The goal of this presentation is to provide useful information how to read the maxon motor specification sheets as can be found in the maxon catalog.
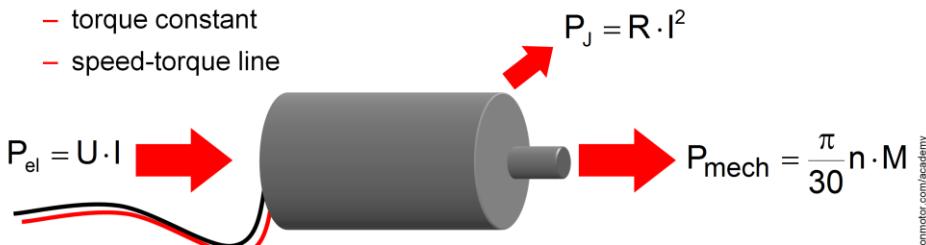
We will derive the characteristic motor lines from basic consideration and explain what the data of DC and EC motors mean and how they depend on each other.

There is also an E-learning tutorial on the same subject on the maxon website for free download.

DC motor as an energy converter

- ■ electrical in mechanical energy
  - – speed constant
  - – torque constant
  - – speed-torque line

$$P_{el} = U \cdot I$$

$$P_J = R \cdot I^2$$

$$P_{mech} = \frac{\pi}{30} n \cdot M$$

- ■ applies to DC and EC motors
  - – "EC" = "brushless DC" (BLDC)
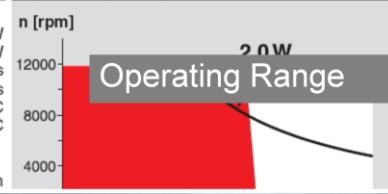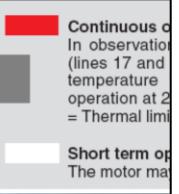
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In a very general frame motors can be considered as energy converters. DC motors convert the electrical input power (DC voltage V and current I) into mechanical output power consisting of angular speed ω and torque M. Engineers prefer to use rotational speed n measured in rpm instead of rad/s; that's why there is a factor of π/30 to get the unit of power right in Watts.

The theory described in this presentation applies to any DC motor, in particular to the maxon DC motor and the brushless maxon EC motor.

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			110061	110062	110063	110064	110065	110066	110067	110068	110069	110070
Motor Data												
	Values at nominal voltage											
1	Nominal voltage	V	1.5	3.0	6.0	9.0	12.0	14.0	15.0	18.0	21.0	30.0
2	No load speed	rpm	10200	11700	9620	11800	11800	11800	11200	11200	11600	10800
3	No load current	mA	201	117	46.7	39.1	29.3	25.1	22.2	18.5	16.5	10.7
4	Nominal speed	rpm	867								70	4160
5	Nominal torque (max. continuous torque)	mNm	0.68								39	2.35
6	Nominal current (max. continuous current)	A	0.720	0.720	0.494	0.394	0.294	0.253	0.225	0.186	0.162	0.105
7	Stall torque	mNm	4.93	4.51	4.02	4.82	4.76	4.81	4.53	4.47	4.48	4.03
8	Starting current	A	3.76	1.97	0.721	0.700	0.519	0.450	0.377	0.310	0.275	0.164
9	Max. efficiency	%	58	57	56	58	58	58	58	57	57	55
	Characteristics											
10	Terminal resistance	Ω	0.399	1.52	8.32	12.8	23.1	31.1	39.8	58.0	76.2	183
11	Terminal inductance	mH	0.017	0.0519	0.306	0.467	0.831	1.13	1.42	2.05	2.61	6.01
12	Torque constant	mNm / A	1.3								.3	24.7
13	Speed constant	rpm / V	729								7	387
14	Speed / torque gradient	rpm / mNm	2220	2770	2560	2600	2630	2600	2630	2670	2750	2880
15	Mechanical time constant	ms	24.5	23.7	23.2	23.2	23.2	23.2	23.4	23.3	23.4	23.8
16	Rotor inertia	gcm²	1.05	0.816	0.864	0.854	0.844	0.854	0.848	0.834	0.811	0.788

Specifications

Operating Range

Comments

Thermal data
17 Thermal resistance housing-ambient   29.8 K / W
18 Thermal resistance winding-housing   5.5 K / W
19
20
21 Ambient temperature   -30 ... +85°C
22 Max. permissible winding temperature   +125°C

Mechanical data (sleeve bearings)
23 Max. permissible speed   11900 rpm

n [rpm]

2.0 W

12000–

8000–

4000–

Continuous o
In observation
(lines 17 and
temperature
operation at 2
= Thermal limi

Short term o
The motor ma

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The specification sheets of maxon group the motor data in three blocks and an operating range diagram. On one catalog page the data of one motor type (i.e. motor size) is given, each column representing the data of this motor type containing a different winding (i.e. wire diameter). Depending on the wire used the electrical characteristics of the motor change.

Let's start with the **characteristic motor data** that can be found in the second block of motor data in the catalog.

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Characteristic motor data

describe the motor design and general behaviour

- independent of actual voltage or current

- strongly winding dependent values (electromechanical)
  - terminal resistance (phase to phase) R
  - terminal inductance (phase to phase) L
  - torque constant k_M
  - speed constant k_n
- almost independent of winding (mechanical)
  - speed-torque gradient $\Delta n/\Delta M$
  - mechanical time constant τ_m
  - rotor mass inertia J_{Mot}

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The characteristic motor data describe the intrinsic **motor design** and are **independent of the applied voltage or current**. They reflect the mechanical dimensions, the strength of the permanent magnet and the type of winding used.

A distinction can be made between characteristic data that have an electrical content and purely mechanical data.

Data with an **electromechanical content** vary considerably with the winding. The most prominent being the terminal resistance and inductance. The speed constant k_n and the torque constant k_M describe part of the energy conversion from electrical to mechanical. Depending of which winding you look at their value will vary considerably.

The last three values are purely **mechanical**. It does not matter which winding you take, their values are more or less the same for one motor type. As we will later see, the speed torque-gradient can be considered a measure of the motor strength, which is defined by the motor size (i.e. the motor type) and not the exact winding used. The rotor mass inertia - another purely mechanical parameter - is almost independent of the wire used, since a thinner wire diameter is compensated for by more winding turns.

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Winding resistance
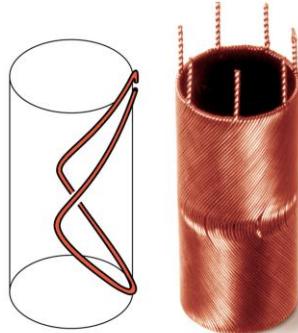
resistance increases from left to right

low resistance winding ⬌ high resistance winding

- thick wire, few turns
- low rated voltage
- high rated and starting currents
- high specific speed (min⁻¹/V)
- low specific torque (mNm/A)

- thin wire, many turns
- high rated voltage
- low rated and starting currents
- low specific speed (min⁻¹/V)
- high specific torque (mNm/A)

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The different windings of a motor type are listed in columns; the resistance increasing from left to right.

The first winding on the left is made with a wire of the largest diameter. Only a few winding turns can be placed in the air gap between housing and permanent magnet. Correspondingly, the resistance is low and the currents needed high, however at a low voltage. (In some cases the terminal resistance is even dominated by the brush resistance.)

The last winding on the right is made with the thinnest wire and many turns. The resistance is more important and the needed voltages are high; but there is only a **low current** flow.
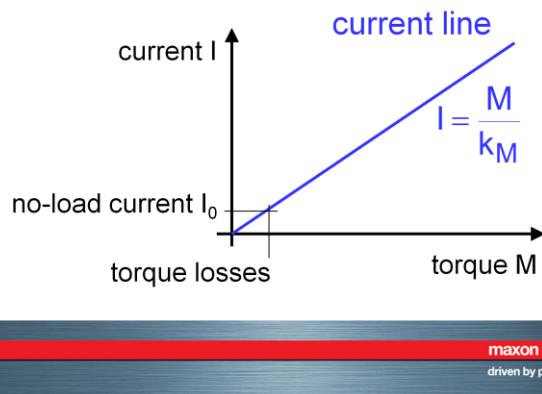
A given application (speed and torque) may be operated with all the different windings. However, the required motor voltage increases from left to right, while the current consumption decreases.

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Torque constant k_M

- produced torque is proportional to motor current

$$M = k_M \cdot I$$

  - defined by motor geometry and magnetic flux densities
  - measuring torques by measuring the current
  - for the motor: torque = current
  - unit: mNm/A

current I

current line

$$I = \frac{M}{k_M}$$

no-load current I_0

torque losses

torque M

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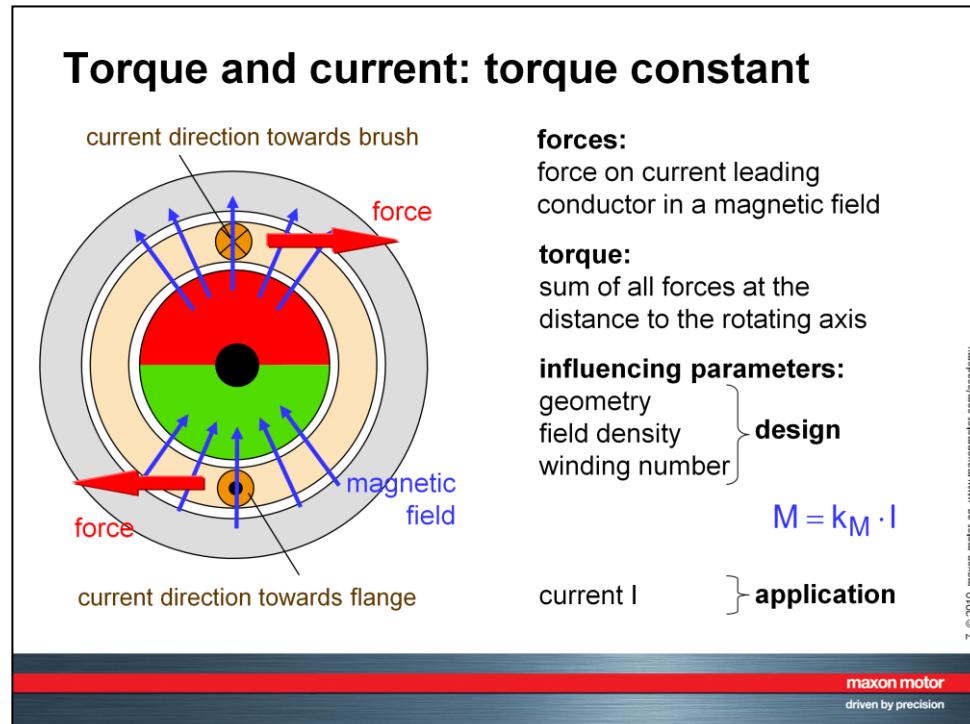
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The **torque constant k_M** is an electromechanical constant describing one part of the power transformation in the motor. It relates the motor current I to the produced torque M.

Torque and current are strictly proportional for coreless maxon motors. Basically, one can say that the two are equivalent for a given motor. This allows to use a motor as a torque probe; all you have to do is to measure the current.

For the small maxon motors the torque constant is given in **units of mNm/A**.

Torque and current: torque constant

current direction towards brush

force

magnetic field

force

current direction towards flange

forces:
force on current leading conductor in a magnetic field

torque:
sum of all forces at the distance to the rotating axis

influencing parameters:
geometry
field density } **design**
winding number

$$M = k_M \cdot I$$

current I } **application**

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This schematic motor cross section shows the origin of the simple proportional relationship between torque and current. The underlying physical principle is the **force on a current conducting wire in an external magnetic field**.

The amount of torque produced depends on the **geometrical arrangement of the winding**, its distance to the rotation axis, the density of winding turns, the strength of the **magnetic field** in the air gap and the amount of **current applied**. With the exception of the current all the other parameters are defined by the intrinsic design and cannot be changed on the finished motor. That's why they are summed up in one constant, the torque constant k_M. The amount of torque produced by the motor becomes proportional to the motor current.

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Speed constant k_n

- Induced voltage U_{ind} is proportional to motor speed n
  - law of induction: changing flux in a conductor loop
  - induced voltage proportional to speed
  - basically the inverse of k_M, but in different units

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

- Speed constant k_n
  - mostly used for calculating no-load speeds n_0
  - unit: min^{-1} / V

$$n_0 = k_n \cdot U$$

- Generator constant k_e
  - inverse of k_n: motor as a generator (e.g. DC-Tacho). How much voltage is produced per rpm?
  - units: mV / min^{-1}

    $V / 1000\ min^{-1}$

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The second electromechanical constant is the **speed constant k_n**. It describes how much voltage is induced in the winding rotating in the inhomogeneous magnetic field in the air gap. According to the law of induction the induced voltage is larger, the faster the flux changes, i.e. the faster the motor speed. Hence, the basic relationship must again be a proportionality between speed and induced voltage that can be measured across the terminals.

The unit of the speed constant is **rpm/V**.

One can show that the speed constant depends on the same design factors as the torque constant, but inversely. Therefore, the speed constant is essentially the same as the inverse of the torque constant – but expressed in different units.
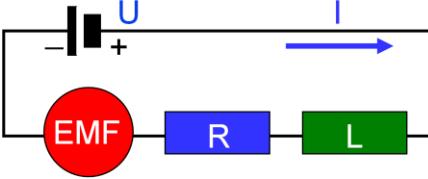
Multiplying the two constants gives:

$k_M * k_n = 1$ (in SI units)

$k_M * k_n = 30'000/\pi = 9549$ rpm/V*mNm/A (in maxon catalog units)

A related parameter is the **generator constant**, e.g. of DC tachos.

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Motor as an electrical circuit

applied motor voltage U:

$$U = L \cdot \frac{\partial I}{\partial t} + R \cdot I + EMF \cong R \cdot I + U_{ind}$$

$$U_{ind} = U - R \cdot I$$

$$\frac{n}{k_n} = U - R \cdot \frac{M}{k_M}$$

EMF: induced voltage U_{ind}

(winding) resistance R

winding inductance L

- **voltage losses over L can be neglected in DC motors**

$$n = k_n \cdot U - \left(\frac{30'000}{\pi} \cdot \frac{R}{k_M^2} \right) \cdot M$$

$$n = k_n \cdot U - \frac{\Delta n}{\Delta M} \cdot M$$

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In the following let's deduce the behavior of the motor.

For this purpose we consider the **motor as an electrical circuit**. The applied voltage U has to overcome the resistance R of the motor, its inductance L and the back EMF or induced voltage U_{ind}. This is expressed in the first equation which can be further simplified in quasi-stationary condition, i.e. under the assumption that in a DC motor the time derivative of the current can be neglected.
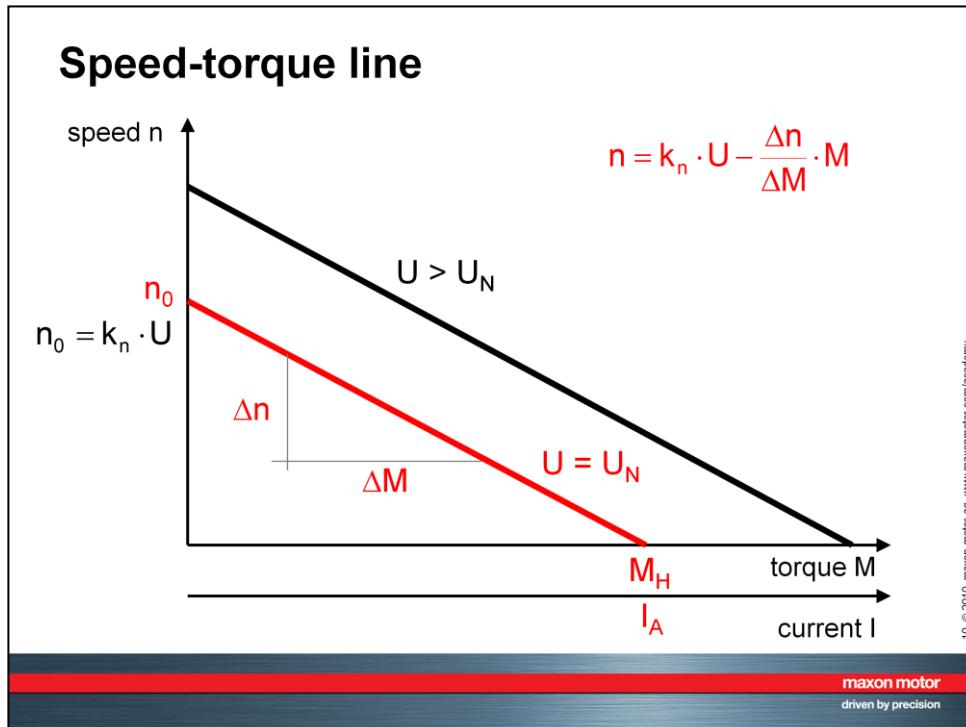
Rearranging terms we get an equation for the induced voltage which equals the applied voltage minus the resistance times the motor current, $U_{ind} = U - RI$.

Now we use the speed and torque constants to replace the electrical parameter U_{ind} and current with the mechanical parameters speed and torque. Multiplying the equation by k_n and using the relationship between k_n and k_M one obtains the first equation in the box. It states that the motor speed n equals the speed constant times the applied motor voltage U minus a *motor constant* times the torque M.

This motor constant is an intrinsic motor parameter representing the motor design, independent of the applied voltage or current. The unit of the motor constant is rpm/mNm (speed/torque), hence we use the symbol $\Delta n/\Delta M$.

The last equation is the sought relationship between speed and torque describing the mechanical behavior of the motor.

Remark: An alternative way to deduce this relationship is to look at the detailed power balance as figured out on the second slide of this presentation

Speed-torque line

$$n = k_n \cdot U - \frac{\Delta n}{\Delta M} \cdot M$$

$$n_0 = k_n \cdot U$$

(diagram: speed n on vertical axis, torque M / current I on horizontal axis; black line for $U > U_N$, red line for $U = U_N$ passing through n_0, with Δn and ΔM marked, reaching M_H / I_A)

The relationship between speed and torque is the equation of a straight line in our standard representation where the speed is traced as a function of the torque (red line).

- At zero torque, the speed is highest. This speed is called **no-load speed n_0**. The no-load speed can easily be calculated from the applied voltage and the speed constant of the motor.

- Enhancing the load torque leads to a linear reduction of the speed. It becomes clear what the meaning of $\Delta n / \Delta M$ is: It's the **gradient of the speed-torque line**.

- Increasing the torque further reduces speed up to the point where the motor stops. The corresponding torque is called **stall torque M_H**.

- We have learned that torque and current are equivalent. Hence, we can draw a current axis in parallel to the torque axis. The current corresponding to the stall torque is named **starting current I_A**.

A different view on the speed-torque line is to look at the **start-up of the motor**, i.e. we start at the right end of the speed-torque line. Applying a voltage at zero speed results in a high current, the starting current; there is no back-EMF to counteract the applied voltage. The current produces a high torque that accelerates the motor, the induced voltage increases and less current can flow. Hence, the faster the motor turns, the less torque is produced.
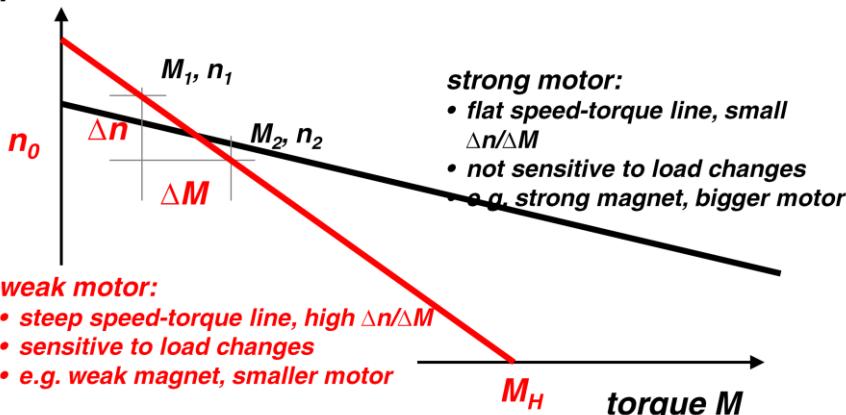
All these considerations are valid for a fixed **applied voltage U**. What happens if the voltage is changed, e.g. at a higher voltage? The applied voltage has only an influence on the first term, which is the no-load speed. A higher voltage results in a higher no-load speed. The speed-torque gradient is unaffected. As a net result: Changing the applied voltage results in a parallel shift of the speed-torque line.

Remark: An important feature of the speed-torque line is the fact that the produced torque is highest at start, which makes these motors very dynamic.

Speed-torque gradient

by how much is the speed reduced $\triangle n$, if the output motor torque is enhanced by $\triangle M$?

$$\frac{\triangle n}{\triangle M} = \frac{30'000}{\pi \cdot k_M^2} \cdot R = \frac{n_i}{M_{iH}}$$

speed n

M_1, n_1

n_0 $\triangle n$

M_2, n_2

$\triangle M$

strong motor:
• flat speed-torque line, small $\triangle n/\triangle M$
• not sensitive to load changes
• e.g. strong magnet, bigger motor

weak motor:
• steep speed-torque line, high $\triangle n/\triangle M$
• sensitive to load changes
• e.g. weak magnet, smaller motor

M_H torque M

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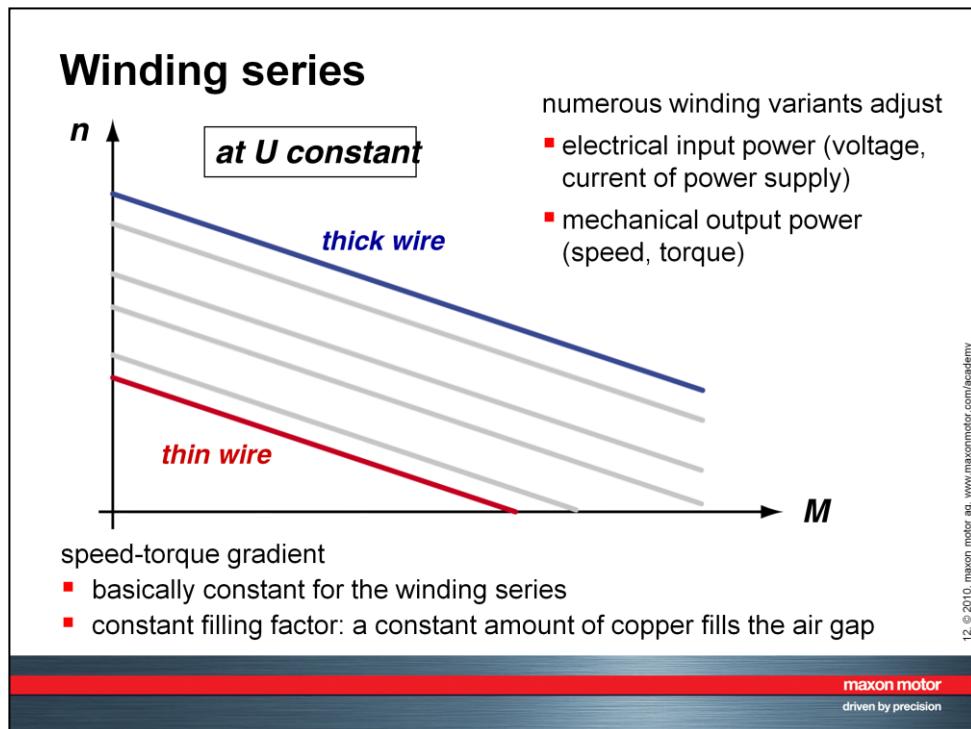
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Some remarks about the speed-torque gradient.

Essentially, it describes by how much the speed drops if the load is increased. It can be considered as one of the parameters related to motor strength.

• A **strong motor** is characterized by a flat speed-torque line. The speed drops only slightly when the load torque is enhanced. The value of the gradient is small.

• On a **weaker motor** the speed drop is larger. The speed-torque line is steeper and the value of its gradient is high.

• Indeed, in the maxon catalog one finds: the larger the motor, the smaller the speed-torque gradient.

The speed-torque gradient can be calculated from the resistance R and the torque constant k_M of the motor. An alternative way is to divide the no-load speed n_0 by the stall torque M_H.

Winding series

at U constant

thick wire

thin wire

numerous winding variants adjust
- electrical input power (voltage, current of power supply)
- mechanical output power (speed, torque)

speed-torque gradient
- basically constant for the winding series
- constant filling factor: a constant amount of copper fills the air gap
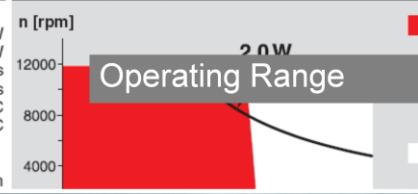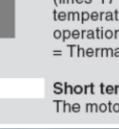
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Interestingly, the value of the speed-torque gradient is almost **independent of the winding** used in a particular motor type. Therefore, the speed-torque gradient can be considered a characteristic parameter of the motor type and size and not of the specific winding

If we look at all the windings of a motor type **at one and the same voltage U**, we get a **series of parallel speed-torque lines**; the one with the lowest resistance lying highest, the one with the highest resistance lying lowest.

This picture is useful in the process of winding selection.

Remark: Having different windings for one motor type allows the adjustment of the mechanical load (speed and torque given by the application and requiring a particular motor type) and the electrical input power available (voltage and current of the power supply).

Motor Data		110061	110062	110063	110064	110065	110066	110067	110068	110069	110070
Values at nominal voltage											
1 Nominal voltage	V	1.5	3.0	6.0	9.0	12.0	14.0	15.0	18.0	21.0	30.0
2 No load speed	rpm	10200	11700	9620	11800	11800	11800	11200	11200	11600	10800
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4 Nominal speed	rpm	867								70	4160
5 Nominal torque (max. continuous torque)	mNm	0.68								39	2.35
6 Nominal current (max. continuous current)	A	0.720	0.720	0.494	0.394	0.294	0.253	0.225	0.186	0.162	0.105
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9 Max. efficiency	%	58	57	56	58	58	58	58	57	57	55
Characteristics											
10 Terminal resistance	Ω	0.399	1.52	8.32	12.8	23.1	31.1	39.8	58.0	76.2	183
11 Terminal inductance	mH	0.017	0.0519	0.306	0.467	0.831	1.13	1.42	2.05	2.61	6.01
12 Torque constant	mNm / A	1.31								3	24.7
13 Speed constant	rpm / V	7296								7	387
14 Speed / torque gradient	rpm / mNm	2220	2770	2560	2600	2630	2600	2630	2670	2750	2880
15 Mechanical time constant	ms	24.5	23.7	23.2	23.2	23.2	23.2	23.4	23.3	23.4	23.8
16 Rotor inertia	gcm²	1.05	0.816	0.864	0.854	0.844	0.854	0.848	0.834	0.811	0.788

Specifications

Thermal data
17 Thermal resistance housing-ambient 29.8 K / W
18 Thermal resistance winding-housing 5.5 K / W
19 ... 3 s
20 ... 3 s
21 Ambient temperature -30 ... +85°C
22 Max. permissible winding temperature +125°C

Mechanical data (sleeve bearings)
23 Max. permissible speed 11900 rpm

Operating Range

n [rpm]

2.0 W

12000

8000

4000

Comments

Continuous o
In observation
(lines 17 and
temperature
operation at 2
= Thermal limi

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With all this knowledge at hand, we can now turn to the first block of motor data in the maxon catalog. Here, one finds the operational data which depend on the applied voltage.

As a reference voltage the rated voltage (also called **nominal voltage**) is defined in the first line. The different motor parameters are given for this motor voltage. The nominal voltage is not the voltage at which the motor must be run, basically any voltage may be applied. In many practical cases however, the operating voltage will be similar to rated one.

Values at nominal voltage

describe the special working points:
- at rated voltage U_N
- at rated current I_N

- No-load operating point
  - resulting no-load speed n_0
  - resulting no-load current I_0

n

- rated working point
  - resulting rated speed n_N
  - resulting rated torque M_N

- Motor at stall
  - resulting stall torque M_H
  - resulting starting current I_A

M

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The values at nominal voltage basically reflect three special operating points on the speed-torque line at nominal voltage.

The first point is the **no-load operating point**.
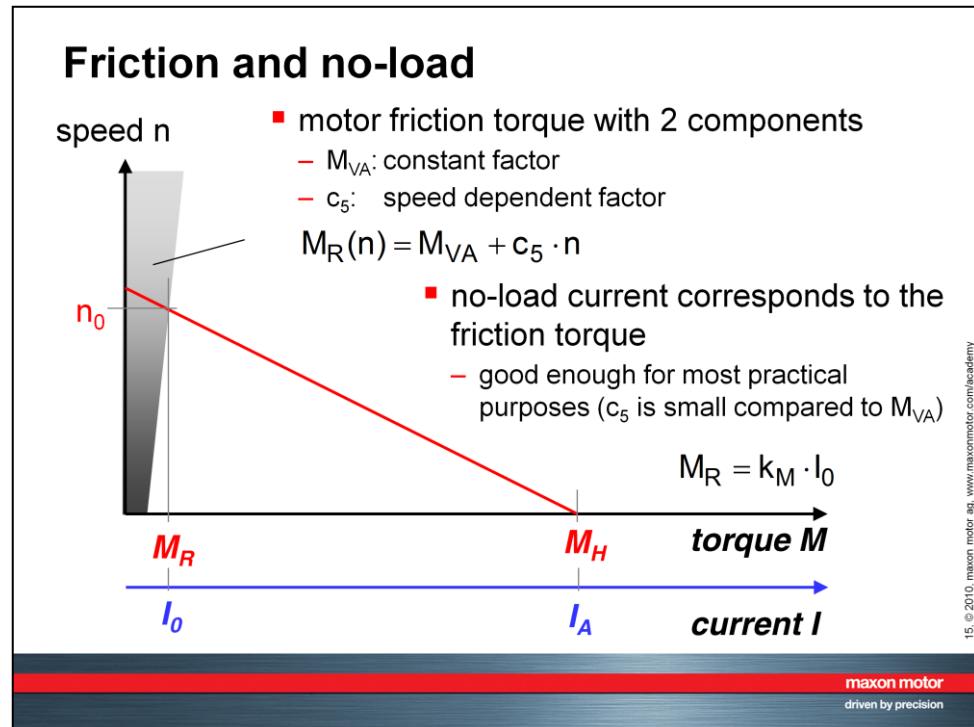
- The no-load speed is the resulting speed if no external output torque has to be delivered.
- The no-load current is the current needed to overcome internal losses, e.g. friction. (More on the next slide)

The second operating point is the **rated or nominal operating point**. It is defined by the **maximum permissible continuous current** or nominal current. This is the maximum current at which the motor can be operated for long periods of time without overheating.

- The rated or nominal torque is the motor torque corresponding to the nominal current.
- The nominal speed has no deeper meaning. It's just the resulting speed at this load.

The last operating point on the far right is **at stall or start**.

- The stall torque describes at which load torque the motor stalls, when supplied with the nominal voltage.
- The starting current is the corresponding current, that will also be present just after powering the motor with the nominal voltage.

Friction and no-load

speed n

- motor friction torque with 2 components
  - M_{VA}: constant factor
  - c_5: speed dependent factor

$$M_R(n) = M_{VA} + c_5 \cdot n$$

n_0

- no-load current corresponds to the friction torque
  - good enough for most practical purposes (c_5 is small compared to M_{VA})

$$M_R = k_M \cdot I_0$$

M_R M_H *torque M*

I_0 I_A *current I*

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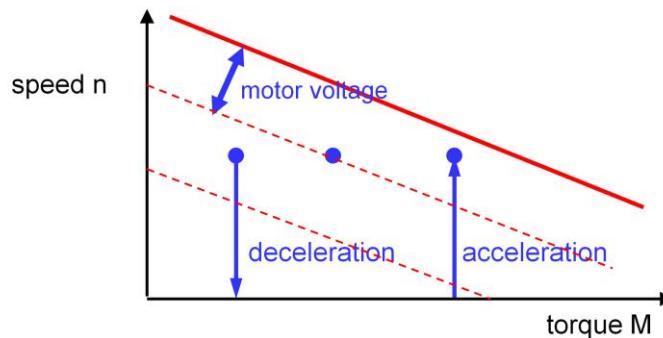
A closer look at the no-load operating point shows that it is influenced by the **losses in the motor**.

- These losses are shown as a grey area in the diagram and are modeled mathematically by a constant and a speed dependent term.

- The no-load speed is in reality a little bit lower than the ideal one calculated by $n_{0i} = k_n * U$.

In most cases the loss torque is a few percent of the rated torque. For most practical purposes, therefore, we can neglect the speed dependency of the no-load current as well as the tiny error made when calculating the no-load speed.

Operating points

- Load operating points are characterized by a load speed n_L at a given load torque M_L
- Motor operating points lie on the speed-torque-line: select the motor voltage accordingly
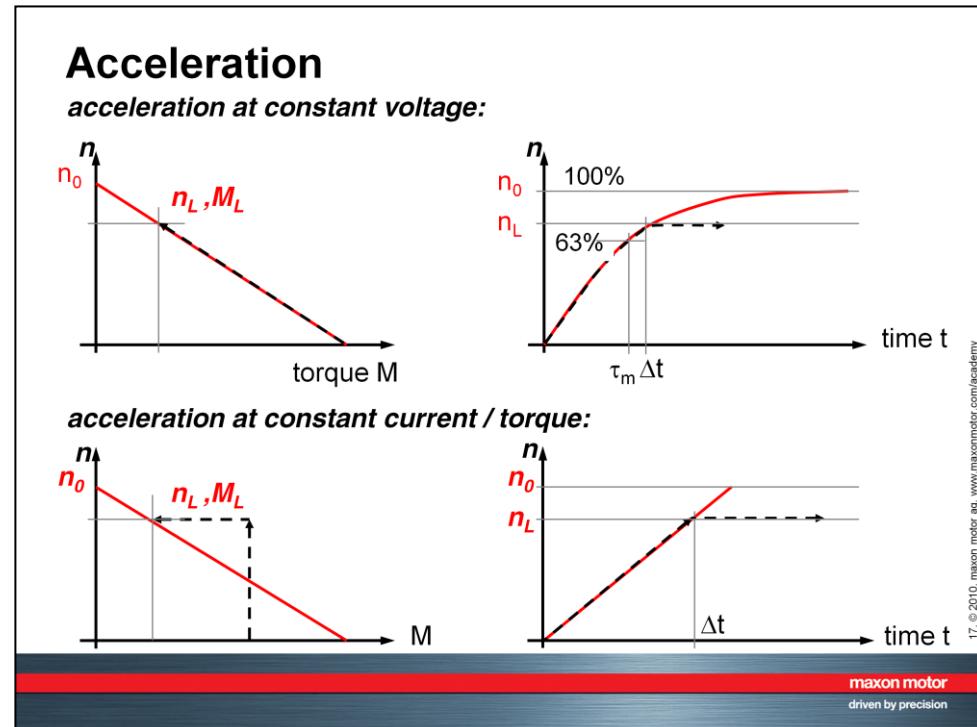

An important concept are the **operating points**. We have to distinguish between the

- **Load operating points**: These are pairs of speed and torque values that are required by application. In the diagram they are represented by the blue points.

  - Typically, during acceleration the highest torque is needed and all the points on the acceleration arrow are operating points that are run through.

  - The single point in the middle represents a constant motor operation at given load and speed.

  - During deceleration, usually less torque is needed. Friction helps.

- The **motor operating points** are located on the speed-torque line at the relative voltage.

Running the motor at the operating points demanded by the load requires the motor voltage to be adjusted correspondingly, and hence the speed-torque line. That's the task of a controller.

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Acceleration

acceleration at constant voltage:

acceleration at constant current / torque:

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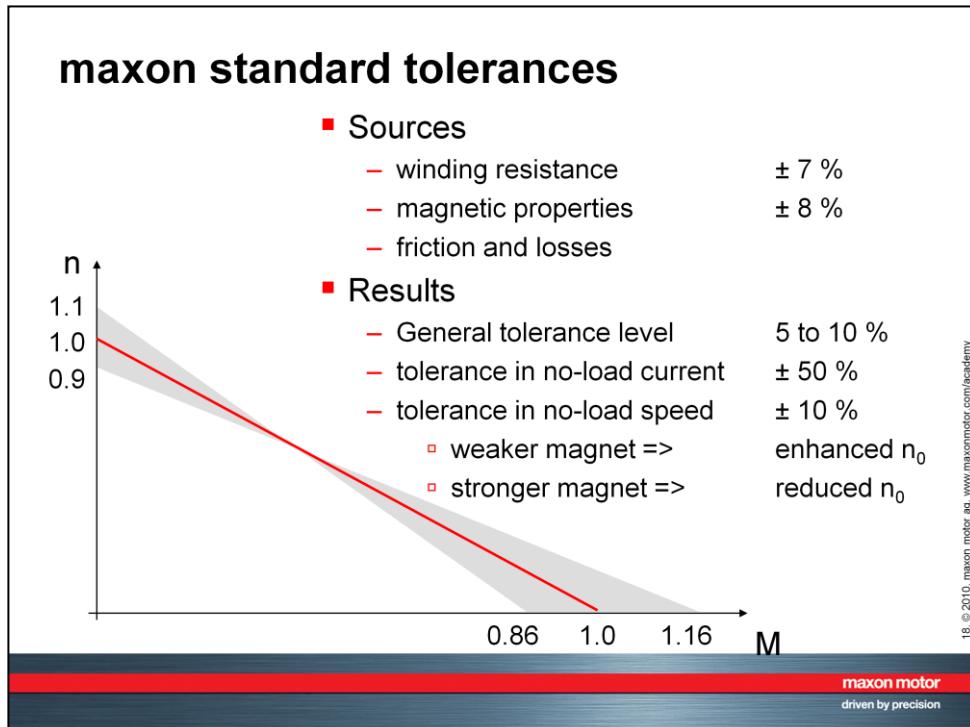
Acceleration: There are two situations that must be distinguished.

- The first is **acceleration at constant voltage**. It's assumed that a fixed voltage is applied and the motor will accelerate along the speed-torque line of the motor at that voltage (top left). The torque and hence the acceleration is highest at the beginning. The faster the motor turns, the less current can flow and the acceleration rate is reduced. The speed as a function of time (top right) shows an exponential behavior which is best characterized by the mechanical time constant τ_m. Prerequisite of this type of acceleration is that the high starting currents can be provided.

- This is not necessarily the case for bigger motors. The capability of power supply or controller can put a limit to the current available. So we have the situation of **acceleration at constant torque**, when acceleration takes place at the maximum current that can be delivered by the power supply or the controller (bottom left). In such cases the speed will increase linearly with time (lower right), and the acceleration time can easily be calculated.

Additional remarks

- Very often there is even a mixed situation: Fist acceleration at the current limit and later acceleration at the maximum voltage.

- The mechanical time constant of the motor includes the rotor inertia only. Any load inertia and friction will increase this value.

maxon standard tolerances

- **Sources**
  - winding resistance   ± 7 %
  - magnetic properties   ± 8 %
  - friction and losses
- **Results**
  - General tolerance level   5 to 10 %
  - tolerance in no-load current ± 50 %
  - tolerance in no-load speed   ± 10 %
    - weaker magnet =>   enhanced n_0
    - stronger magnet =>   reduced n_0

Tolerances

In spite of the fact that the maxon motor data are represented with 3 significant digits they feature quite large tolerances.

- The main sources of tolerances stem from winding resistance (wire diameter) and from the permanent magnets (mechanical and magnetic tolerances).
- In addition, there are quite large relative tolerances in the losses, such as the friction in bearings and commutation. On an absolute scale, however they are small.

The most important results, from a practical point of view are:

- During motor selection allow for tolerances of typically 5 to 10%. Respect this by selecting motors with this amount of margin.
- The tolerance in no-load speed is ±10%.
- The tolerance in no-load current is ±50%.

Influence of temperature

temperature coefficients

Cu	+ 0.39 % per K	AlNiCo	- 0.02 % per K
		Ferrite	- 0.2 % per K
		NdFeB	- 0.1 % per K

temperature   **resistance**   **magnetic properties**

- example: RE motor

$\Delta T = + 50K$ R: + 19.5 % k_n + 5 % (no-load speed)

k_M - 5 % (more current!)

stall torque M_H : - 22 %

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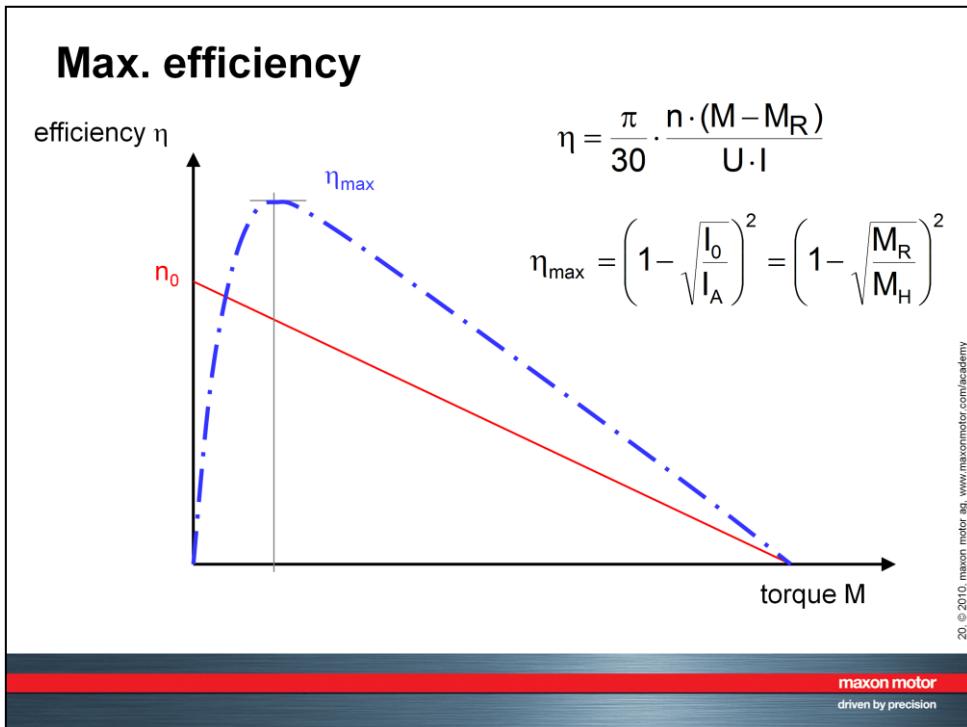
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Temperature has an influence on motor data as well.

- Generally, the permanent magnets become weaker at higher temperature, but this is a reversible effect within the permissible temperature range of the motors; the magnets regain their original strength when they cool down.

- AlNiCo magnets show the weakest temperature dependency. That's why they are used in DC Tachos, a measuring device that should give the same output independent of temperature.

- Neodymium magnets have a stronger temperature dependency. A motor that is 50°C hotter exhibits a speed constant that is about 5% higher and a torque constant that is about 5% lower.

- When the motor heats up, the winding resistance increases by about 0.4% per Kelvin. The main effect is that power losses will be even more pronounced at higher temperature.

The variation of the motor data with temperature create problems in applications very seldom. Although motor selection is done with the data specified for the cold motor at room temperature, there is usually enough margin left to compensate for the weakening of the motor when it becomes hot in prolonged operation.
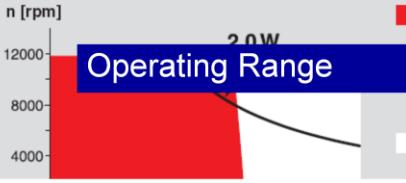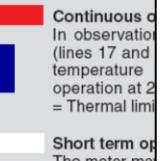
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Max. efficiency

efficiency η

η_{max}

n_0

torque M

$$\eta = \frac{\pi}{30} \cdot \frac{n \cdot (M - M_R)}{U \cdot I}$$

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

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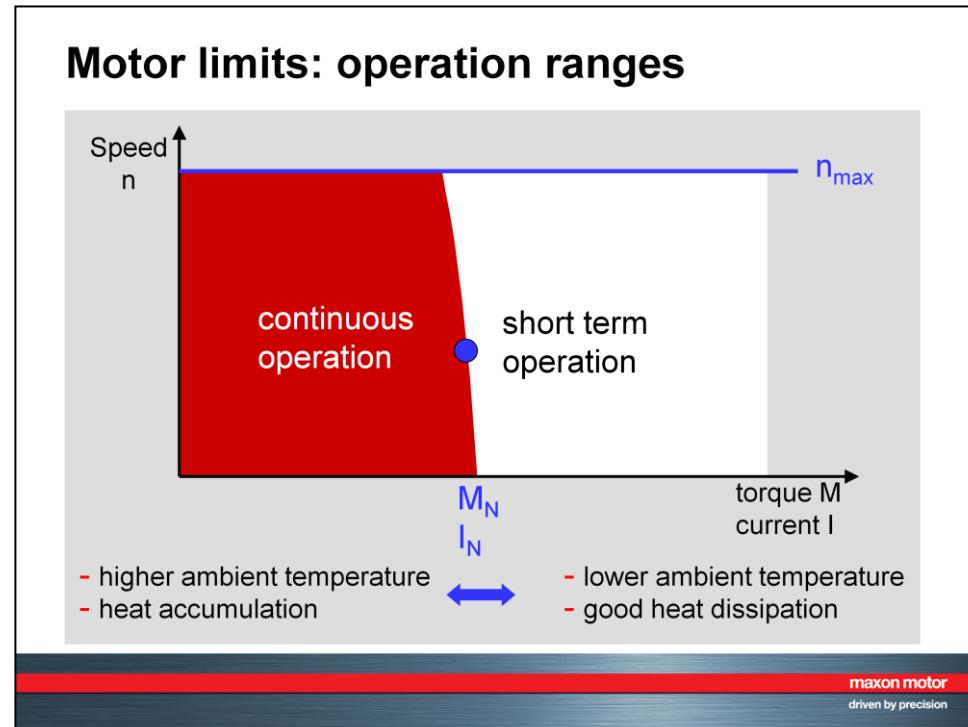
A high **maximum efficiency at nominal voltage** is a nice sales argument. However one should be aware of the fact that this number depends on the applied motor voltage (it increases with increasing voltage) and on the motor torque as shown in the diagram. Running the motor at higher or lower torques results in a lower efficiency.

In our opinion it is much better to account for the losses in the motor by looking at the no-load current.

In battery driven applications the most important point to consider is that the motor makes good use of the available voltage and uses the least current.

			110061	110062	110063	110064	110065	110066	110067	110068	110069	110070
Motor Data												
	Values at nominal voltage											
1	Nominal voltage	V	1.5	3.0	6.0	9.0	12.0	14.0	15.0	18.0	21.0	30.0
2	No load speed	rpm	10200	11700	9620	11800	11800	11800	11200	11200	11600	10800
3	No load current	mA	201	117	46.7	39.1	29.3	25.1	22.2	18.5	16.5	10.7
4	Nominal speed	rpm	867								70	4160
5	Nominal torque (max. continuous torque)	mNm	0.68								39	2.35
6	Nominal current (max. continuous current)	A	0.720	0.720	0.494	0.394	0.294	0.253	0.225	0.186	0.162	0.105
7	Stall torque	mNm	4.93	4.51	4.02	4.82	4.76	4.81	4.53	4.47	4.48	4.03
8	Starting current	A	3.76	1.97	0.721	0.700	0.519	0.450	0.377	0.310	0.275	0.164
9	Max. efficiency	%	58	57	56	58	58	58	58	57	57	55
	Characteristics											
10	Terminal resistance	Ω	0.399	1.52	8.32	12.8	23.1	31.1	39.8	58.0	76.2	183
11	Terminal inductance	mH	0.017	0.0519	0.306	0.467	0.831	1.13	1.42	2.05	2.61	6.01
12	Torque constant	mNm / A	1.31								.3	24.7
13	Speed constant	rpm / V	7290								7	387
14	Speed / torque gradient	rpm / mNm	2220	2770	2560	2600	2630	2600	2630	2670	2750	2880
15	Mechanical time constant	ms	24.5	23.7	23.2	23.2	23.2	23.2	23.4	23.3	23.4	23.8
16	Rotor inertia	gcm²	1.05	0.816	0.864	0.854	0.844	0.854	0.848	0.834	0.811	0.788

Specifications

Thermal data
17 Thermal resistance housing-ambient 29.8 K / W
18 Thermal resistance winding-housing 5.5 K / W
19 ... 3 s
20 ... 3 s
21 Ambient temperature -30 ... +85°C
22 Max. permissible winding temperature +125°C

Mechanical data (sleeve bearings)
23 Max. permissible speed 11900 rpm

Operating Range

n [rpm]

2.0 W

12000

8000

4000

Comments

Continuous o
In observatio
(lines 17 and
temperature
operation at 2
= Thermal limi

Short term op
The motor ma

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In the third part we look at the limits of motor operation which are represented in the operation range diagram.

Motor limits: operation ranges

Speed n

n_{max}

continuous operation

short term operation

M_N
I_N

torque M
current I

- higher ambient temperature
- heat accumulation

- lower ambient temperature
- good heat dissipation

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The red area in the operation range diagram represents the **continuous operation range**. Running the motor at speeds and torque in this area will not lead to overheating and a reasonable motor life can be expected.

The continuous operation range is limited on top by the **max. permissible speed n_{max}**. This speed is not an absolute limit but is based on consideration about brush and bearing life. Approaching and exceeding this speed will gradually lead to enhanced audible noise and reduced motor life.
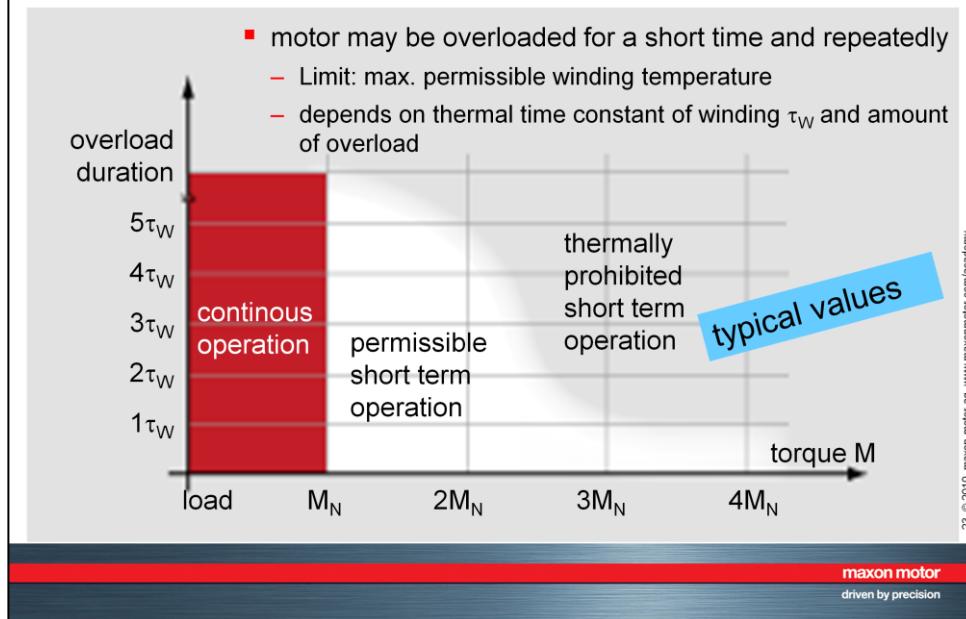
On the right, the continuous operation range is limited by **the maximum continuous (rated or nominal) torque** or current. Exceeding this torque or current will lead to an inacceptable motor heating. Again, this is not a sharp limit but depends on the details of heat dissipation. In a cold ambient or with good heat dissipation – e.g. by forced air cooling – more current is allowed and this limit moves to the right. In situations where the heat gets stuck near the motor the continuous torque is reduced.

At higher speeds internal losses increase and less current is available for output torque production. That's why in most cases the maximum permissible torque is lower at high speeds.

On the right there is the **short term operation range** depicted in white. The diagram in the catalog expands to only about twice the nominal torque, but the motor may be overloaded much more.

Short term operation means, that the motor can be operated at higher torque than nominal but only for a limited amount of time. The big question is, how long is "short"?

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Short-term operation at overload

- motor may be overloaded for a short time and repeatedly
  - Limit: max. permissible winding temperature
  - depends on thermal time constant of winding τ_W and amount of overload

overload duration

$5\tau_W$

$4\tau_W$

thermally prohibited short term operation

$3\tau_W$ continous operation

$2\tau_W$ permissible short term operation

$1\tau_W$

typical values

torque M

load M_N $2M_N$ $3M_N$ $4M_N$

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The amount of permissible overload depends on the heating of the thermally weakest part in the motor, i.e. the winding. The winding temperature should remain below the **maximum permissible winding temperature** T_{max}. The heating of the winding follows an exponential behavior which is characterized by the **thermal time constant of the winding** τ_W.

This time constant amounts to several seconds for the smallest maxon motors up to about 1 minute for the biggest ones. It gives the intrinsic time unit of the overload duration.

The **amount of overload** is best described in units of the nominal torque; again this is an intrinsic motor parameter. Hence we can give a general frame for overload operation that can be applied more or less to all motors.

The diagram shows the overload duration as a function of the required torque.

- The higher the torque, the shorter it may be applied.

- At twice the rated current, the motor may be operated as long as about 5 times the thermal time constant of the winding.

- Between 2 and 3 times the nominal torque the possible duration of overload is strongly reduced. At three times the rated torque, the duration is about 60% of the thermal time constant of the winding.

The diagram gives **general directives** and in many cases it allows a quick decision if a thermal overload situation is permitted or not. Overload conditions at relatively low torque and duration can be achieved without problems, while overloading the motor for a long time and at a high torque cannot be done without damaging the motor. In between there is a "gray" zone where it is difficult to give a clear answer without testing and additional experiments. The detailed thermal reaction of the motor depends on the heat dissipation situation as well as the thermal history of the motor.

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15 Mechanical time constant	ms	24.5	23.7	23.2	23.2	23.2	23.2	23.4	23.3	23.4	23.8
16 Rotor inertia	gcm²	1.05	0.816	0.864	0.854	0.844	0.854	0.848	0.834	0.811	0.788

Values at nominal voltage

Characteristic motor data

Specifications

Thermal data
17 Thermal resistance housing-ambient   29.8 K / W
18 Thermal resistance winding-housing   5.5 K / W
19   3 s
20   3 s
21 Ambient temperature   -30 ... +85°C
22 Max. permissible winding temperature   +125°C

Further Specifications

Mechanical data (sleeve bearings)
23 Max. permissible speed   11900 rpm

Operating Range

n [rpm]

2.0 W

12000

8000

4000

Operating Range

Comments

Continuous o
In observatio
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The last part of this presentation gives an overview of the additional specification. In particular the thermal and mechanical data.

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Thermal motor data

describe the motor heating and thermal limits
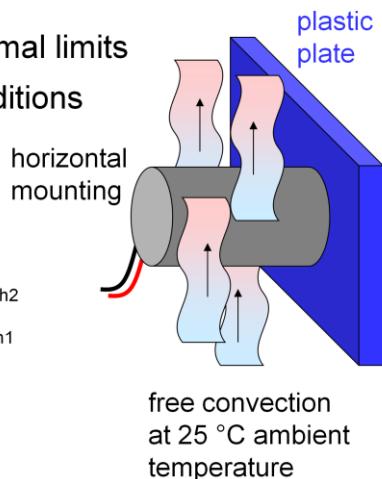
- depend strongly on mounting conditions
- standard mounting:

- heating and cooling
  - thermal resistance housing-ambient R_{th2}
  - thermal resistance winding-housing R_{th1}
  - thermal time constant of winding τ_{thW}
  - thermal time constant of motor τ_{thS}
- temperature limits
  - ambient temperature range
  - max. winding temperature T_{max}

plastic plate

horizontal mounting

free convection at 25 °C ambient temperature

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The thermal data are needed to evaluate and calculate the thermal response of the motor. Thermal data depend on the details of heat dissipation. Thus, the values on the data sheet are given for **standard conditions** which are defined as follows
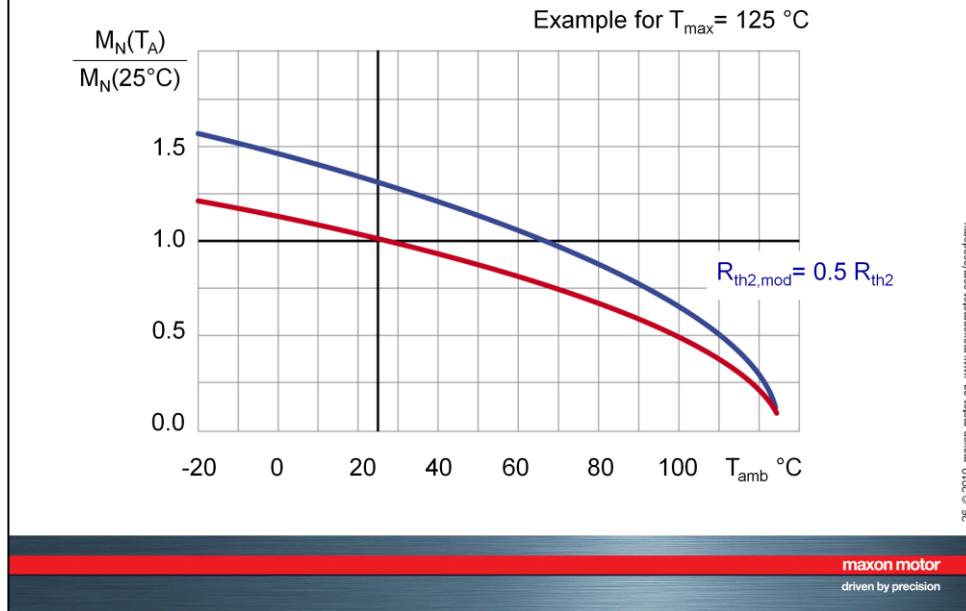
- Ambient temperature of 25°C
- Motor mounted horizontally on plastic plate: There is not much heat dissipation through the flange.
- Free air convection, no additional cooling. Free air convection is quite effective for heat dissipation.

These standard conditions represent **average mounting conditions**. Mounting the motor on a metallic frame (heat sink) will increase heat dissipation and hence there is more current allowed (see next slide). When the motor is encapsulated, there is no air convection, the ambient temperature increases and less current is permitted.

The **thermal resistances** describe how well heat can flow from winding to housing and from the housing to the ambient. It's this second parameter which is influenced by the mounting conditions.

The **thermal time constants** give the typical time frames for the heating of the winding and of the motor as a whole. While the winding temperature reacts with in a few seconds it takes several minutes to heat up – or even longer for bigger motors. Measuring the housing temperature will not give short term information about the winding temperature. The housing will have reached its thermal equilibrium after typically half an hour or more.

Nominal Torque and Temperature

Example for $T_{max} = 125\ °C$

$\dfrac{M_N(T_A)}{M_N(25°C)}$

$R_{th2,mod} = 0.5\ R_{th2}$

1.5

1.0

0.5

0.0

-20   0   20   40   60   80   100 T_{amb} °C

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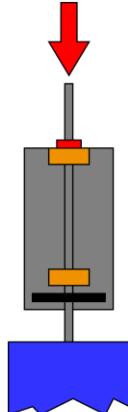
This diagram shows the **influence of the ambient temperature** on the maximal permissible torque (**red curve**). One can see that at temperatures below 25° the permissible torque is higher, while it decreases at higher ambient temperatures.

The influence of an **improved heat dissipation** is shown in the **blue curve**. Reducing the thermal resistance between housing and ambient by 2 leads to a maximum permissible current (or torque) which is about 30% higher at standard ambient conditions. Such a reduction of the thermal resistance is easily obtained, e.g. by mounting the motor on a metallic chassis.

Mechanical motor data

describe maximum speed and the properties of bearings

- **max. permissible speed**
  - limited by bearing life considerations (EC)
  - limited by relative speed between collector and brushes (DC)
- **axial and radial play**
  - suppressed by a preload
- **axial and radial bearing load**
  - dynamic: in operation
  - static: at stall

axial press fit force
(shaft supported)

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The **mechanical data** contain the maximum permissible speed and information about the bearing play and load.

- The **maximum permissible speed** n_{max} limits the continuous operation range. It is based on consideration about bearing and brush life.

- **Radial and axial play** can be reduced to zero by a preload of the ball bearings. As a rule the bearings of brushed motors are not preloaded (There is no gain in life expectation which is limited by the brush system). Large DC motors (diameter 50mm and higher) have preloaded ball bearings as well as all the brushless EC motors.

- The **bearing load** is given for static and dynamic situation. Static means at standstill, dynamic means during operation.

Assigned power rating
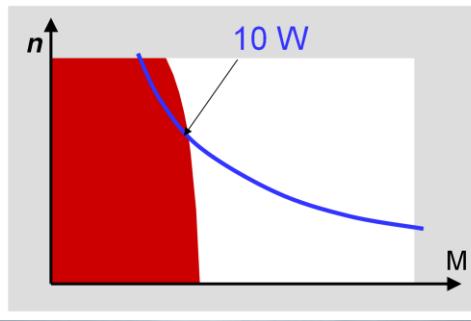
- **no general criteria**
  - electrical power at the rated working point
  - output power at the rated working point:
  - or maximum output power at rated voltage
  - but also "marketing" factors

$$P_{typ} = \frac{\pi}{30} \cdot n_N \cdot M_N$$

- **anyway …**
  - assigned power rating is only a rough estimate
  - drive must fulfill both, torque and speed requirements

10 W

n

M

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A last remark about **assigned power rating**.

Many DC motors data sheets give an assigned power rating. However, there is no unique way of assigning power to small DC motors. Each manufacturer is basically free.

Anyway, the rated power of a motor can only be a general landmark in the motor selection. The important thing is, that the motor must be able to fulfill both, speed and torque requirements of the application independently.

The **torque rating** of the motor is much more important. E.g. a motor can have a high power rating due to its high maximum speed. However, there are situations where this high speed is not needed, but the torque that the motor can provide. The power required by the application might be much lower than the rated motor torque. However one needs this motor "oversized" in power to account for the torque needed.