdot I$$

RPM constant: $k_n \left[\frac{1/min}{V} \right]$

This constant allows to calculate the induced, field weakening voltage for a given RPM value

$$U_{ind} = \frac{1}{k_n} \cdot n$$

Motordata

| Values for nominal voltage | | | | | | |
|----------------------------|--|-------------------------------------|-------|-------|-------|------|
| 1 | nominal Voltage | V | 48.0 | 48.0 | 48.0 | 48.0 |
| 2 | idle RPM | min ⁻¹ | 10100 | 7240 | 4720 | 3610 |
| 3 | idle current | mA | 348 | 202 | 105 | 71.4 |
| 4 | nominal RPM | min ⁻¹ | 9280 | 6290 | 3770 | 2670 |
| 5 | nominal torque (max. permanent torque) | mNm | 164 | 183 | 203 | 212 |
| 6 | nominal current (max. permanent current) | A | 3.95 | 3.08 | 2.19 | 1.74 |
| 7 | stall torque | mNm | 2090 | 1490 | 1050 | 838 |
| 8 | start current | A | 46.7 | 23.7 | 10.9 | 6.68 |
| 9 | max. efficiency | % | 84 | 83 | 82 | 81 |
| Motor characteristics | | | | | | |
| 10 | Phase to phase resistance | Ω | 1.03 | 2.02 | 4.40 | 7.19 |
| 11 | Phase to phase inductivity | mH | 0.204 | 0.400 | 0.937 | 1.60 |
| 12 | Torque constant | mNm A ⁻¹ | 44.8 | 62.8 | 96.1 | 126 |
| 13 | RPM constant | min ⁻¹ V ⁻¹ | 213 | 152 | 99.4 | 76.1 |
| 14 | Characteristic gradient | min ⁻¹ mNm ⁻¹ | 4.89 | 4.90 | 4.55 | 4.35 |
| 15 | Mechanical Time Constant | ms | 5.17 | 5.19 | 4.81 | 4.61 |
| 16 | Rotor inertia | gcm ² | 101 | 101 | 101 | 101 |

Quelle: maxon motor, Sachseln, OW, CH

Parameters and formulas

Elektrical Power:

$$P_{el} = U \cdot I = P_{mech} + P_{loss}$$

Mechanical Power:

$$P_{mech} = \omega \cdot T = 2\pi \cdot n \cdot T$$

Elektrical Power Loss

$$P_{loss,el} = U_{ind} \cdot I_0^2$$

Mechanical Power Loss

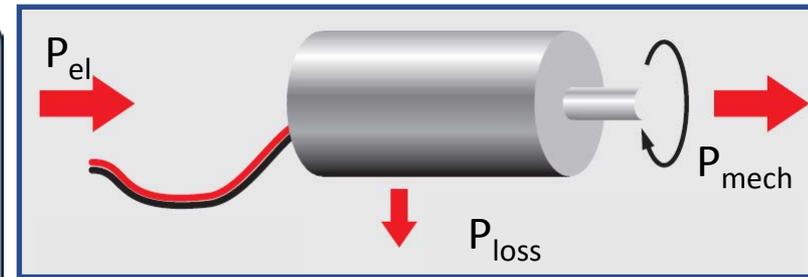
$$P_{loss,mech} = \omega \cdot T_R = \omega \cdot k_M \cdot I_0$$

Shaft Torque

$$T = k_M \cdot I$$

Induced Voltage

$$U_{ind} = \frac{1}{k_n} \cdot n = k_\omega \cdot \omega$$



Idle RPM

$$n = 10100 \cdot \frac{1}{\text{min}}$$

RPM constant:

$$k_n = 213 \cdot \frac{1/\text{min}}{\text{V}}$$

Ind. Voltage

$$U_{ind} = \frac{10100}{213} \cdot \text{V} = 47.4 \cdot \text{V}$$

Torque constant:

$$k_M = 44.8 \cdot \frac{\text{mNm}}{\text{A}}$$

Idle current

$$I_0 = 0.348 \cdot \text{A}$$

Torque loss

$$T_R = k_M \cdot I_0 = 15,59 \cdot \text{mNm}$$

Power loss

$$P_{loss,mech} = 16,5 \cdot \text{W}$$

Motordata

| Values for nominal voltage | | | | | | |
|----------------------------|--|-------------------------------------|-------|-------|-------|------|
| 1 | nominal Voltage | V | 48.0 | 48.0 | 48.0 | 48.0 |
| 2 | idle RPM | min ⁻¹ | 10100 | 7240 | 4720 | 3610 |
| 3 | idle current | mA | 348 | 202 | 105 | 71.4 |
| 4 | nominal RPM | min ⁻¹ | 9280 | 6290 | 3770 | 2670 |
| 5 | nominal torque (max. permanent torque) | mNm | 164 | 183 | 203 | 212 |
| 6 | nominal current (max. permanent current) | A | 3.95 | 3.08 | 2.19 | 1.74 |
| 7 | stall torque | mNm | 2090 | 1490 | 1050 | 838 |
| 8 | start current | A | 46.7 | 23.7 | 10.9 | 6.68 |
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| 14 | Characteristic gradient | min ⁻¹ mNm ⁻¹ | 4.89 | 4.90 | 4.55 | 4.35 |
| 15 | Mechanical Time Constant | ms | 5.17 | 5.19 | 4.81 | 4.61 |
| 16 | Rotor inertia | gcm ² | 101 | 101 | 101 | 101 |

Quelle: maxon motor, Sachseln, OW, CH

Parameters and formulas

Elektrical Power: $P_{el} = U \cdot I = P_{mech} + P_{loss}$

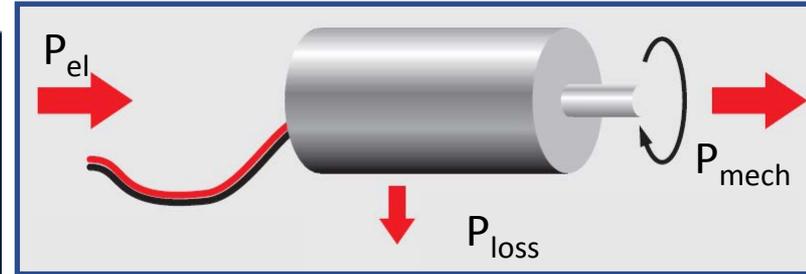
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Elektrical Power Loss $P_{loss,el} = U_{ind} \cdot I_0^2$

Mechanical Power Loss $P_{loss,mech} = \omega \cdot T_R = \omega \cdot k_M \cdot I_0$

Shaft Torque $T = k_M \cdot I$

Induced Voltage $U_{ind} = \frac{1}{k_n} \cdot n$



Idle current $I_0 = 0.348 \cdot A$

Torque constant: $k_M = 44.8 \cdot \frac{mNm}{A}$

Power loss $P_{loss,mech} = 16.5 \cdot W$

Ind. Voltage $U_{ind} = 47.4 \cdot V$

Electrical power loss: $P_{loss,el} = 16.5 \cdot W$

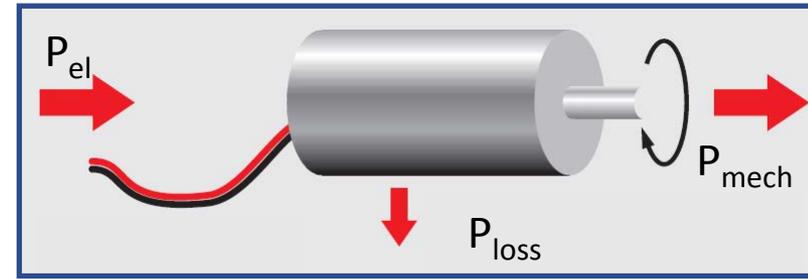
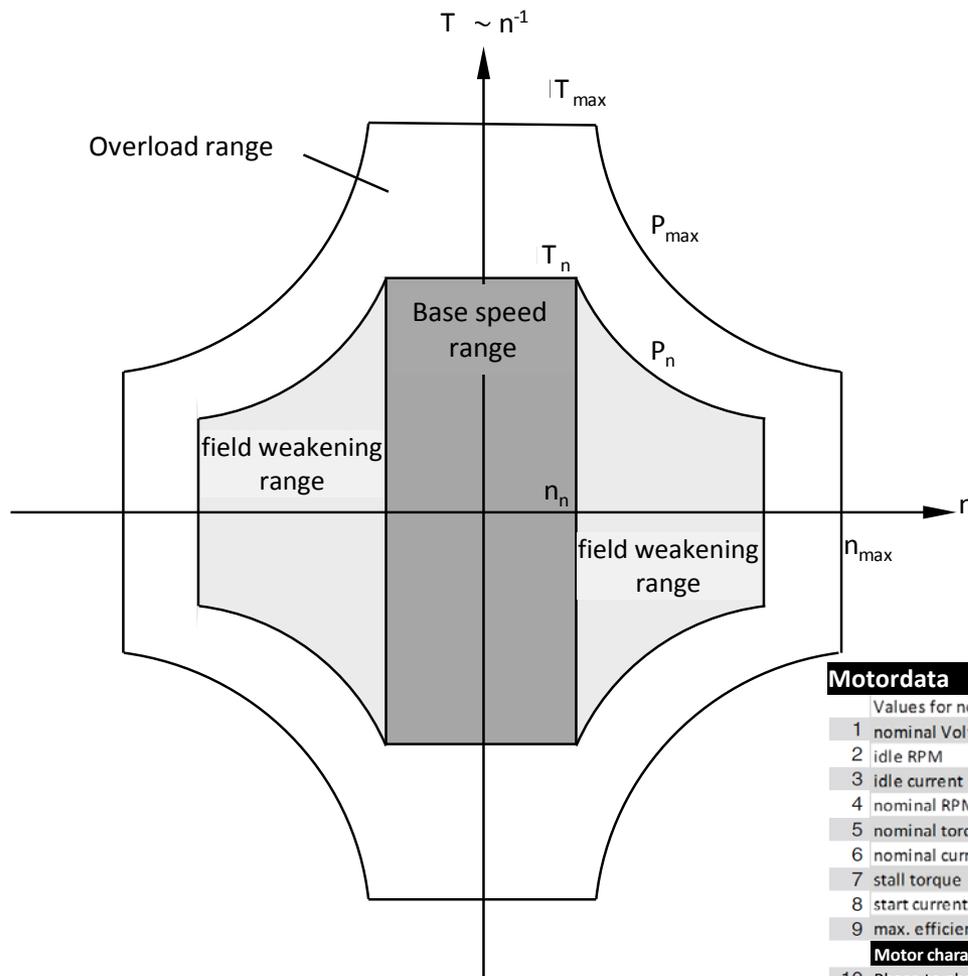
Nom. el. Power. $P_{el} = U_{nom} \cdot I_{nom} = 189.6 \cdot W$

Efficiency $\eta = \frac{P_{el} - P_{loss}}{P_{el}}$

$$\eta = \frac{189.6 - (16.5 + 16.5)}{189.6} = 0.826$$

| Motordata | | | | | | |
|----------------------------|--|-------------------------------------|-------|-------|-------|------|
| Values for nominal voltage | | | | | | |
| 1 | nominal Voltage | V | 48.0 | 48.0 | 48.0 | 48.0 |
| 2 | idle RPM | min ⁻¹ | 10100 | 7240 | 4720 | 3610 |
| 3 | idle current | mA | 348 | 202 | 105 | 71.4 |
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| 10 | Phase to phase resistance | Ω | 1.03 | 2.02 | 4.40 | 7.19 |
| 11 | Phase to phase inductivity | mH | 0.204 | 0.400 | 0.937 | 1.60 |
| 12 | Torque constant | mNm A ⁻¹ | 44.8 | 62.8 | 96.1 | 126 |
| 13 | RPM constant | min ⁻¹ V ⁻¹ | 213 | 152 | 99.4 | 76.1 |
| 14 | Characteristic gradient | min ⁻¹ mNm ⁻¹ | 4.89 | 4.90 | 4.55 | 4.35 |
| 15 | Mechanical Time Constant | ms | 5.17 | 5.19 | 4.81 | 4.61 |
| 16 | Rotor inertia | gcm ² | 101 | 101 | 101 | 101 |

Quelle: maxon motor, Sachseln, OW, CH



Motordata

| Values for nominal voltage | | | | | | |
|----------------------------|--|-------------------------------------|-------|-------|-------|------|
| 1 | nominal Voltage | V | 48.0 | 48.0 | 48.0 | 48.0 |
| 2 | idle RPM | min ⁻¹ | 10100 | 7240 | 4720 | 3610 |
| 3 | idle current | mA | 348 | 202 | 105 | 71.4 |
| 4 | nominal RPM | min ⁻¹ | 9280 | 6290 | 3770 | 2670 |
| 5 | nominal torque (max. permanent torque) | mNm | 164 | 183 | 203 | 212 |
| 6 | nominal current (max. permanent current) | A | 3.95 | 3.08 | 2.19 | 1.74 |
| 7 | stall torque | mNm | 2090 | 1490 | 1050 | 838 |
| 8 | start current | A | 46.7 | 23.7 | 10.9 | 6.68 |
| 9 | max. efficiency | % | 84 | 83 | 82 | 81 |
| Motor characteristics | | | | | | |
| 10 | Phase to phase resistance | Ω | 1.03 | 2.02 | 4.40 | 7.19 |
| 11 | Phase to phase inductivity | mH | 0.204 | 0.400 | 0.937 | 1.60 |
| 12 | Torque constant | mNm A ⁻¹ | 44.8 | 62.8 | 96.1 | 126 |
| 13 | RPM constant | min ⁻¹ V ⁻¹ | 213 | 152 | 99.4 | 76.1 |
| 14 | Characteristic gradient | min ⁻¹ mNm ⁻¹ | 4.89 | 4.90 | 4.55 | 4.35 |
| 15 | Mechanical Time Constant | ms | 5.17 | 5.19 | 4.81 | 4.61 |
| 16 | Rotor inertia | gcm ² | 101 | 101 | 101 | 101 |

Source: maxon motor, Sachseln, OW, CH

Motor start with constant current under consideration of induced voltage and with linear load inertia:

conservation of angular momentum:

$$J_{\text{mot}} \ddot{\phi} = k_M \cdot I$$

Static Circuit Consideration

$$I = \frac{U_{\text{start}} - U_{\text{ind}}}{R} \quad \text{with } U_{\text{ind}} = k_{\omega} \cdot \omega$$

Final differential equation

$$\frac{d\omega}{dt} = \frac{k_M \cdot k_{\omega}}{J_{\text{mot}} \cdot R} \cdot \left(\frac{1}{k_{\omega}} \cdot U_{\text{start}} - \omega \right)$$

1st order time lag:

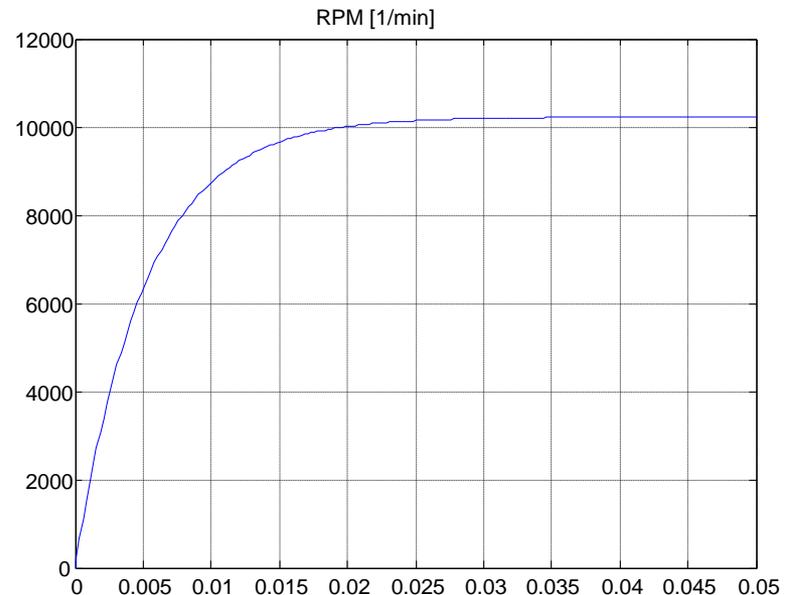
$$\frac{d\omega}{dt} = \frac{1}{T_{\text{mech}}} \cdot \left(\frac{1}{k_{\omega}} \cdot U_{\text{start}} - \omega \right)$$

$$\text{with } T_{\text{mech}} = \frac{J_{\text{mot}} \cdot R}{k_M \cdot k_{\omega}}$$

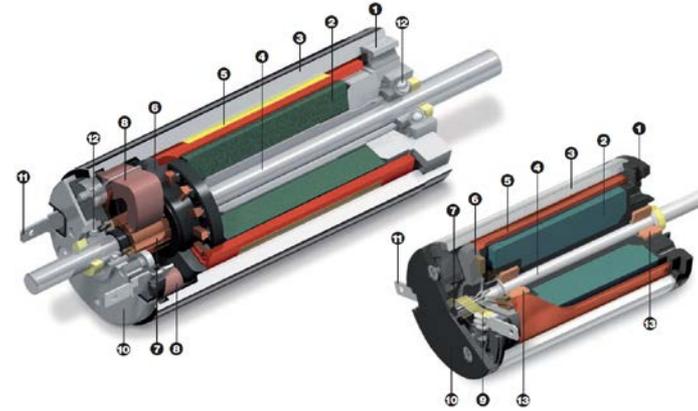
Motordata

| Values for nominal voltage | | | |
|----------------------------|--|-------------------------------------|-------|
| 1 | nominal Voltage | V | 48.0 |
| 2 | idle RPM | min ⁻¹ | 10100 |
| 3 | idle current | mA | 348 |
| 4 | nominal RPM | min ⁻¹ | 9280 |
| 5 | nominal torque (max. permanent torque) | mNm | 164 |
| 6 | nominal current (max. permanent current) | A | 3.95 |
| 7 | stall torque | mNm | 2090 |
| 8 | start current | A | 46.7 |
| 9 | max. efficiency | % | 84 |
| Motor characteristics | | | |
| 10 | Phase to phase resistance | Ω | 1.03 |
| 11 | Phase to phase inductivity | mH | 0.204 |
| 12 | Torque constant | mNm A ⁻¹ | 44.8 |
| 13 | RPM constant | min ⁻¹ V ⁻¹ | 213 |
| 14 | Characteristic gradient | min ⁻¹ mNm ⁻¹ | 4.89 |
| 15 | Mechanical Time Constant | ms | 5.17 |
| 16 | Rotor inertia | gcm ² | 101 |

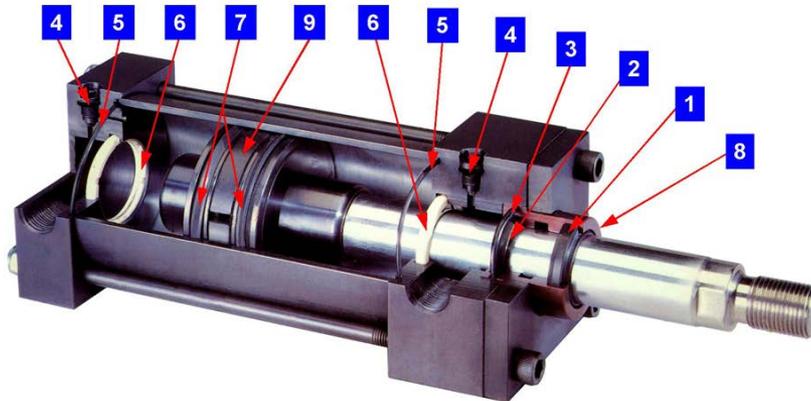
Source: maxon motor, Sachseln, OW, CH



1 Drive Systems



- ▶ 1.1 Rotational Electrical Drives
- ▶ 1.2 Linear Electrical Drives
- 1.3 Linear Pneumatic Drives



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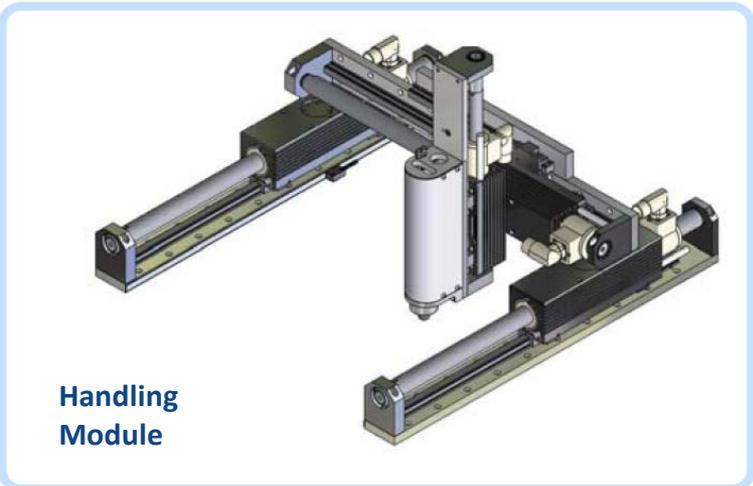


Motors with cable outlet



Motors with connector housing

Source : linmot, Spreitenbach, ZH, CH



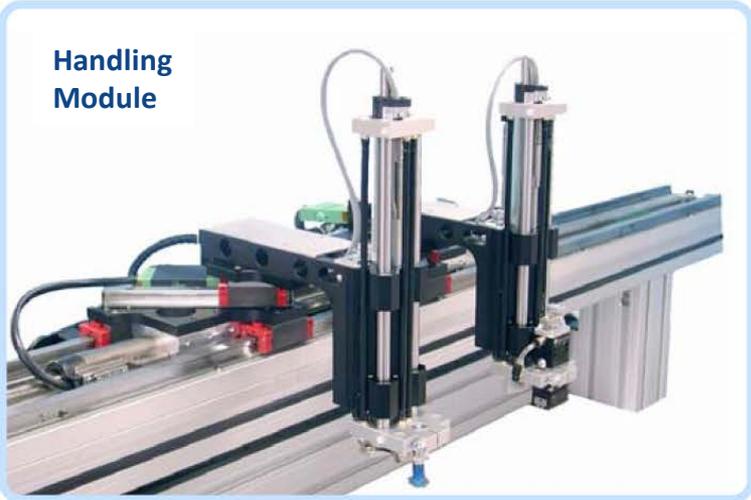
Source: linmot, Spreitenbach, ZH, CH

Packaging Machine



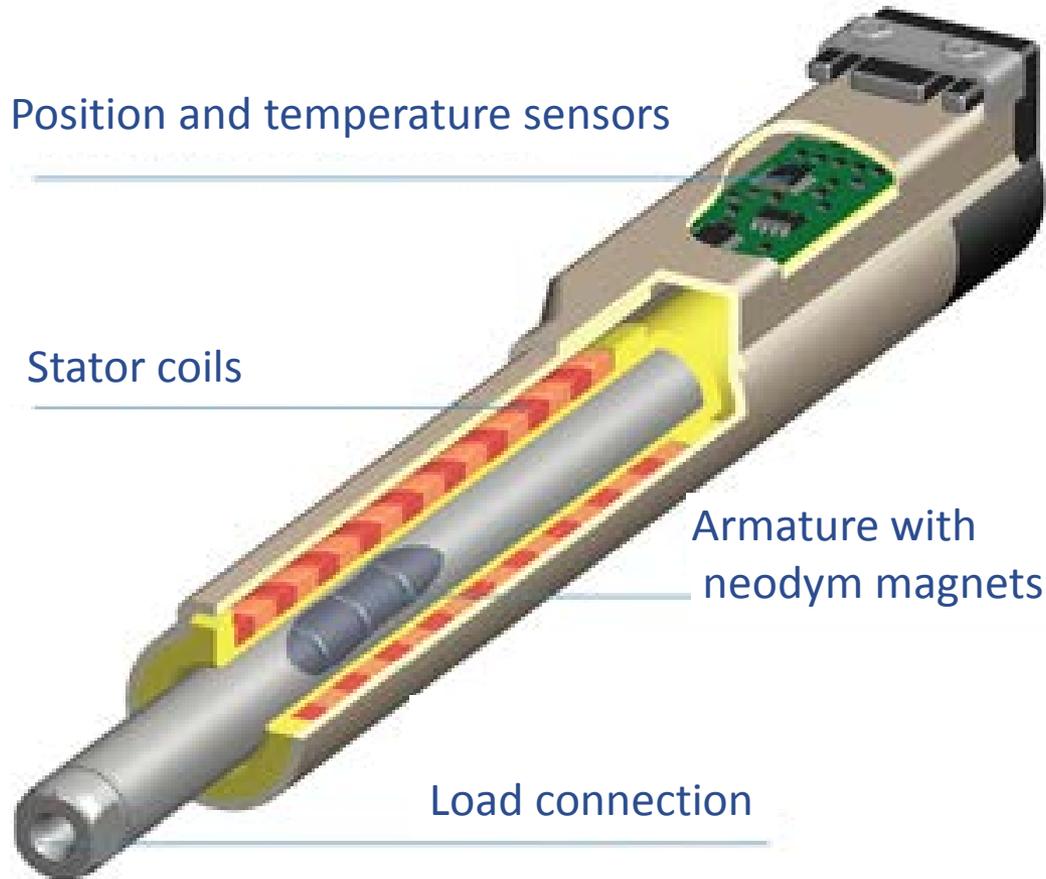
High Speed Palletizer

Handling Module

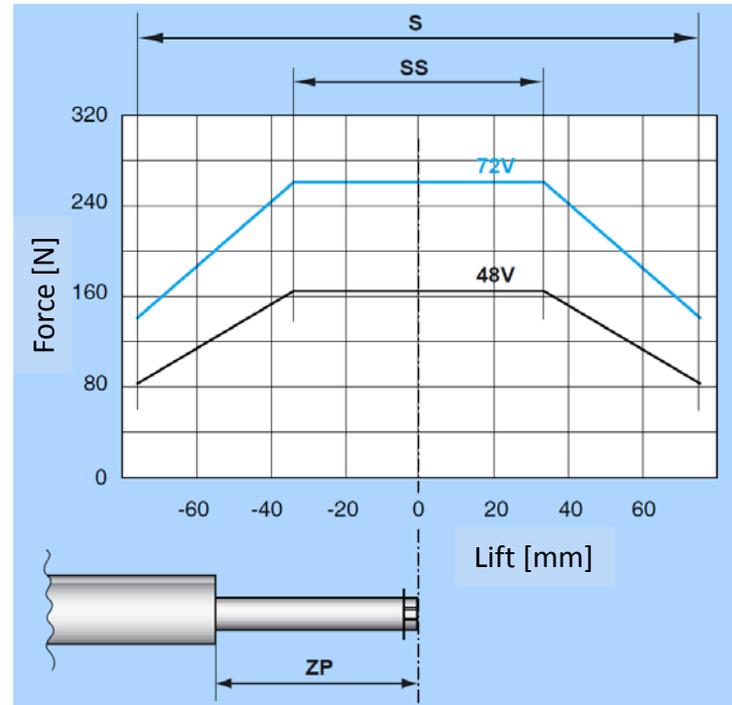


Logistic System

Source: linmot, Spreitenbach, ZH, CH



Characteristic stroke-force curve of a linear motor

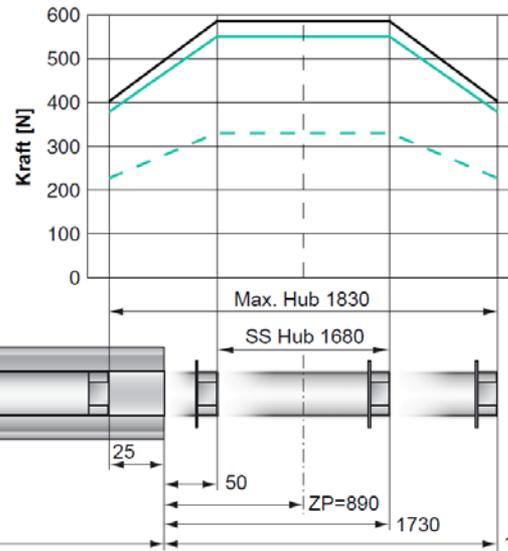


Source: linmot, Spreitenbach, ZH, CH

P01-48x240/1680x1830

LinMot®

Maximum Lift: 1830 mm
Peak Force 585 N

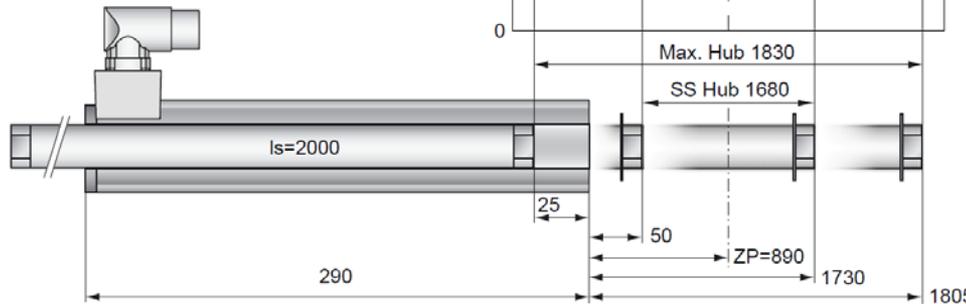


Standard Wicklung:
 — E1100-XC, 72VDC
 — E1100-HC, 72VDC

F - Wicklung
 — E1100-XC, 72VDC
 - - E1100-HC, 72VDC

Motor Specification

| | | Standard Winding |
|-------------------------|-------------|--------------------|
| | | 48x240/1680x1830-C |
| Extended Stroke ES | mm (in) | 1830 (72.05) |
| Standard Stroke SS | mm (in) | 1680 (66.14) |
| Peak Force E1100-XC | N (lbf) | 585 (131.5) |
| Peak Force E1100-HC | N (lbf) | 585 (131.5) |
| Cont. Force | N (lbf) | 145 (32.5) |
| Cont. Force Fan cooling | N (lbf) | 258 (58.0) |
| Border Force | % | 69 |
| Force Constant | N/A (lbf/A) | 39.0 (8.77) |
| Max. Current @ 72VDC | A | 15.0 |
| Max. Current @ 48VDC | A | 12.7 |
| Max. Velocity @ 72VDC | m/s (in/s) | 1.7 (67) |
| Max. Velocity @ 48VDC | m/s (in/s) | 1.1 (45) |
| Phase Resist. 25/80 °C | Ohm | 3.1/3.7 |
| Phase Inductance | mH | 3.1 |
| Thermal Resistance | °K/W | 1.1 |
| Thermal Time Const. | sec | 3000 |
| Stator Diameter | mm (in) | 48 (1.89) |
| Stator Length | mm (in) | 290 (11.40) |
| Stator Mass | g (lb) | 1930 (4.25) |
| Slider Diameter | mm (in) | 28 (1.10) |
| Slider Length | mm (in) | 2000 (78.74) |
| Slider Mass | g (lb) | 9140 (20.15) |
| Position Repeatability | mm (in) | ±0.05 (±0.0020) |
| Linearity | % | ±0.10 |
| Repeatability with EPS | mm (in) | ±0.01 (±0.0004) |
| Linearity with EPS | mm (in) | ±0.01 (±0.0004) |



Abmessungen mm

Electromechanical Motor Constants

Force Constant:

$$k_M \left[\frac{N}{A} \right]$$

Force in lift direction:

$$F = k_M \cdot I$$

Velocity Constant:

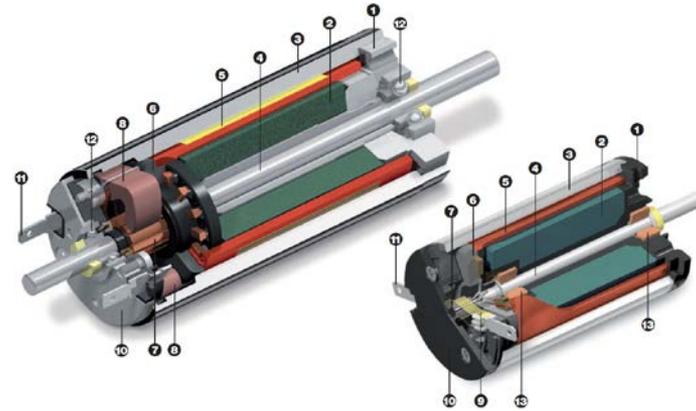
$$k_v \left[\frac{m/s}{V} \right]$$

Induced Voltage:

$$U_{ind} = \frac{1}{k_v} \cdot v$$



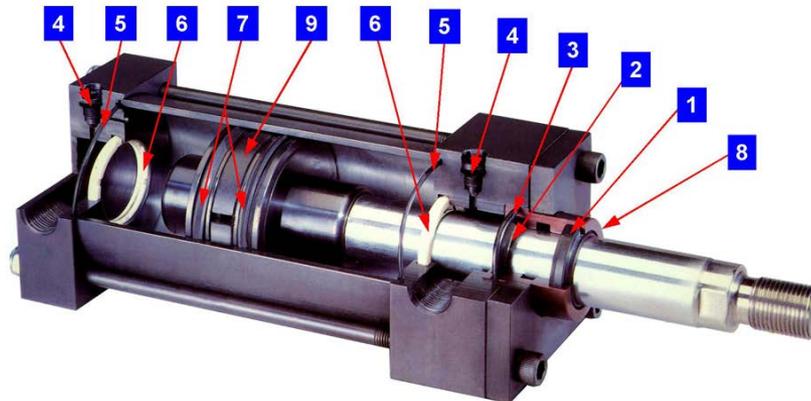
1 Drive Systems



1.1 Rotational Electrical Drives

▶ 1.2 Linear Electrical Drives

▶ 1.3 Linear Pneumatic Drives

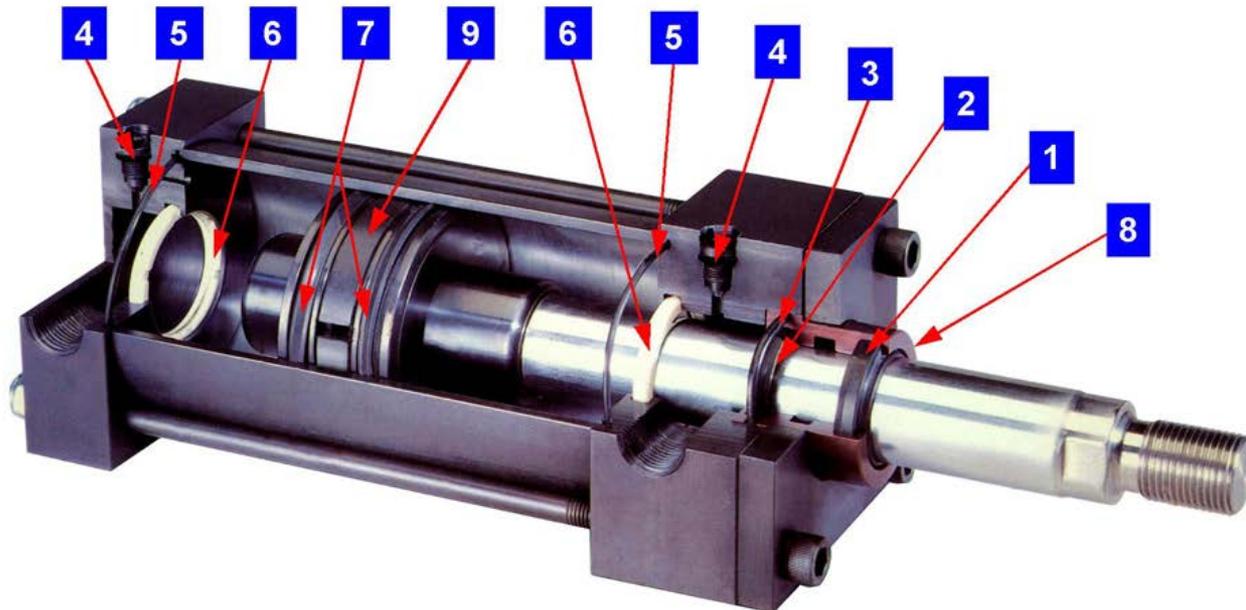


- 1** (1) Rod Wiper Seal
- 2** (1) Rod Seal
- 3** (1) Rod Bearing Cartridge O-Ring Seal
- 4** (2) Cushion Screws / O-Ring Seals
- 5** (2) End Cap to Tube O-Ring Seals
- 6** (2) Cushion Seal Inserts
- 7** (2) Piston U-Cup Seals
- (1) Packet of Lubrication Grease (not shown)

Includes all of the seals, etc. in the "Complete Cylinder Seal" Kit plus:

- 8** (1) Rod Bearing Cartridge
- 9** (1) Piston Wear Band

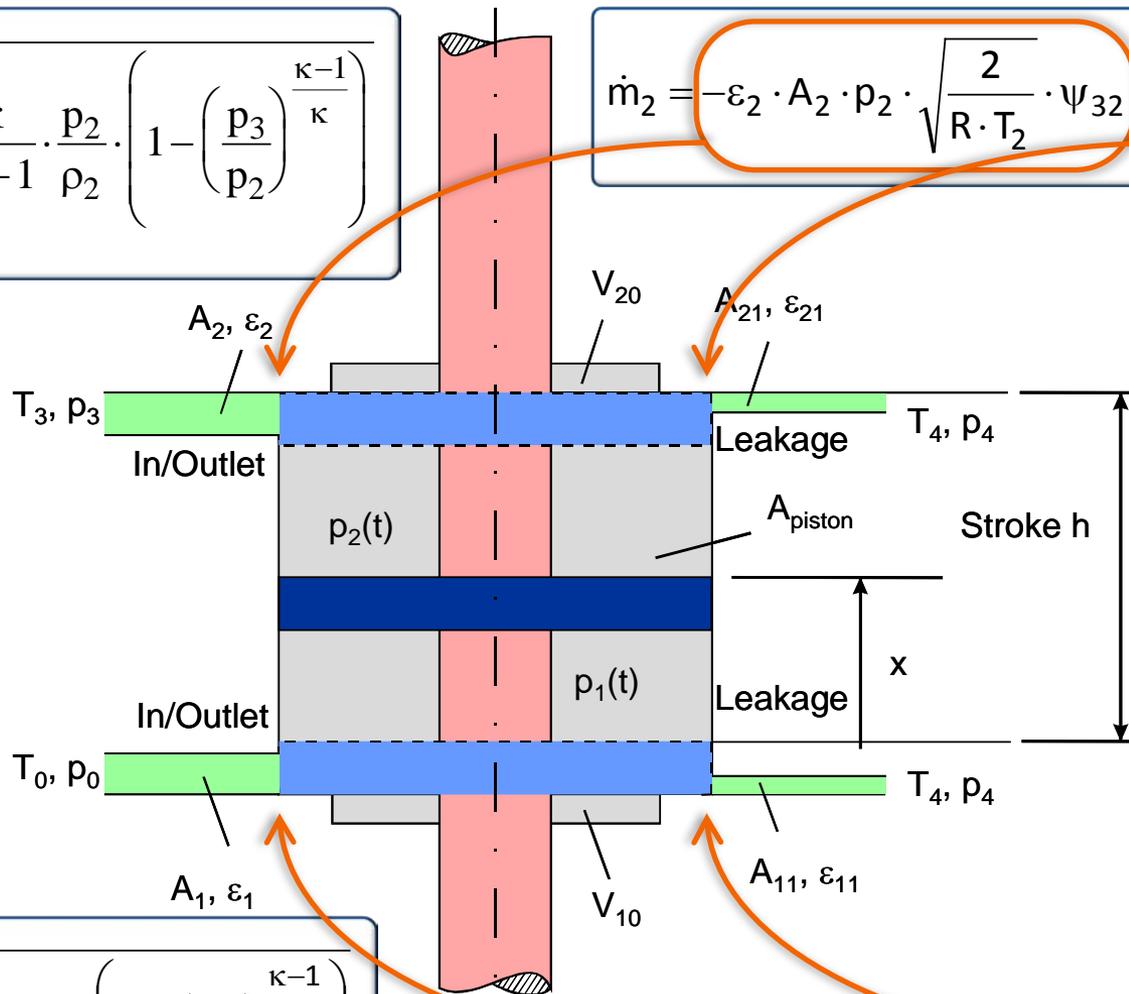
Model MH Cylinder shown:



Source: Peninsular Cylinder Company, Michigan, USA

$$v_2 = \sqrt{2 \cdot \frac{\kappa}{\kappa - 1} \cdot \frac{p_2}{\rho_2} \cdot \left(1 - \left(\frac{p_3}{p_2} \right)^{\frac{\kappa - 1}{\kappa}} \right)}$$

$$\dot{m}_2 = -\varepsilon_2 \cdot A_2 \cdot p_2 \cdot \sqrt{\frac{2}{R \cdot T_2}} \cdot \psi_{32} - \varepsilon_{21} \cdot A_{21} \cdot p_2 \cdot \sqrt{\frac{2}{R \cdot T_2}} \cdot \psi_{42}$$



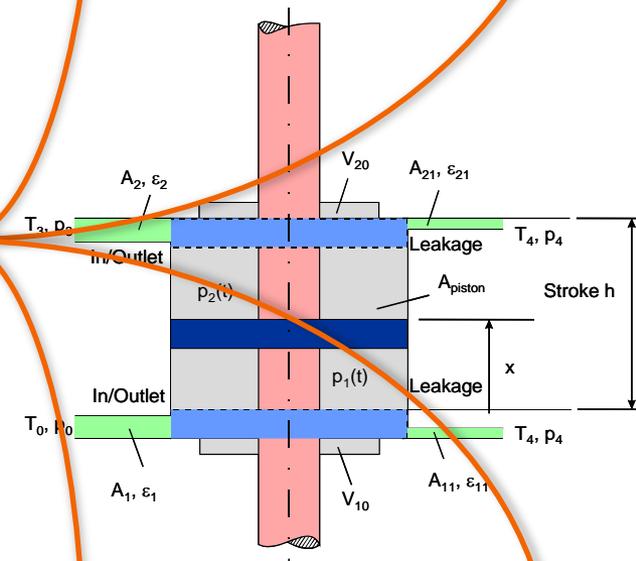
$$v_1 = \sqrt{2 \cdot \frac{\kappa}{\kappa - 1} \cdot \frac{p_0}{\rho_0} \cdot \left(1 - \left(\frac{p_1}{p_0} \right)^{\frac{\kappa - 1}{\kappa}} \right)}$$

$$\dot{m}_1 = \varepsilon_1 \cdot A_1 \cdot p_0 \cdot \sqrt{\frac{2}{R \cdot T_0}} \cdot \psi_{10} - \varepsilon_{11} \cdot A_{11} \cdot p_1 \cdot \sqrt{\frac{2}{R \cdot T_1}} \cdot \psi_{41}$$

$$\dot{m}_2 = -\varepsilon_2 \cdot A_2 \cdot p_2 \cdot \sqrt{\frac{2}{R \cdot T_2}} \cdot \Psi_{32} - \varepsilon_{21} \cdot A_{21} \cdot p_2 \cdot \sqrt{\frac{2}{R \cdot T_2}} \cdot \Psi_{42}$$

$$\Psi_{i,j} = \sqrt{\frac{\kappa}{\kappa-1} \cdot \left(\left(\frac{p_i}{p_j} \right)^{\frac{2}{\kappa}} - \left(\frac{p_i}{p_j} \right)^{\frac{\kappa+1}{\kappa}} \right)} \quad \text{for } \frac{p_i}{p_j} \geq \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}} = \left(\frac{p_i}{p_j} \right)_{\text{krit}}$$

$$\Psi_{i,j} = \sqrt{\frac{\kappa}{\kappa-1} \cdot \left(\left(\frac{2}{\kappa+1} \right)^{\frac{2}{\kappa-1}} - \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa+1}{\kappa-1}} \right)} \quad \text{für } \frac{p_i}{p_j} < \left(\frac{p_i}{p_j} \right)_{\text{krit}}$$



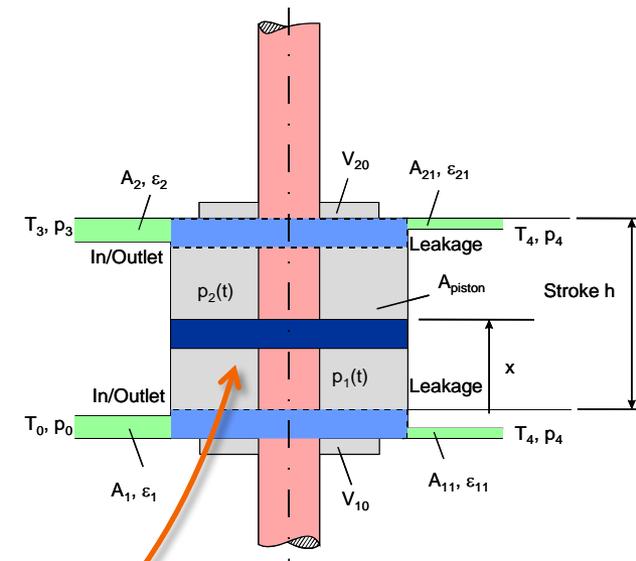
$$\dot{m}_1 = \varepsilon_1 \cdot A_1 \cdot p_0 \cdot \sqrt{\frac{2}{R \cdot T_0}} \cdot \Psi_{10} - \varepsilon_{11} \cdot A_{11} \cdot p_1 \cdot \sqrt{\frac{2}{R \cdot T_1}} \cdot \Psi_{41}$$

$$\dot{m}_1 = \frac{dm_1}{dt} = \frac{d(V_1 \cdot \rho_1)}{dt} = \frac{dV_1}{dt} \cdot \rho_1 + V_1 \cdot \frac{d\rho_1}{dt}$$

$$V_1 = V_{10} + x \cdot A_{\text{piston}}$$

$$\dot{m}_1 = \varepsilon_1 \cdot A_1 \cdot p_0 \cdot \sqrt{\frac{2}{R \cdot T_0}} \cdot \Psi_{10} - \varepsilon_{11} \cdot A_{11} \cdot p_1 \cdot \sqrt{\frac{2}{R \cdot T_1}} \cdot \Psi_{41}$$

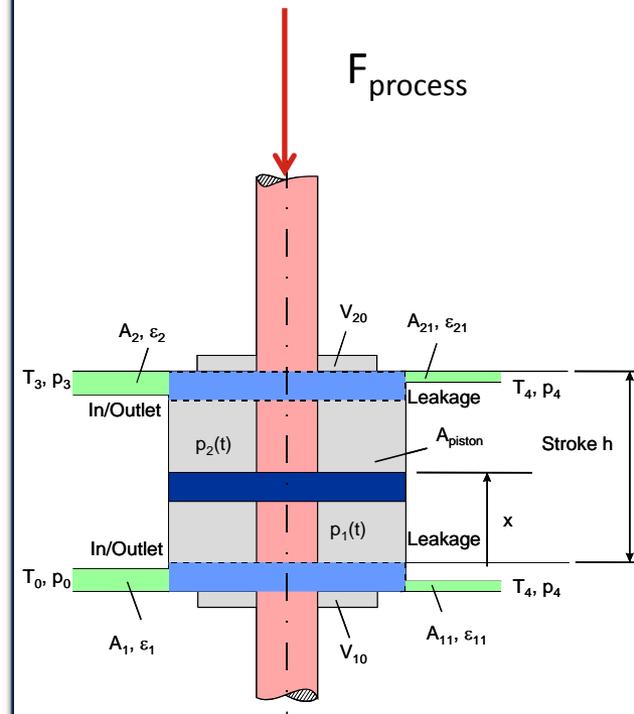
$$\frac{dp_1}{dt} = \frac{n}{V_{10} + x \cdot A_{\text{piston}}} \left[\begin{array}{l} \varepsilon_1 \cdot A_1 \cdot p_0 \cdot \sqrt{2 \cdot R \cdot T_0} \cdot \left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}} \cdot \Psi_{10} \\ - \varepsilon_{11} \cdot A_{11} \cdot p_4 \cdot \sqrt{2 \cdot R \cdot T_4} \cdot \left(\frac{p_1}{p_4}\right)^{\frac{3\kappa-1}{2\kappa}} \cdot \Psi_{41} \\ - \dot{x} \cdot A_{\text{piston}} \cdot p_1 \end{array} \right]$$



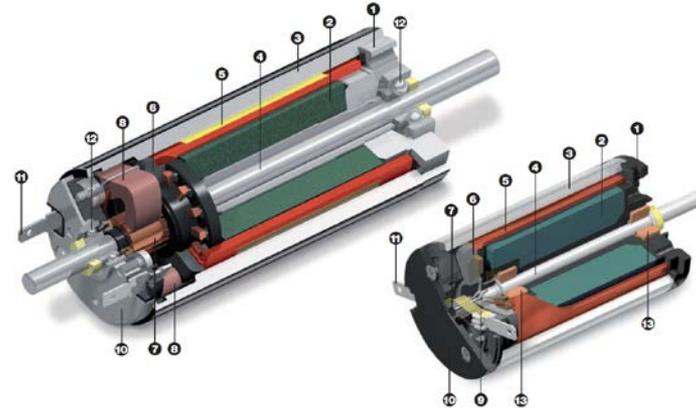
$$\frac{dp_1}{dt} = \frac{n}{V_{10} + x \cdot A_{\text{piston}}} \begin{bmatrix} \varepsilon_1 \cdot A_1 \cdot p_0 \cdot \sqrt{2 \cdot R \cdot T_0} \cdot \left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}} \cdot \psi_{10} \\ - \varepsilon_{11} \cdot A_{11} \cdot p_4 \cdot \sqrt{2 \cdot R \cdot T_4} \cdot \left(\frac{p_1}{p_4}\right)^{\frac{3\kappa-1}{2\kappa}} \cdot \psi_{41} \\ - \dot{x} \cdot A_{\text{piston}} \cdot p_1 \end{bmatrix}$$

$$\frac{dp_2}{dt} = \frac{n}{V_{20} + (h-x) \cdot A_{\text{piston}}} \begin{bmatrix} - \varepsilon_2 \cdot A_2 \cdot p_3 \cdot \sqrt{2 \cdot R \cdot T_3} \cdot \left(\frac{p_2}{p_3}\right)^{\frac{3\kappa-1}{2\kappa}} \cdot \psi_{32} \\ - \varepsilon_{21} \cdot A_{21} \cdot p_4 \cdot \sqrt{2 \cdot R \cdot T_4} \cdot \left(\frac{p_2}{p_4}\right)^{\frac{3\kappa-1}{2\kappa}} \cdot \psi_{42} \\ + \dot{x} \cdot A_{\text{piston}} \cdot p_2 \end{bmatrix}$$

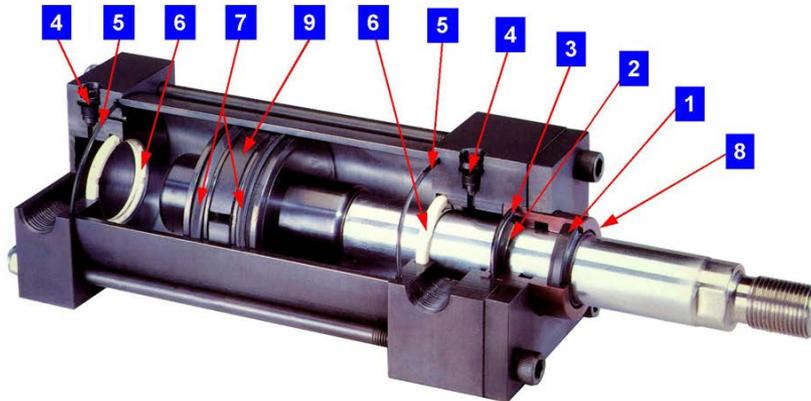
$$m_{\text{pist\&rod}} \cdot \ddot{x} = A_{\text{piston}} \cdot (p_1 - p_2) - F_{\text{process}} - F_{\text{friction}} - c_{\text{stop}} \cdot \Delta x - k_{\text{stop}} \cdot \Delta \dot{x}$$



1 Drive Systems



- 1.1 Rotational Electrical Drives
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Thanks for your attention.

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