EPFL

Introduction to the Design of Space Mechanisms

Theme 6 part 4:

Components

Actuators (continued), …

Gilles Feusier

Theme 6 Part 3 Summary

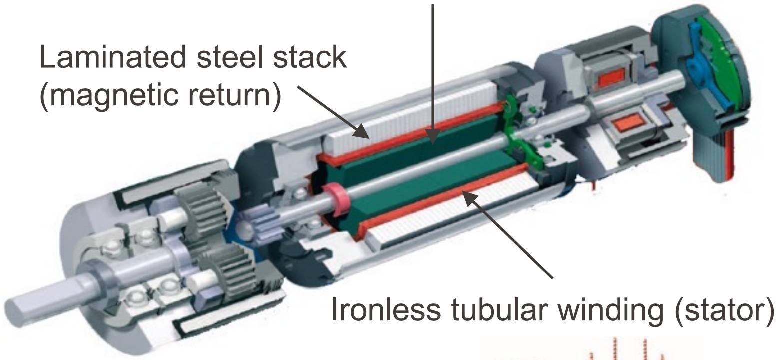
- Actuators
  - Passive
    - Spring based …
  - Active
    - Electromagnetic:
      - brushless DC motors,
      - stepper motors (detent torque, holding torque),
      - brushed motors (not adapted to vacuum),
      - …
    - Others: paraffin actuators, SMA actuators, pyro-actuators, thermal cutters …
  - Electromagnetic actuators
    - Working principles
    - Classification

Motors and Actuators

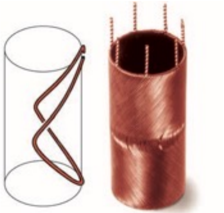
- Sizing of the motors
  - Required functional parameters
  - Torque (T)
  - Angular speed (ω)
  - Supplied current and voltage
  - Available space
- Calculation of motor power
  - Useable mechanical power + friction losses + Joule losses + iron losses + circuit losses
    - Useable mechanical power: $P_l = \omega \cdot T$ [W]
    - Friction losses: $P_f = \sum \omega_i \cdot T_{fi}$ [W]
    - Joule losses: $P_R = I^2 \cdot R$ [W]
    - Iron losses (eddy currents, hysteresis, and anomalous):
      - Mainly determined through tests
      - Small at low speed and negligeable for ironless motors

Brushless DC motor

- Permanent magnet of the rotor side
- Stator composed of two or more pole pairs, electronically commutated in order to generate a rotating field
- If the stator does not contain any ferromagnetic component the detent torque is equal to zero
- Specific windings permit to get very compact size motors or large diameter frameless torque motors



Source: Maxon Motor AG



Source: Avior Contol Technologies, Inc.

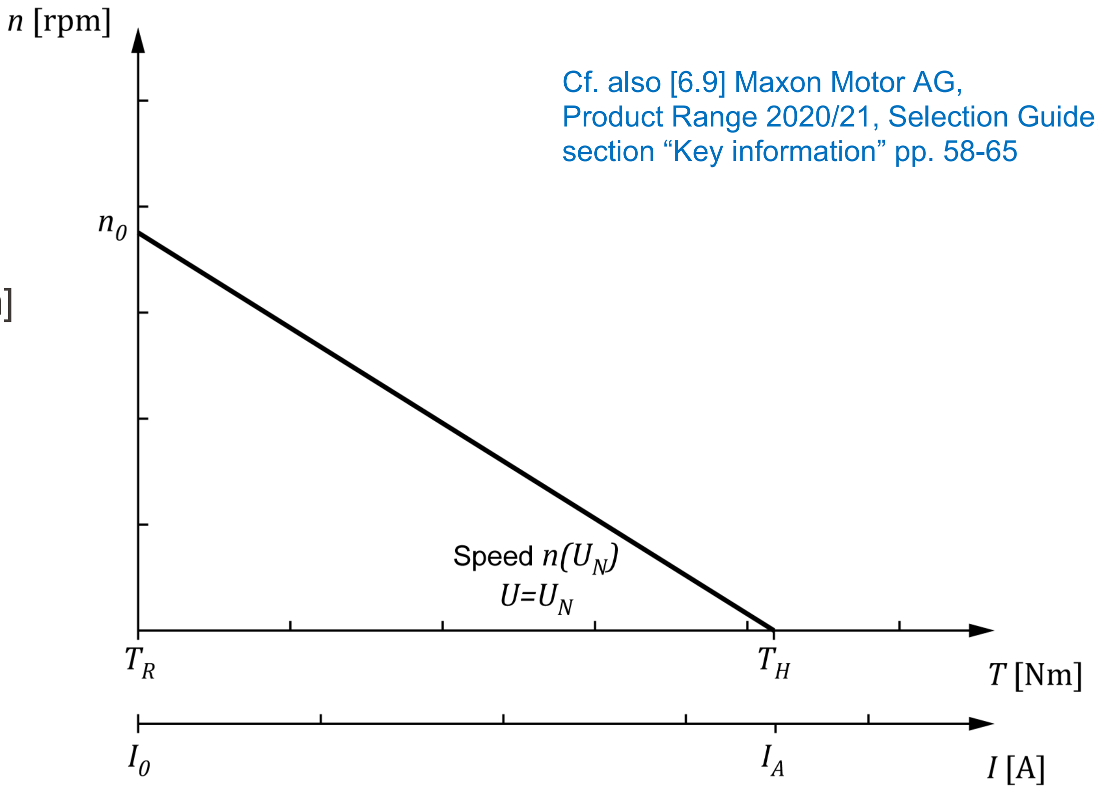
Source: Soterem

Motor Diagram

- Speed constant k_n

  $n = k_n \cdot U_{ind}$
- Torque constant

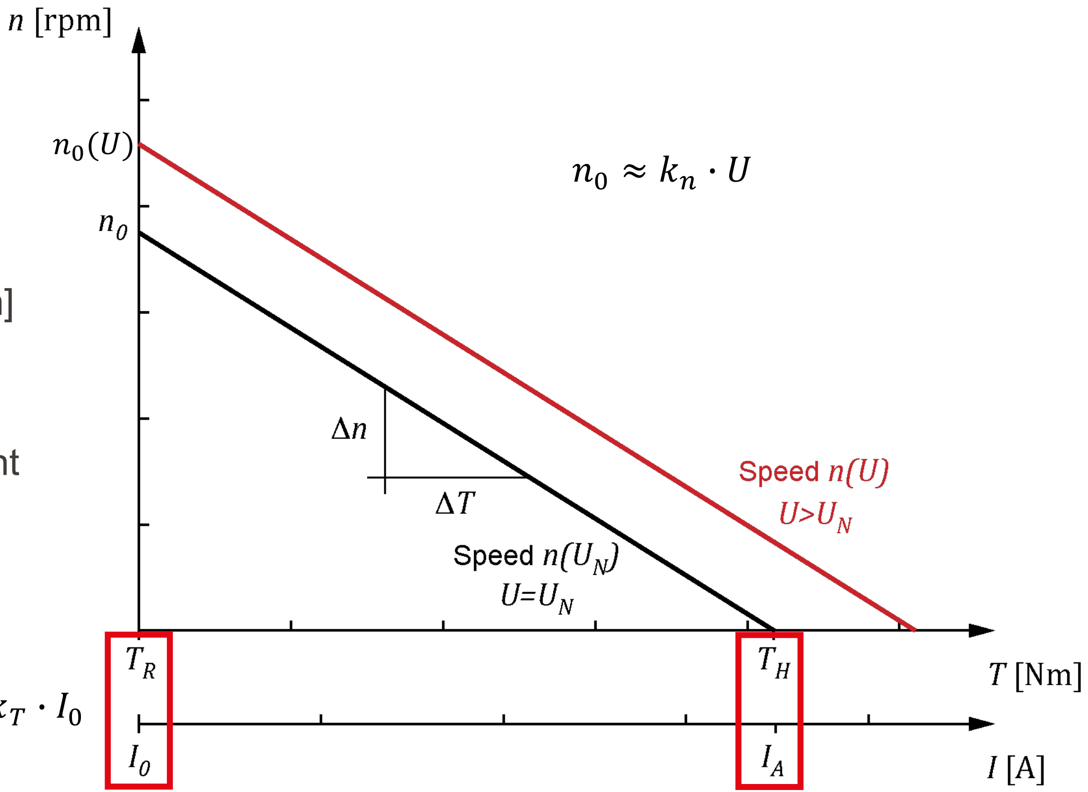
  $k_T = \frac{T}{I}$ [Nm/A]
- No load speed n_0 [rpm]
- Stall torque T_H [Nm]



Cf. also [6.9] Maxon Motor AG, Product Range 2020/21, Selection Guide, section “Key information” pp. 58-65

Motor Diagram

- Speed constant k_n
  $n = k_n \cdot U_{ind}$
- Torque constant
  $k_T = \frac{T}{I}$ [Nm/A]
- No load speed n_0 [rpm]
- Stall torque T_H [Nm]
- Speed / torque gradient
  $\frac{\Delta n}{\Delta T} = \frac{n_0}{T_H}$ [rpm/Nm]
- No load current I_0 [A]
- Friction torque $T_R = k_T \cdot I_0$
- Starting current I_A [A]



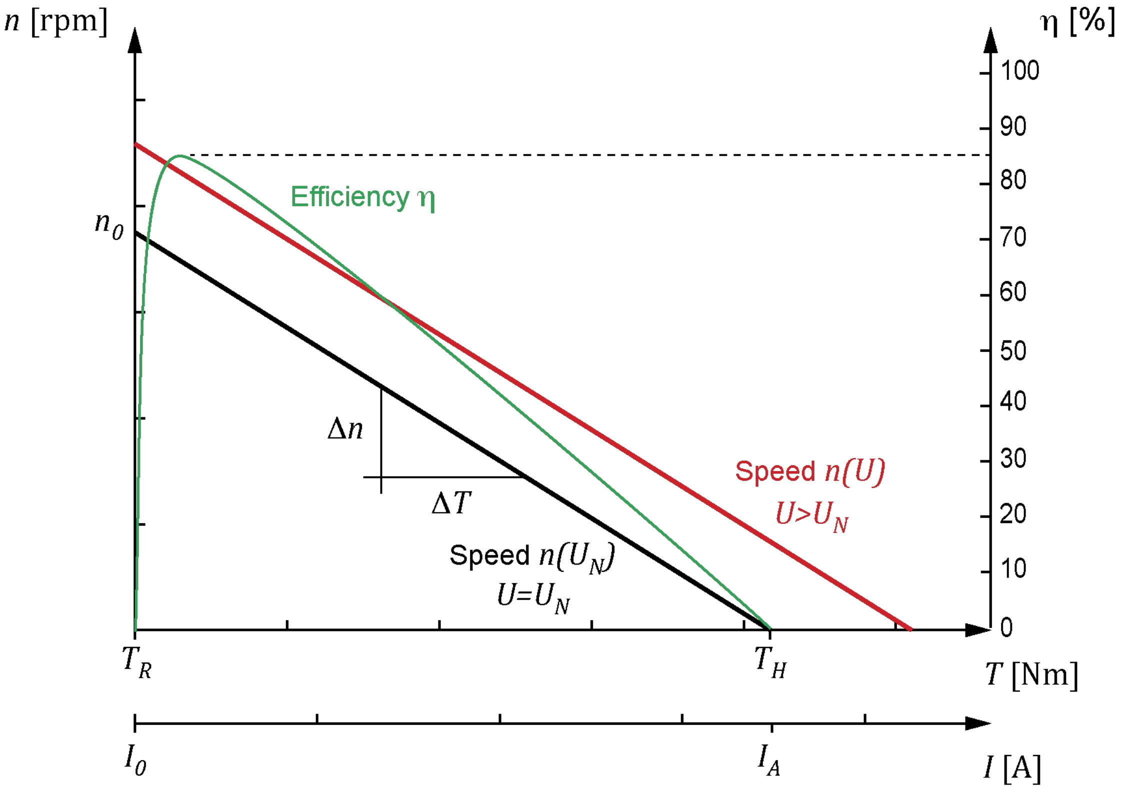
Motor Diagram

- Efficiency curve

$$\eta = \frac{2\pi}{60} \cdot \frac{n \cdot (T - T_R)}{U \cdot I}$$

- Maximum efficiency

$$\eta_{max} = \left(1 - \sqrt{\frac{I_0}{I_A}}\right)^2$$

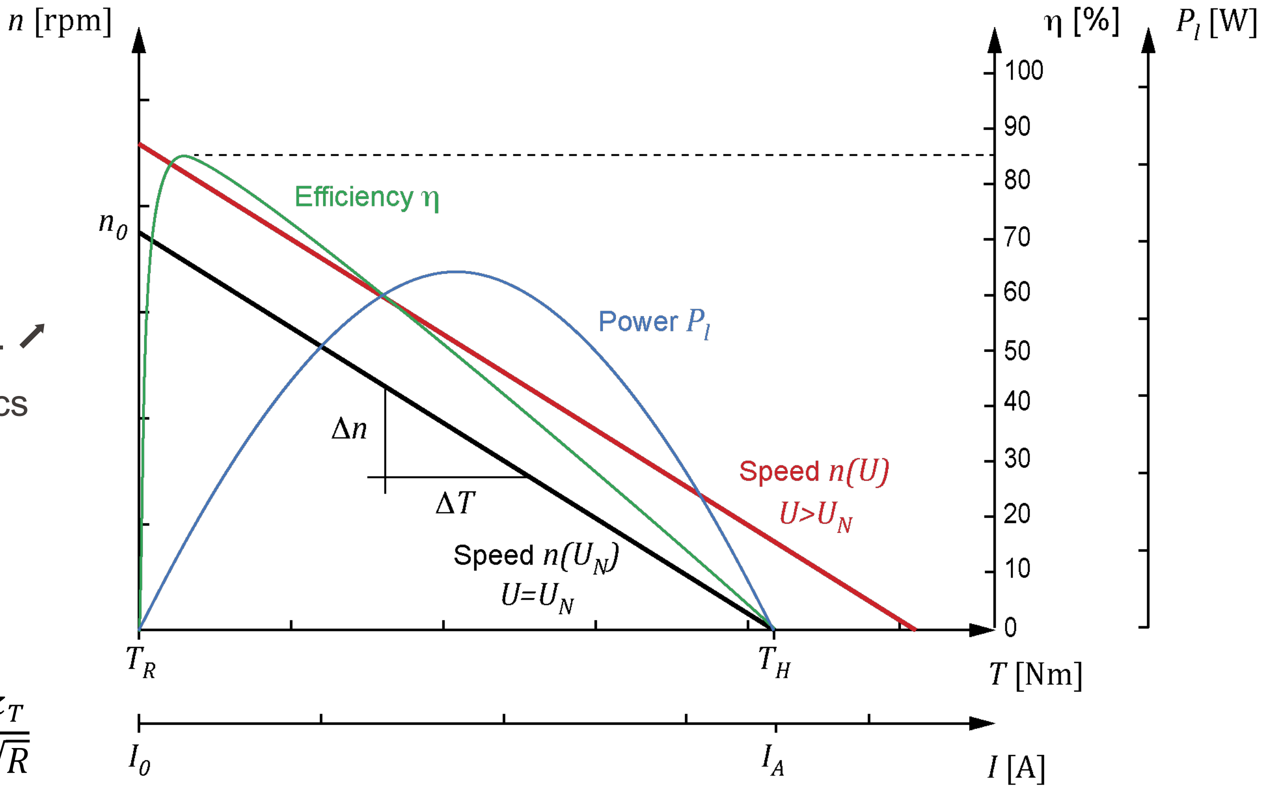


Motor Diagram

- Mechanical power

$$P_l = \omega \cdot T = \frac{2\pi}{60} \cdot n \cdot T$$

- Effect of temperature
  - Change of winding resistance
    Temp. ↗ => Elec. Res. ↗
  - Magnetic characteristics
  - Damage of the motor (windings)



- Motor constant [N·m/√W]

$$k_m = \frac{T}{\sqrt{P_{in} - P_{out}}} = \frac{k_T}{\sqrt{R}}$$

For motor constant k_m, cf. reading [6.10]

Motor Diagram

- Rated operating point
  - nominal voltage U_N
  - nominal current I_N

Nominal current

- Thermally maximum permissible continuous current
- I.e. max. winding temperature (25°C ambient)

Overload ($I>I_N$, $T>T_N$)

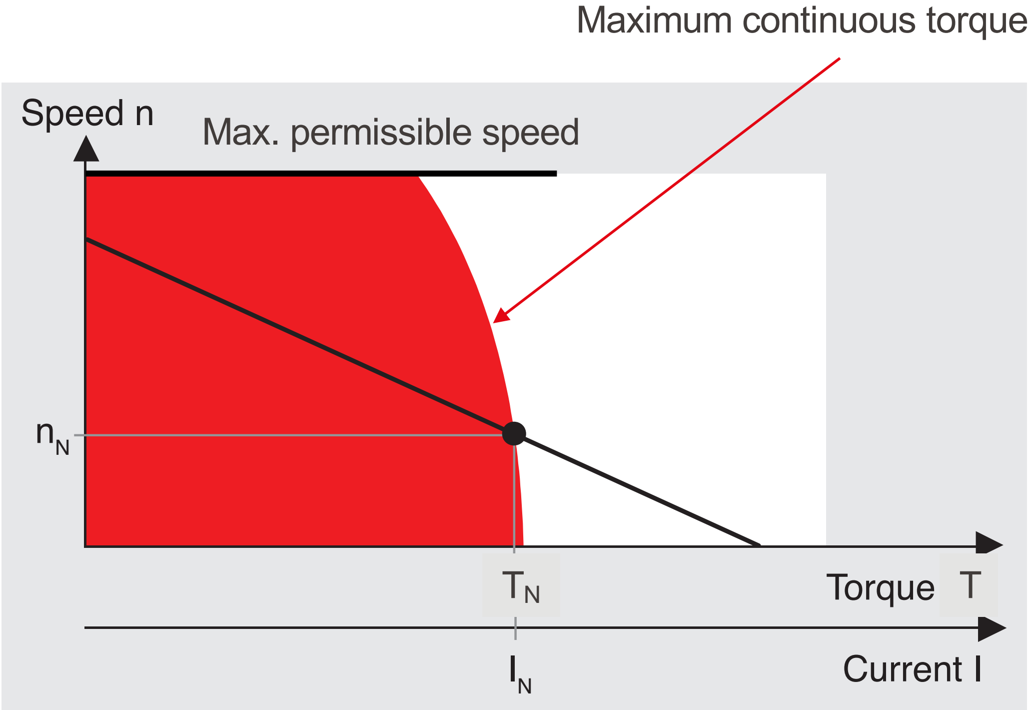
- thermal time constant of the winding

Max. permissible speed

- Ball-bearings life

  @ max res. imbalance

  @ max bearing load



Source: Maxon Motor AG

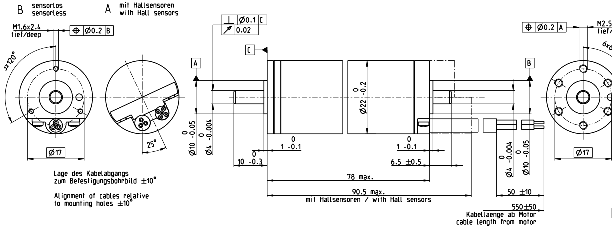
Motor Selection

Max. permissible speed

Maximum continuous torque

EC 22 ∅22 mm, brushless, 80 Watt

Heavy Duty – for applications in air



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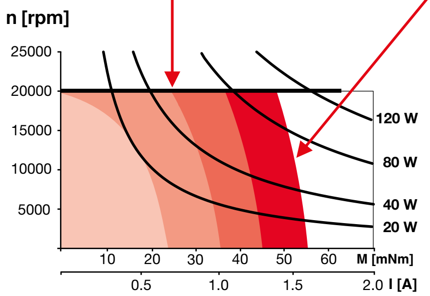
Operating Range



Comments

TA = 25°C
TA = 100°C
TA = 150°C
TA = 200°C

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

Stock program
Standard program
Special program (on request)

		Part Numbers
	A with Hall sensors	426448
	B sensorless	426449

Motor Data (provisional)

Symbol		Values at nominal voltage and ambient temperature °C	Unit	25	100	150	200
	1	Nominal voltage	V	48	48	48	48
n_0	2	No load speed	rpm	13300	13600	13800	14100
	3	No load current	mA	63.9	53.4	54.9	56.5
	4	Nominal speed[1]	rpm	11400	11700	12200	13200
T_N	5	Nominal torque (max. continuous torque)[1]	mNm	57.9	44	32.4	14.9
	6	Nominal current (max. continuous current)	A	1.72	1.35	1.03	0.515
T_H	7	Stall torque	mNm	460	346	295	256
	8	Stall current	A	13.4	10.3	8.98	7.93
η_{max}	9	Max. efficiency	%	87	86	85	84
		Characteristics					
	10	Terminal resistance phase to phase	Ω	3.59	4.64	5.35	6.05
	11	Terminal inductance phase to phase	mH	0.626	0.626	0.626	0.626
k_T	12	Torque constant	mNm/A	34.4	33.5	32.9	32.3
k_n	13	Speed constant	rpm/V	278	285	290	296
$\frac{\Delta n}{\Delta T}$	14	Speed / torque gradient	rpm/mNm	29	39.5	47.2	55.4
	15	Mechanical time constant	ms	2.31	3.16	3.77	4.43
	16	Rotor inertia	gcm^2	7.63	7.63	7.63	7.63

Specifications

	Thermal data	
17	Thermal resistance housing-ambient	9.12 K/W
18	Thermal resistance winding-housing	0.92 K/W
19	Thermal time constant winding	5.84 s
20	Thermal time constant motor	462 s
21	Ambient temperature	-55...+200°C
22	Max. winding temperature	+240°C
	Mechanical data (preloaded ball bearings)	
23	Max. speed	20 000 rpm
24	Axial play at axial load < 5 N	0 mm
	> 5 N	max. 0.14 mm
25	Radial play	preloaded
26	Max. axial load (dynamic)	8 N
27	Max. force for press fits (static)	98 N
	(static, shaft supported)	250 N
28	Max. radial load, 5 mm from flange	16 N
	Other specifications	
29	Number of pole pairs	1
30	Number of phases	3
31	Weight of motor	210 g

Source: Maxon Motor AG, Product Range 2020/21, Selection Guide [6.9]

Motor Selection: ECSS-E-ST-33-01C Rev.2 - Mechanisms

- Actuators shall be sized to provide throughout the operational lifetime and over the full range of travel actuation torques or forces
- To derive the factored worst-case resistive torques or forces, each contributors, considering all mission phases worst-case conditions , shall be multiplied by the applicable minimum uncertainty factor:

Table 4-2: Minimum uncertainty factors for actuation function

Resistive torque or force contributors	Symbol	Theoretical Factor	Measured Factor
Inertia	I	1,1	1,1
Spring	S	1,2	1,1
Magnetic effects	H_M	1,5	1,1
Friction	F_R	3	1,5
Hysteresis	H_Y	3	1,5
Others (e.g. Harness)	H_A	3	1,5
Adhesion	H_D	3	3

Associated torque:

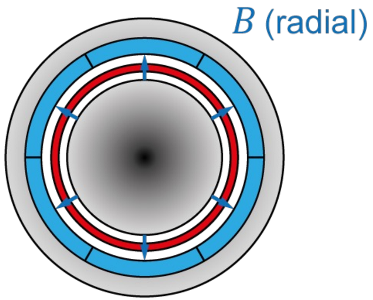
I_{res}
S
H_M
F_R
H_Y
H_A
H_D

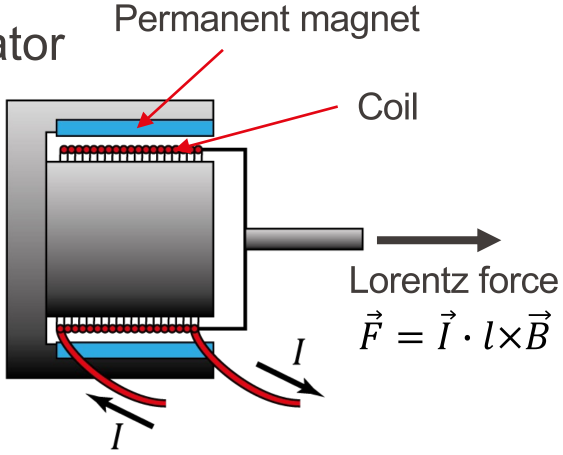
$$T_{min} = 2 \cdot [1.1 \cdot I_{res} + 1.2 \cdot S + 1.5 \cdot H_M + 3 \cdot F_R + 3 \cdot H_Y + 3 \cdot H_A + 3 \cdot H_D] + 1.25 \cdot T_D + T_L$$

T_D: the inertial resistance torque caused by the worst-case acceleration function (at the mechanism level)
T_L: is the deliverable output torque

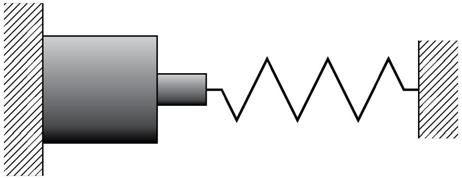
Motors and Actuators

- Voice coil actuator





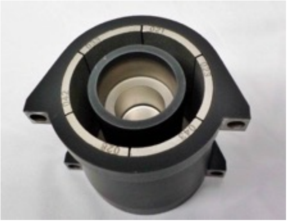
This actuator shall operate against a spring



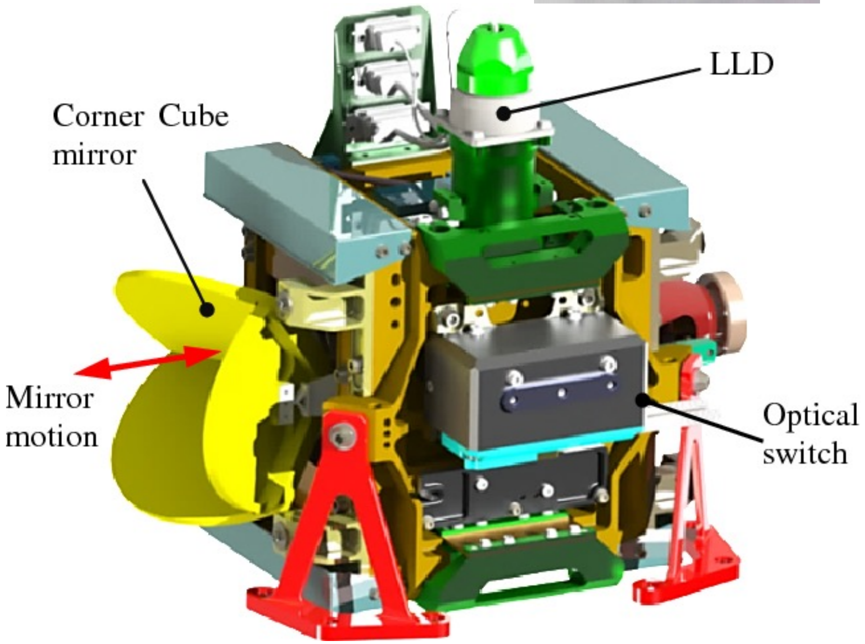
- Possible long stroke, high precision
- Small hysteresis (simple magnetic circuit)
- Small mass: high speed/acceleration
- Small inductance: fast response, high bandwidth
- Limited continuous operation: heat dissipation

Source: BEI Kimko

Motors and Actuators

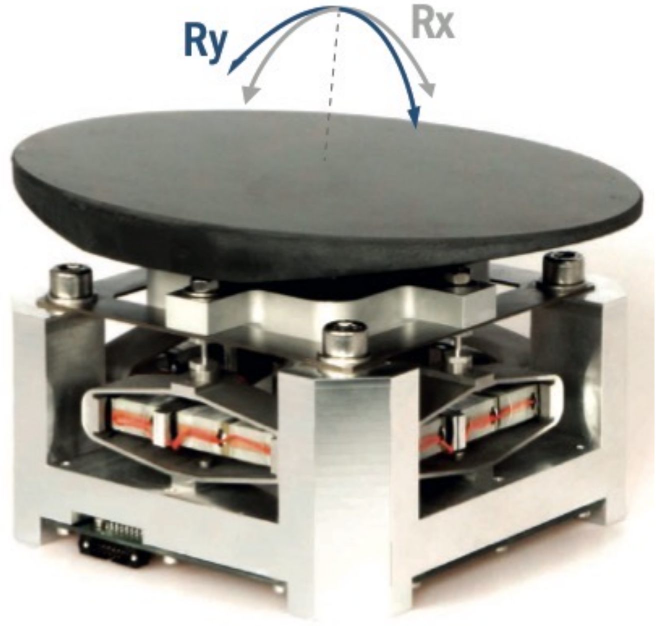


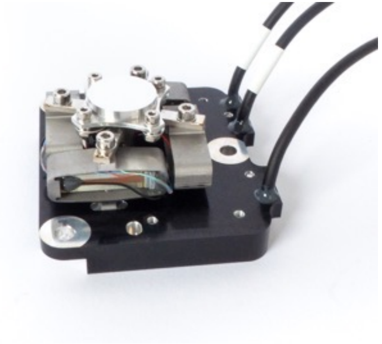
Corner Cube Mechanism (CCM) of the Infra-Red Sounder (IRS) for the Meteosat Third Generation (MTG): voice-coil actuator and flexural blades

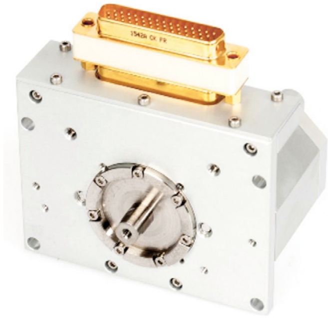


Sources: Spanoudakis et al., Proc. 16. European Space Mechanisms and Tribology Symposium (2015) and Proc. 18. European Space Mechanisms and Tribology Symposium (2019)

Piezoelectric actuators and motors







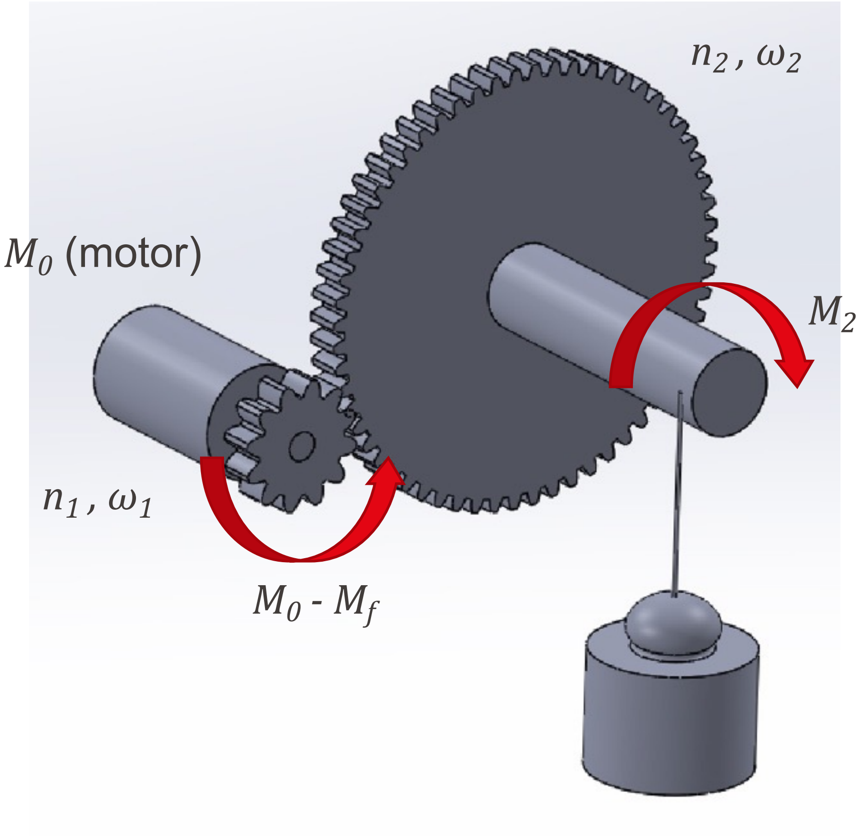
Sources: Cedrat Technologies

Cf. https://www.cedrat-technologies.com/en/technologies/actuators.html

Motors and Actuators: Accessories

- Gear boxes
  - Gear trains (one stage typical reduction ratio: < 5:1)
  - Planetary, epicyclic gear train (one stage typical reduction ratio: < 7:1)
  - Worm drive (high reduction ratio, mostly non-reversible)
  - Harmonic gearing (high reduction ratio, typically 160:1 for one stage)
- Angular sensor
  - Optical (resolution up to 25bits)
  - Inductive
  - Hall (mainly speed sensor, low resolution, typ. 10bits)
  - Resistive (potentiometer: analog signal, wear)
  - Others (MEMS, capacitive)
- Brake (to block the rotation in case of power failure)
  - Electromagnetic
  - Centrifuge
  - Friction
- Clutch

Gear Box



Gear ratio:

$$i = {}^{\omega_1}/_{\omega_2} = {}^{n_2}/_{n_1} = {}^{d_2}/_{d_1}$$

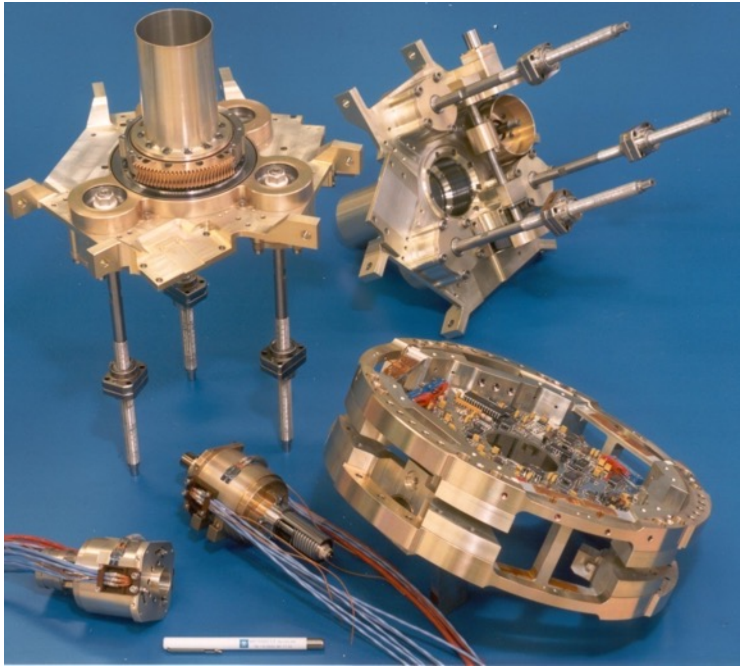
$$M_1 = M_0 - M_f = M_0 \cdot \rho$$

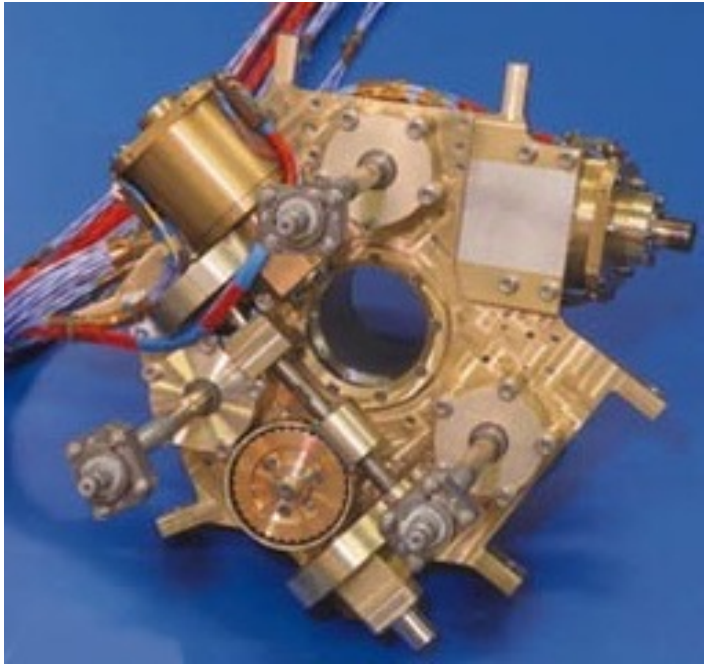
$$M_2 = M_1 \cdot i = M_0 \cdot \rho \cdot i$$

with ρ: efficiency

Motors and Actuators

- European Robotic Arm (ERA): End effector actuation and sensing unit
  - Example of gear train
  - Example of worm gear

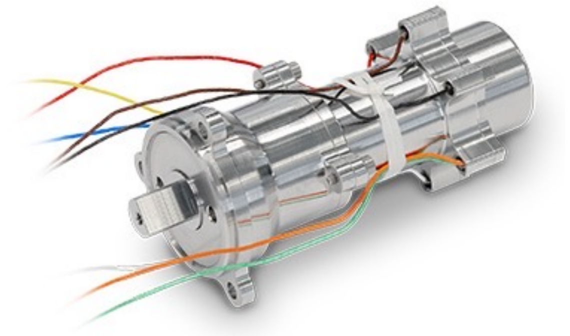


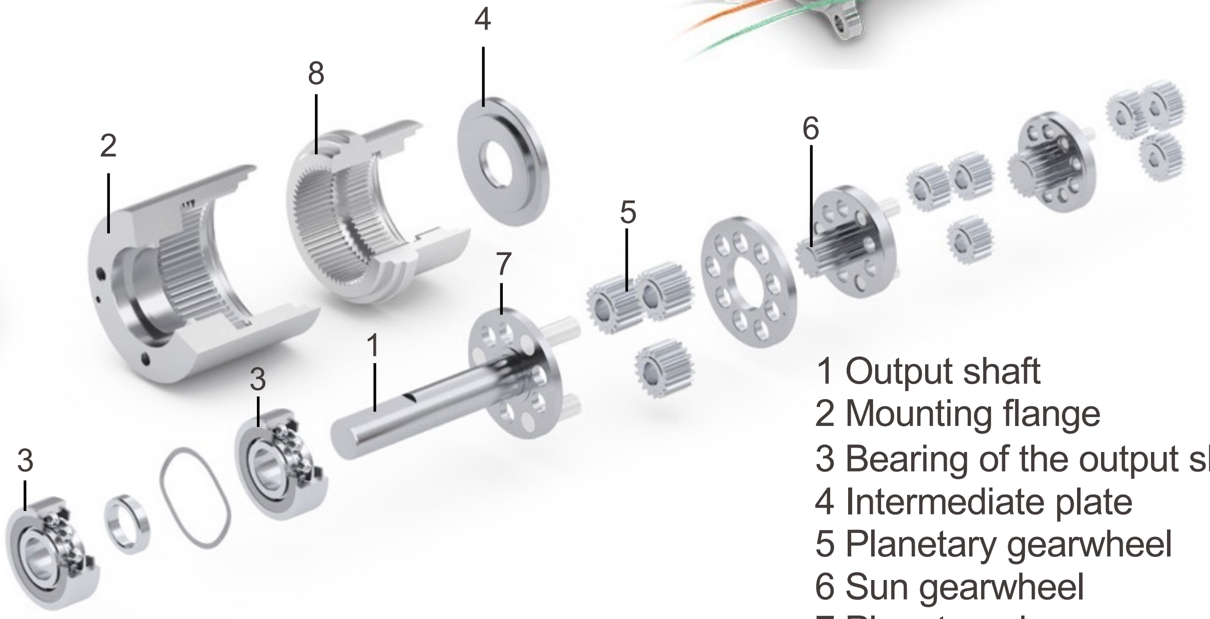


Source: Mecanex SA

Motors and Actuators

- Example of a planetary gearset



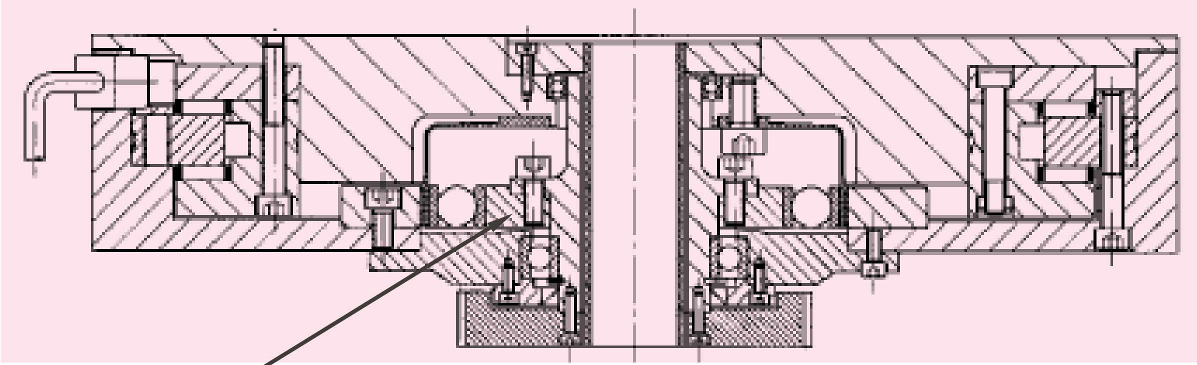


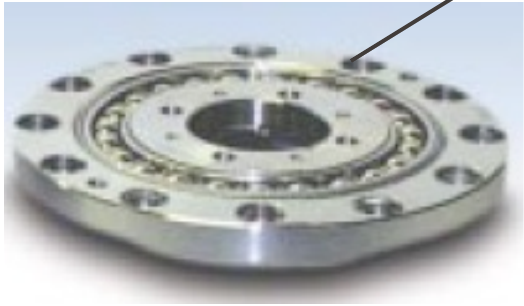
1 Output shaft
2 Mounting flange
3 Bearing of the output shaft
4 Intermediate plate
5 Planetary gearwheel
6 Sun gearwheel
7 Planet carrier
8 Internal gear

Source: Maxon Motor AG/Maxon Group Ltd

Motors and Actuators

- Example of harmonic gearing (strain wave gearing)

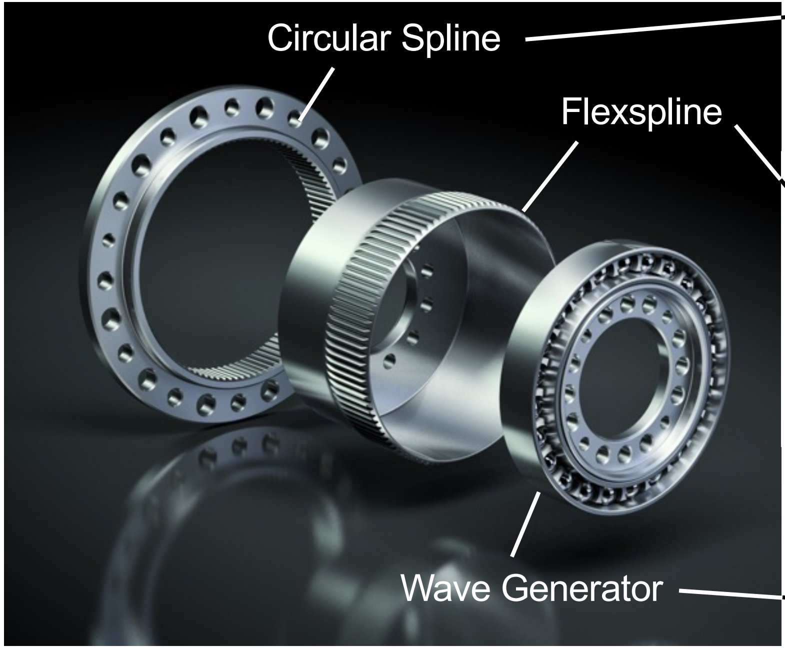




Harmonic Drive SE

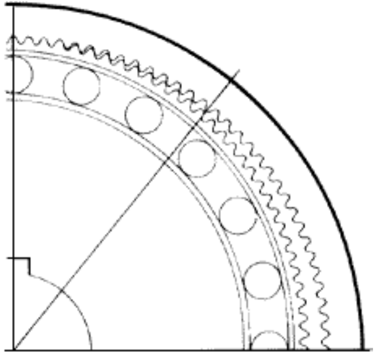
Motors and Actuators

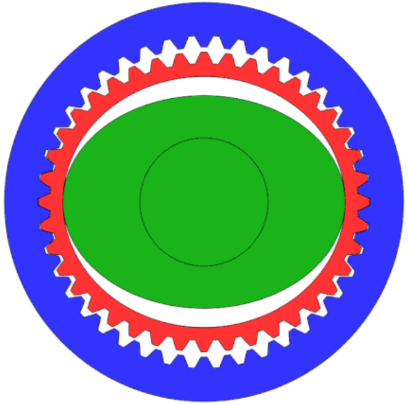
- Principle of harmonic gearing



n_c

n_f





Source: Wikipedia/Jahobr

Harmonic Drive SE

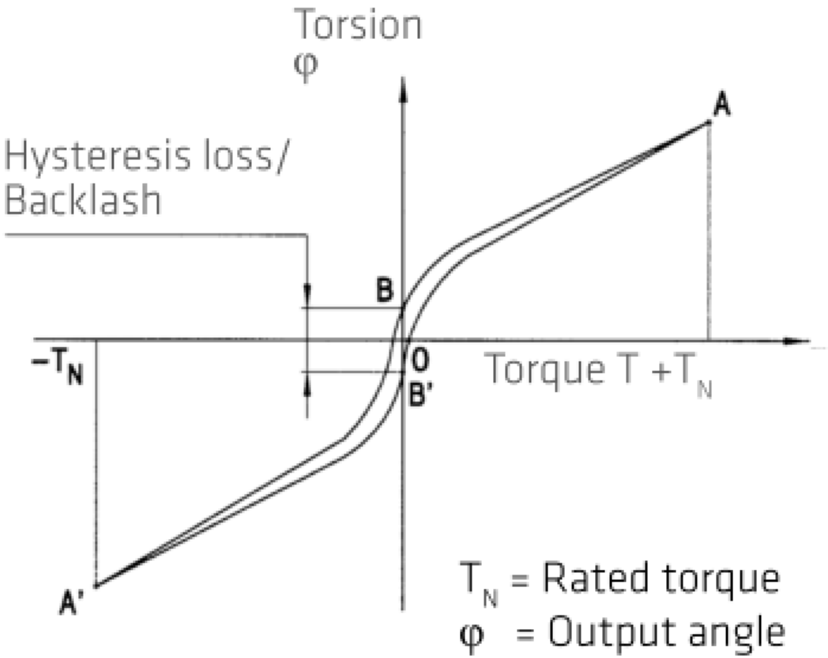
$$i = \frac{n_f - n_c}{n_f} \qquad i = \frac{200 - 202}{200} = -0.01 \rightarrow 1{:}100$$

Motors and Actuators

Harmonic gearing

- Advantages
  - no backlash,
  - high compactness, high gear ratios,
  - high torque capability,
  - coaxial input and output shafts.

- Drawback
  - Lower stiffness at low torque

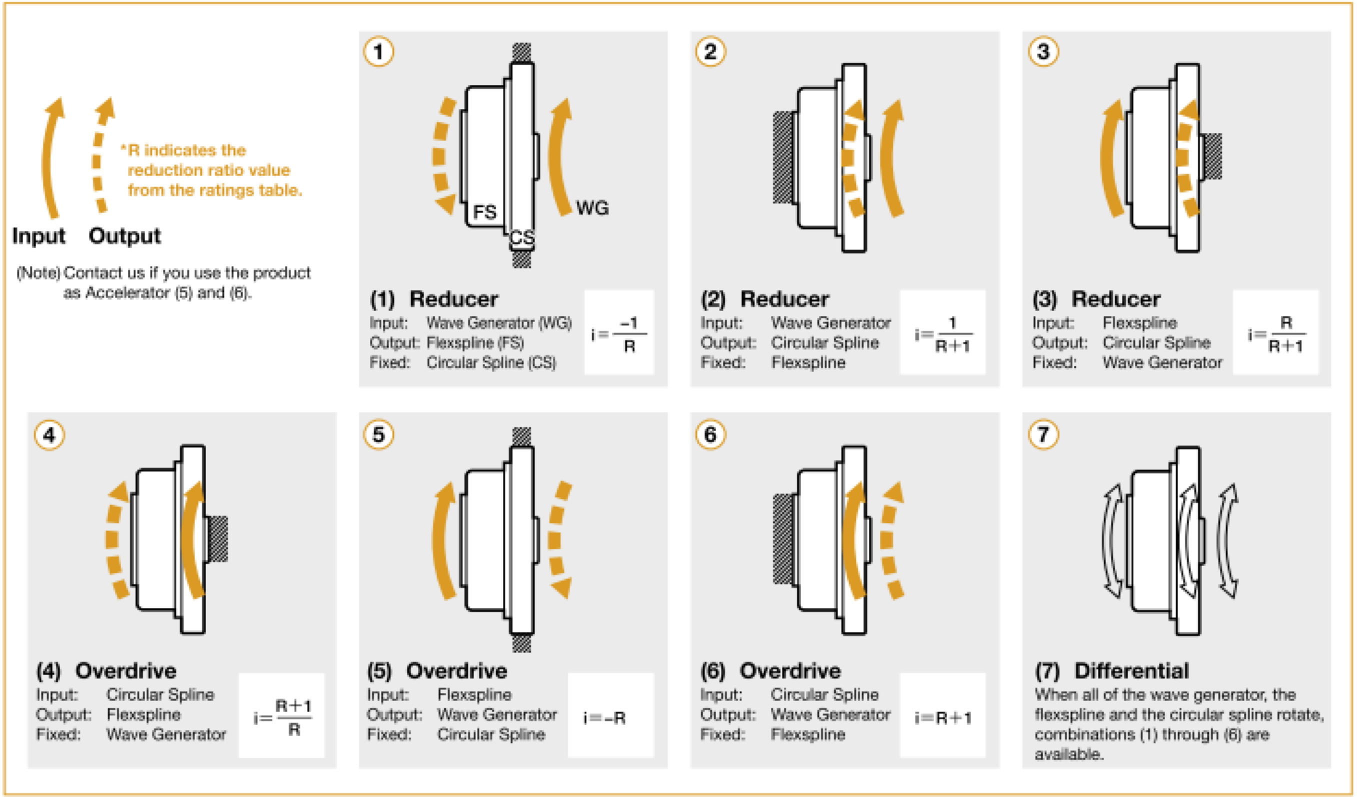


Harmonic Drive SE

Motors and Actuators

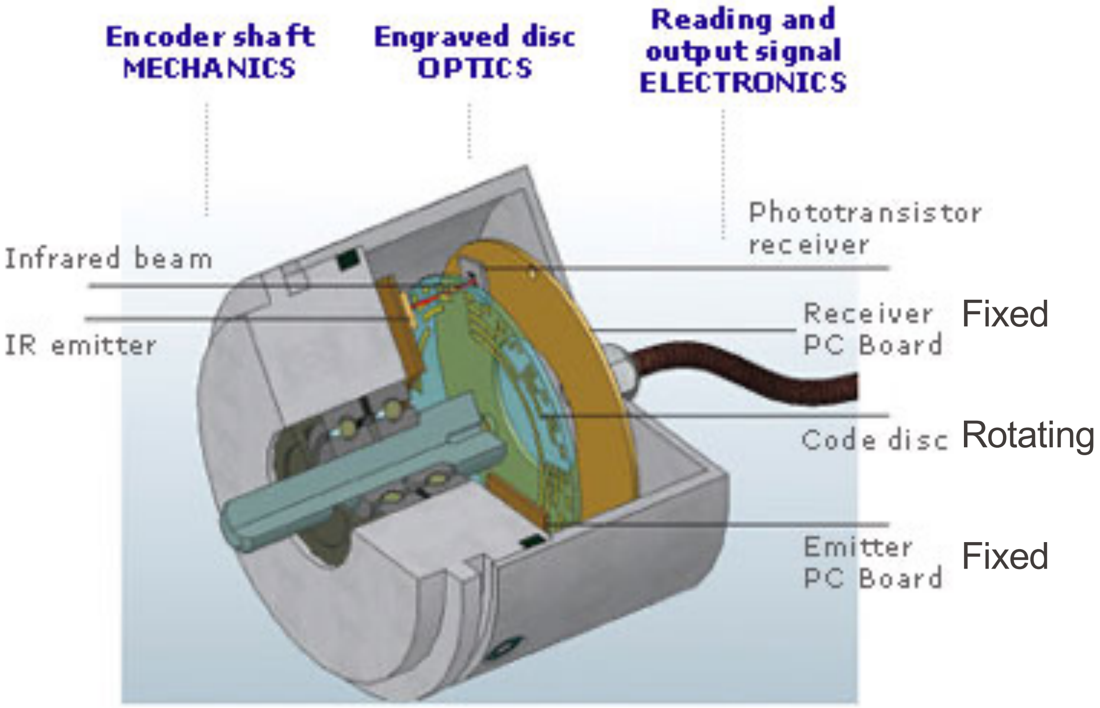
Harmonic Drive SE

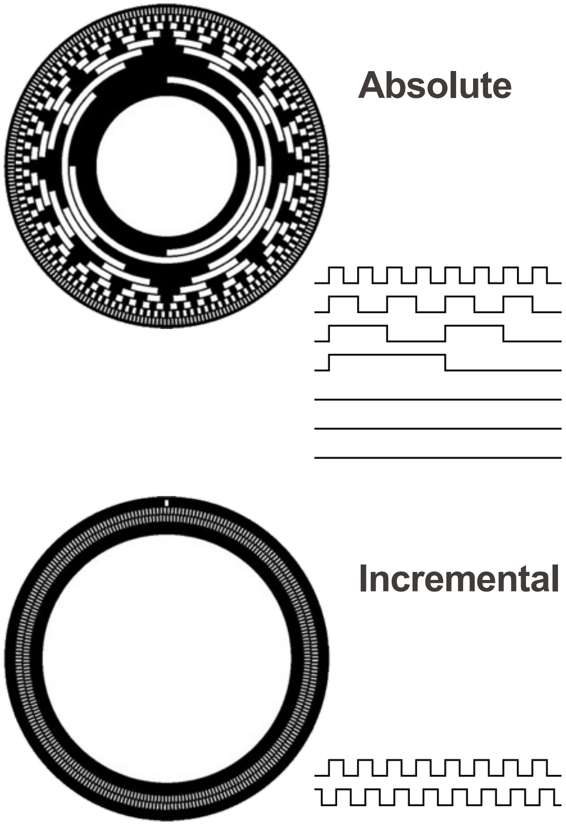
- Different possible arrangements: different gear ratios



Optical Encoders

- Working principle





Source: Codéchamp, France
http://www.optical-encoders.eu/optical-encoder.html

Source: Engineering Notes by Orientalmotor.com

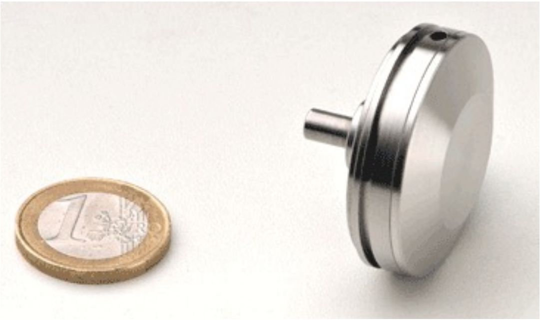
Optical Encoders

Several types of encoders

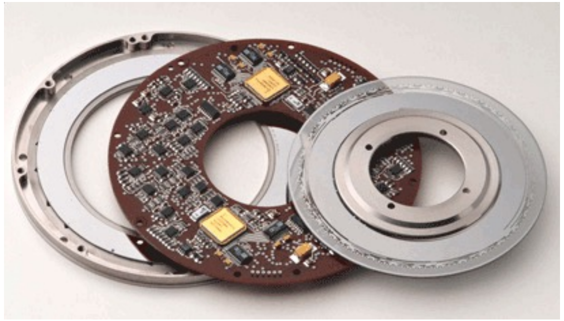
- Incremental
  - Sensitive to power loss: re-initialization of the position
  - Sensitive to electrical parasites: bit counting errors
- Absolute
  - Position coded through data word (binary or other)

Absolute $\frac{360°/\text{rev}}{\text{Cycles/rev}}$

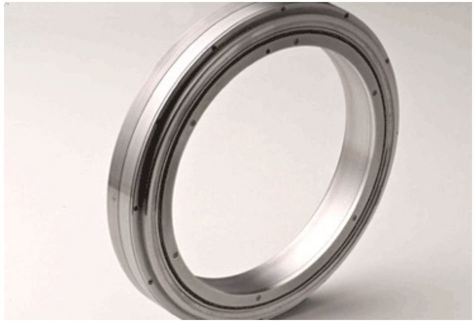
Bits	Cycles/rev.	Resolution
8	256	1.41°
10	1'024	0.35°
	…	
24	16'777'216	0.08 arcsec
27	134'217'728	0.01 arcsec



In a casing, with bearing



Pancake

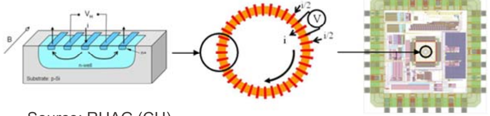
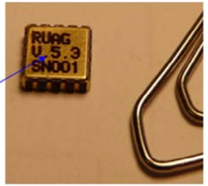


In a casing, hollow shaft, large diameter, with bearing

Source: Codéchamp, France

Other Position Sensors

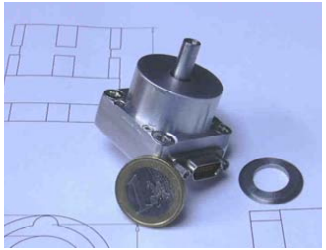
- Potentiometer
  - “Low-cost”
  - Wear (contact friction)
  - Resolution could be better than 0.007°
- Magnetic, inductive: brushless resolver, RVDT, LVDT, Hall sensors
  - Position coded through data word (binary or other)
- Capacitive
- …

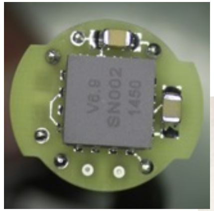
Source: RUAG (CH)

Source: Betatronix

Source: Novotechnik



Source: Carlo Gavazzi Space/OHB IT



Source: ESA

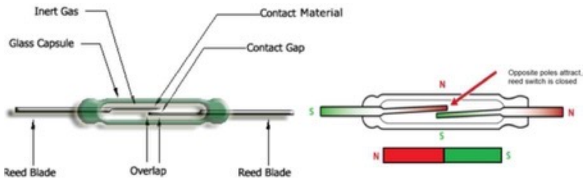
State Sensor/Status Indicator

- In general, use of micro-switches or reed switches
  - Simple and safe electronics → Reliability
  - Accurate adjustment is difficult!
- Other possible types of sensors: optical, capacitive, inductive, …
  - Use of more complex electronics
  - Higher cost (to be justified)

Source: Honeywell International Inc

Typical size: 22.4 x 17.7 x 8.6 mm

Source: Standex Electronics, Inc.



Source: M. Robroek et al., ESMATS 2023 Warsaw

Wires and Cables

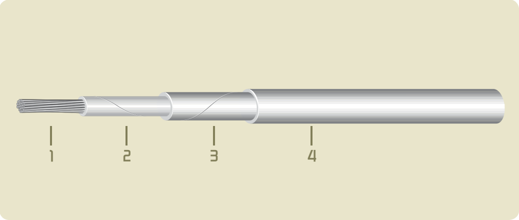
Single wires

ESCC 3901 001

Polyimide insulation

Operating temperature: -100°C up to +200°C

Voltage rating: 600 VAC max.



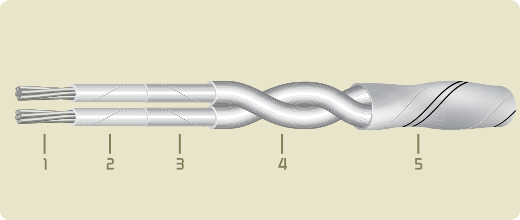
Twisted pairs

ESCC 3901 001

Polyimide insulation

Operating temperature: -100°C up to +200°C

Voltage rating: 600 VAC max.



ESCC: European Space Components Coordination

https://escies.org

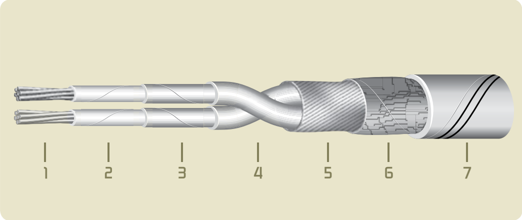
Shielded jacketed twisted pairs

ESCC 3901 001

Polyimide insulation

Operating temperature: -100°C up to +200°C

Voltage rating: 600 VAC max.



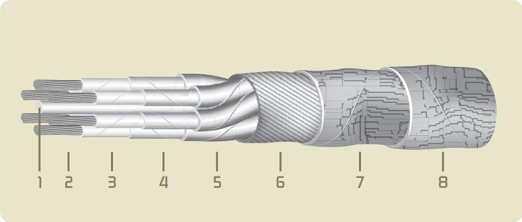
Shielded jacketed twisted 6-core cables

ESCC 3901 019

CELLOFLON® / Polyimide tape

Operating temperature: -200°C up to +200°C

Voltage rating: 600 VAC max.



More than 1 single wire

➡ **Cable derating:**

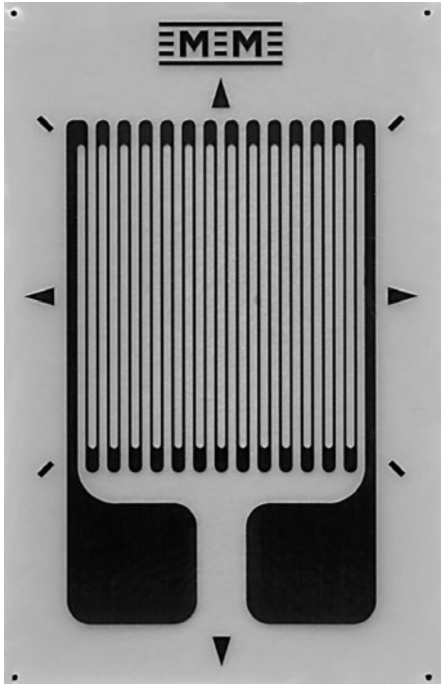
[6.12] ECSS-Q-ST-30-11C Rev 1
Derating - EEE components

Cf. also comments to Mini Project

Source: Source: Axon' Cables S.A.S.
https://www.axon-cable.com/en/04_markets/09_space/00/index.aspx

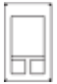
Strain/Stress Gages

Many different models (material, geometry) that must be selected according to the application



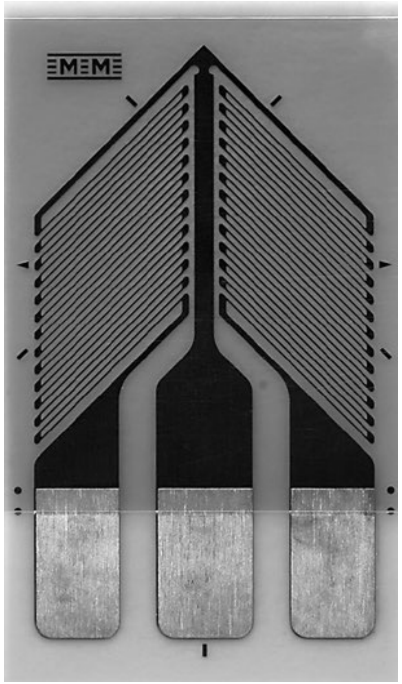
250AE

Linear Pattern



actual size

10.54 x 6.35



187UV

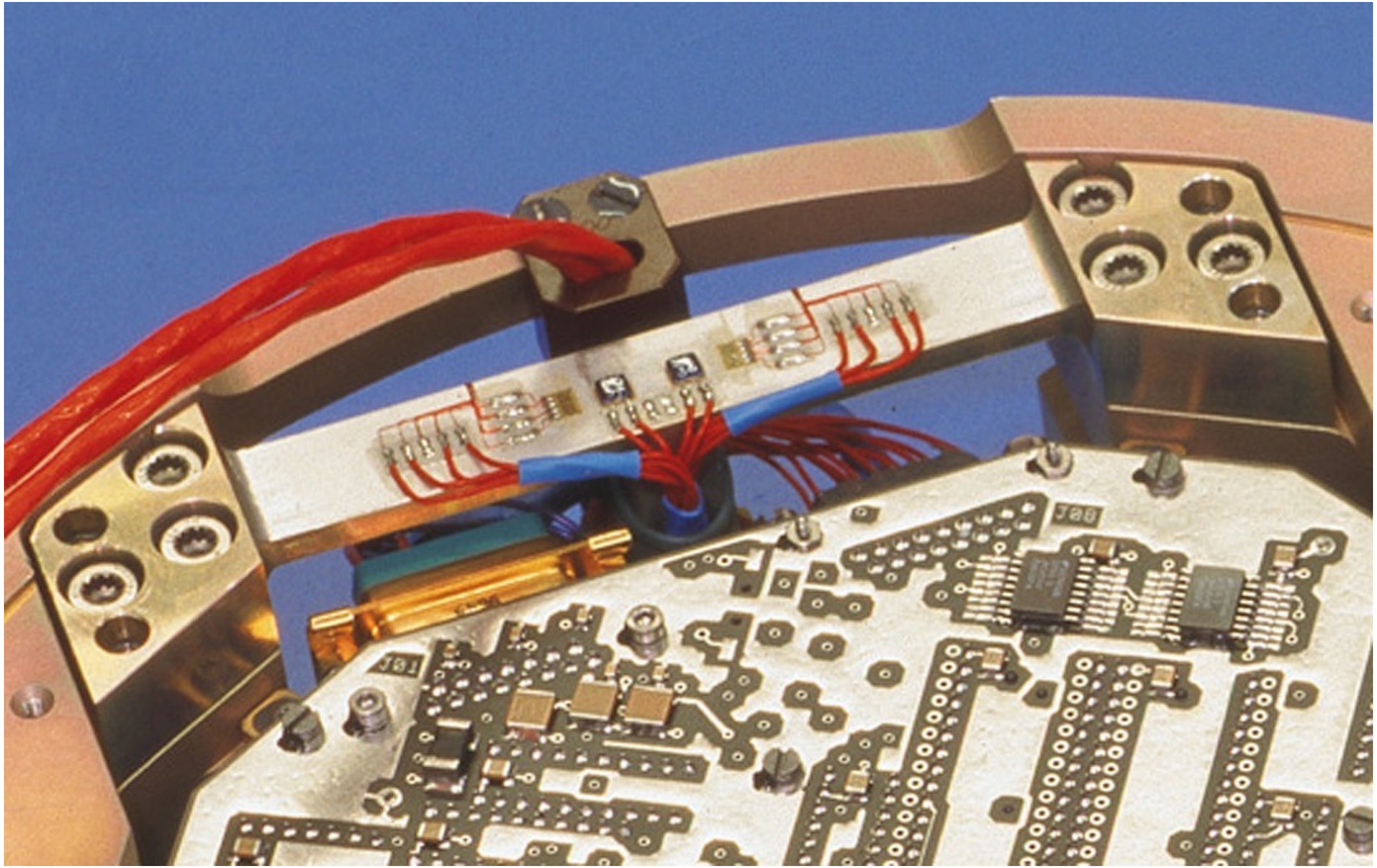
Shear/ Torque Pattern

actual size

14.22 x 8.13

Source: Vishay Precision Group. Precision Strain Gages and Sensors Databook DB0103-1502 (2016). https://micro-measurements.com

Stress Gages

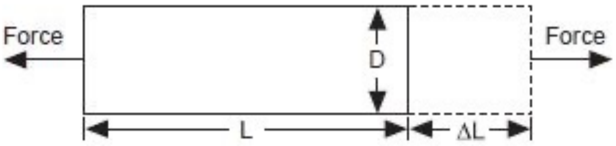


Source: Mecanex SA

Strain Gages small deformations ⇒ very low resistance variations

Source: https://www.ni.com/en-us/innovations/white-papers/07/measuring-strain-with-strain-gages.html (or cf. [6.12])

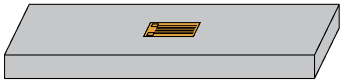
- Relation between the electrical signal and the strain of the gage:
  Gage Factor (GF)



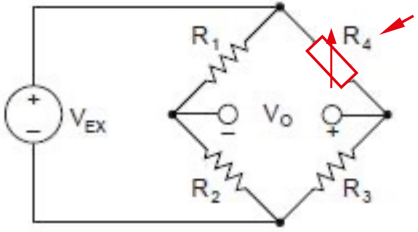
$$\varepsilon = \frac{\Delta L}{L}$$

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}$$

- Wheatstone Bridge configuration



$R_4 = R_G + \Delta R$ (Quarter-Bridge circuit)



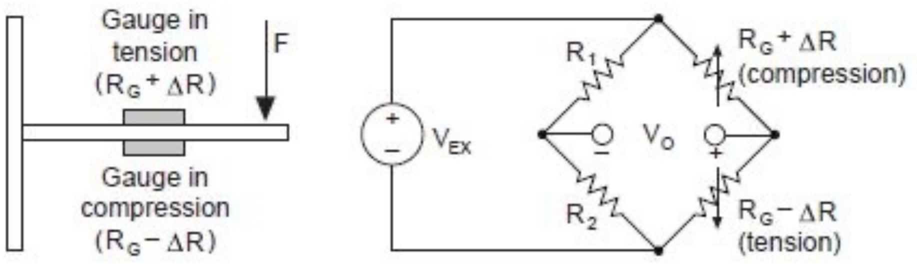
$$V_0 = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right] \cdot V_{EX} \Rightarrow \frac{V_0}{V_{EX}} = -\frac{GF \cdot \varepsilon}{4}\left(\frac{1}{1 + GF \cdot \frac{\varepsilon}{2}}\right)$$

Strain Gages

Thermal compensation

- Is required because:
  - Variation of strain gage resistance and the conductors with the temperature
  - Differential thermal expansion between the strain gage and the material on which it is applied.

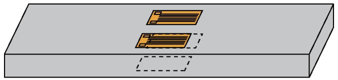
- Wheatstone Half-Bridge configuration

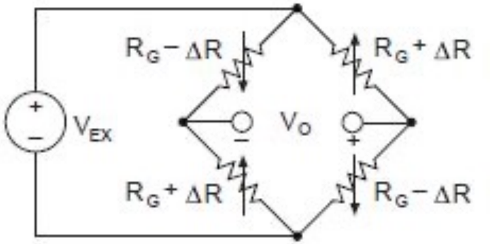


$$\frac{V_0}{V_{EX}} = -\frac{GF \cdot \varepsilon}{2}$$

Strain Gages

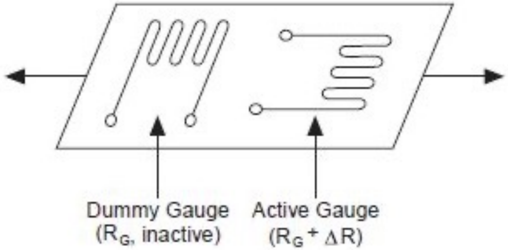
- Wheatstone Full-Bridge configuration





$$\frac{V_0}{V_{EX}} = -GF \cdot \varepsilon$$

- Asymmetric configuration of the Wheatsone bridge



Use of a dummy gage to eliminate the temperature effects

Strain/stress Gages

Thermal compensation through proper selection of the materials

- For a given alloy, the behavior of the strained wire electrical resistance depends on its metallurgical state
- Combination of the effects of:
  - Thermal variation of the electrical resistance.
  - Differential thermal expansion between the strain gage and the material on which it is applied.
  - Substrate/gage material pair in defined metallurgical states.

$\Rightarrow$ Permits a very efficient compensation of the thermal effects in a defined temperature range

- Note: strain gage calculators are available, e.g.:
  - https://micro-measurements.com/calculators#/

Strain Gages

$$\varepsilon = \frac{\Delta L}{L}$$

$$\rightarrow 10^{-6} \cdot \varepsilon = \mu\varepsilon$$

(micro-strain)

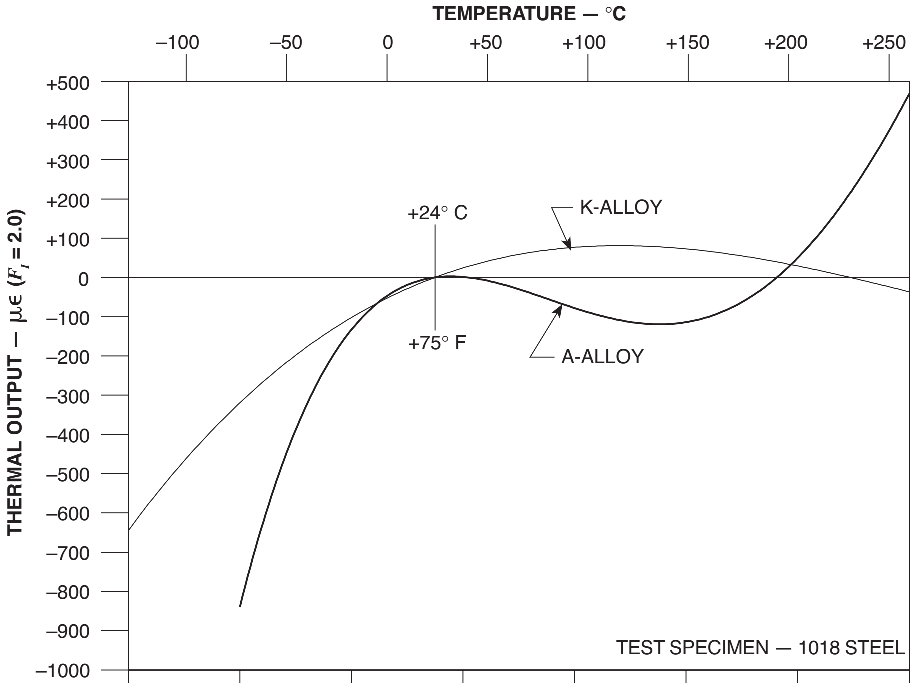


Figure 4. Typical thermal output variation with temperature for self-temperature-compensated constantan (A-alloy) and modified Karma (K-alloy) strain gages.

Source: [6.13] Micro Measurements/Vishay Precision Group. Tech Note TN-504-1

Theme 6 Summary

- Components used in space mechanisms
  - Bearings, flex-pivots: use, limitations, sizing (loads, lifetime, preloads, torque)
  - Actuators and motors: types, sizing
    - Electromagnetic motors
    - Actuators (paraffin, SMA)
    - …
  - Gearboxes (harmonic drive, …)
  - Angular encoders (optical, potentiometer, magnetic …)
  - Switches
  - Cables
  - Strain/stress gages

Next Week

- Invited speaker from CSEM (Lionel Kiener): 3D Printing and Space

- Fill the exam schedule on MOODLE (Exams June 30th & July 1st)
  https://moodle.epfl.ch/mod/scheduler/view.php?id=1206907
  To be filled until June 6th, 17:00.

- Quiz on Moodle: Mission to Europa, one of Jupiter’s moon
  (neither graded, nor corrected)