



Engineers Appendix

Examples of DC Coreless Motor calculations

This section aims to provide all the information necessary to select a DC Coreless Motor and to calculate the values at the desired operating point.

Example: Direct drive without a gearhead attached to the motor.

For this application we are looking for a DC Coreless Motor for a continuous duty application. The application requirements are:

Available voltage:	10 V _{dc}		
Available current:	1 Amp		
Motor operating point:	2,000 rpm	[n]	desired motor speed
	6 mNm	[τ]	desired output shaft torque
	30°C	[T _{amb}]	ambient temperature
	Continuous operation		
Motor dimensions:	25 mm		maximum allowable length
	∅ 40 mm		maximum allowable diameter

The Portescap DC Coreless motor 22N28 can easily deliver 6 mNm of torque continuously, and is a good starting point for our calculation.

Let's examine the motor series 22N 28 213E.286, which has a nominal voltage of 9 V_{dc}. The characteristics we are most interested in are the torque constant (k) of 12.2 mNm/A, and the terminal resistance (R) of 10.3 Ω. Neglecting the no-load current (I_o), for a load torque (τ) of 6 mNm the motor current is:

$$I = \tau / k \quad [A]$$

$$I = 6 \text{ mNm} / 12.2 \text{ mNm/A} = .49 \text{ A}$$

Now we can calculate the drive voltage (U) required for running the motor at 22°C, at a running speed of 2,000 rpm with a load torque of 6 mNm.

$$U = R \times I + k \times \omega \quad [V_{dc}]$$

$$\omega = 2\pi/60 \times n = 2\pi/60 \times 2,000 \text{ rpm} = 209.44 \text{ rad/s} \quad [\text{rad/s}]$$

$$U = 10.3 \Omega \times .49 \text{ A} + (12.2 \times 10^{-3} \text{ Nm/A}) \times 209.44 \text{ rad/s} = 7.60 \text{ V}_{dc}$$

(Note: In this equation the torque constant must be in units of Nm/A.)

We note that the current of 0.49 A is quite close to the rated continuous current of 0.62 A. We therefore need to calculate the final rotor temperature (T_r) to make sure it stays below the max rated coil temperature (from catalog data sheet) of 100 °C, and that the voltage required remains within the 10 V_{dc} available. These thermal considerations are explored in detail below.

Thermal considerations while selecting a motor:

When torque is applied to a motor, joule losses are created ($P_{\text{Joule}} = R \times I^2$) and the rotor temperature increases. The motor dissipates the heat generated at two levels:

1. From the coil to the motor body ($R_{\text{th rotor-body}}$)
2. From the motor body to the ambient environment ($R_{\text{th body-ambient}}$)

The ability for a motor to dissipate heat is determined by these thermal resistances. Moreover, the coil resistance value increases with temperature. Therefore P_{Joule} increases until it reaches a steady state value. In this exercise we would like to check whether at a given continuous operating point the coil temperature stays below the maximum rated coil temperature.

The 22N28-213E.286 requires 0.49 A and 7.62 V at a working point 6 mNm and 2,000 RPM. The given catalogue parameters are:

Maximum rated coil temperature:	100	[°C]
Thermal resistance $R_{\text{th rotor-body}}$:	6	[°C/W]
Thermal resistance $R_{\text{th body-ambient}}$:	22	[°C/W]
Terminal resistance R_0^* :	10.3	[Ω]
Thermal coefficient of resistance for Copper α :	0.0039	[°C ⁻¹]

*The terminal resistance in the catalogue is always given at room temperature (22 °C).

The resistance increase with temperature is given by the following equation:

$$R_{T_{\text{Final}}} = R_0 \times (1 + \alpha \times (T_{\text{Final}} - 22 \text{ °C}))$$

According to the Thermal Law:

$$\Delta T = P_{\text{dissipated}} \times R_{\text{th}}$$

In our case, we consider the following thermal law between the coil and the ambient environment. ΔT [°C] is the temperature difference between the coil and the ambient temperature $T_{coil} - T_{amb}$.

$$P_{dissipated} = P_{Joule} = R \times I^2 = R_0 \times (1 + \alpha \times (T_{coil} - 22 \text{ °C})) \times I^2 \quad [W]$$

$$R_{th} = R_{th \text{ rotor-body}} + R_{th \text{ body-ambient}} = 28 \text{ °C/W} \quad (\text{total thermal resistance between the coil and ambient})$$

Thus:

$$T_{coil} - T_{amb} = R_{th} \times R_0 \times (1 + \alpha \times (T_{coil} - 22 \text{ °C})) \times I^2 \quad [°C]$$

Finally, isolating T_{coil} gives:

$$T_{coil} = \frac{T_{amb} + R_{th} \times R_0 \times (1 - \alpha \times 22 \text{ °C}) \times I^2}{1 - R_0 \times I^2 \times R_{th} \times \alpha} = \frac{22 \text{ °C} + 28 \frac{\text{°C}}{\text{W}} \times 10.3 \Omega \times \left(1 - \frac{0.0039}{\text{°C}} \times 22 \text{ °C}\right) \times (0.492 \text{ A})^2}{1 - 10.3 \Omega \times (0.492 \text{ A})^2 \times 28 \frac{\text{°C}}{\text{W}} \times 0.0039 / \text{°C}} = 118 \text{ °C}$$

At steady state, the final coil temperature is 118°C which is above the limit. In theory the motor cannot be used because the coil insulation would burn and create short circuit in the coil. However, the thermal resistance $R_{th \text{ body-ambient}}$ is usually overestimated. It is measured when the motor is placed in air with no contact with another part. In reality, the motor is always fixed in the application (fixed by the front flange, clamped on the outside diameter, etc.). These fixations usually act as heat sinks and allow the motor to dissipate more heat. Therefore a real value for $R_{th \text{ body-ambient}}$ in the application is usually closer to half of the value given in the datasheet. Doing the math with $R_{th \text{ body-ambient}} = 11 \text{ °C/W}$ ($R_{th} = 17 \text{ °C/W}$) will give you a final coil temperature of 73°C.

With a coil temperature of 73°C the new resistance value would be:

$$R_{T \text{ Final}} = R_0 \times (1 + \alpha \times (T_{\text{Final}} - 22 \text{ °C})) = 10.3 \Omega \times (1 + 0.0039 / \text{°C} \times (73 \text{ °C} - 22 \text{ °C})) = 12.35 \Omega$$

In our case, the resistance has increased and therefore the joule losses have also increased. To keep the same mechanical power output, we need to provide more electrical input:

$$U = R_{T \text{ Final}} \times I + k \times \omega = 12.35 \Omega \times 0.49 \text{ A} + (12.2 \times 10^{-3} \text{ Nm/A}) \times 209.44 \text{ rad/s} = 8.61 \text{ V}$$

Thus, to achieve the requested speed at 73°C coil temperature, the voltage has to be increased at 8.61 V.

$$P_{\text{mech}} = 0.006 \text{ Nm} \times 2,000 \text{ rpm} \times 2\pi/60 \text{ rad-s}^{-1}/\text{rpm} = 1.26 \text{ W}$$

$$P_{\text{elec}} = 8.63 \text{ V} \times 0.49 \text{ A} = 4.23 \text{ W}$$

$$P_{\text{joule}} = 12.35 \Omega \times (0.49 \text{ A})^2 = 2.97 \text{ W}$$

$$\text{Efficiency} = P_{\text{mech}} / P_{\text{elec}} = 30\%$$

Note: The above model is only valid for continuous operation. For intermittent duty, a time step model is necessary to estimate the final temperatures.

In conclusion, the 22N28 will be an appropriate choice since the mountings will help dissipate heat. But to achieve better efficiency, another motor can be selected based on the following:

Selecting a DC Brush Motor for better efficiency and temperature regulation:

Let's consider the fundamental equation of DC motors:

$$U = R \times I + k \times \omega$$

Multiplying both sides of the equation by the current:

$$U \times I = R \times I^2 + k \times I \times \omega$$

From $\tau = k \times I$ we know that $I = \tau/k$. Substituting into the previous equation and simplifying gives:

$$U \times I = R/k^2 \times \tau^2 + \tau \times \omega$$

By examining this equation we can identify the key parameters.

$$U \times I = P_{\text{elec}}$$
 is the electrical power supplied

$$\tau \times \omega = P_{\text{mech}}$$
 is the mechanical power converted by the motor

$$R/k^2 \times \tau^2 = \text{joule losses}$$

Therefore the motor regulation parameter R/k^2 is directly related to the motor's capability of converting electrical power to mechanical power. A lower value of R/k^2 means better heat conversion. R/k^2 values are usually in the same range for a motor family and are very good indicators of motor performance across different motor types.

For example:

22N28 types offer R/k^2 values around $70 \times 10^3/\text{Nms}$.

22N78 types offer R/k^2 values around $16 \times 10^3/\text{Nms}$.

For the same package size (22 mm diameter, 32 mm length) and the same mechanical output power, the Athlonix 22N78 will have four times less joules losses and therefore better efficiency.

To take into consideration thermal properties of the motor, we can compare the values for $R/k^2 \times R_{\text{th}}$ which reflect the ability of a motor to convert electrical power to mechanical power and dissipate joule losses for a given job:

	R/k^2 [$10^3/\text{Nms}$]	$R_{\text{th}} = R_{\text{th rotor-body}} + R_{\text{th body-ambient}}$ [$^{\circ}\text{C}/\text{W}$]	$R/k^2 \times R_{\text{th}}$ [$^{\circ}\text{C} \times 10^3 / (\text{Nm})^2$]
22N28-213E	69	28	1932
22N78-215E	17	28	476

The above table predicts best thermal behavior under load conditions for 22N78 motor. If we do the math, we will have the following parameters and results:

22N78-215E:

$$k = 25.2 \text{ mNm/A}$$

$$I = \tau/k = 0.24 \text{ A}$$

$$R_0 = 10.5 \text{ } \Omega$$

$$R_{\text{th}} = 6 \text{ } ^{\circ}\text{C}/\text{W} + (22 \text{ } ^{\circ}\text{C}/\text{W})/2 = 17 \text{ } ^{\circ}\text{C}/\text{W}$$

Using the method of calculation as the previous example:

$$T_{\text{coil}} = 32.7 \text{ }^{\circ}\text{C}$$

$$R_{T \text{ Final}} = 10.94 \text{ } \Omega$$

$$U_{\text{required}} = 7.90 \text{ V}$$

$$P_{\text{elec}} = 7.90 \text{ V} \times 0.24 \text{ A} = 1.89 \text{ W}$$

$$P_{\text{mech}} = 6 \times 10^{-3} \text{ Nm/A} \times 2,000 \text{ rpm} \times 2\pi/60 \text{ rad-s}^{-1}/\text{rpm} = 1.26 \text{ W}$$

$$P_{\text{Joule}} = R_{T \text{ Final}} \times I^2 = 10.94 \text{ } \Omega \times 0.24 \text{ A}^2 = 0.63 \text{ W}$$

$$\text{Efficiency} = P_{\text{mech}} / P_{\text{elec}} = 1.26 \text{ W} / 1.89 \text{ W} = 66\%.$$

Selecting a motor with better R/k^2 enabled us to double the efficiency. Thermal considerations are important for an optimal motor selection and to ensure best performance.

Examples of DC Coreless Gearmotor calculations

Example: Direct drive with a gearhead attached to the motor.

For this application we are looking for a DC Coreless Motor & Gearhead for a continuous duty application. The application requirements are:

Available voltage:	15 V _{dc}		
Available current:	1.5 Amp		
Motor operating point:	30 rpm	[n]	desired motor speed
	500 mNm	[τ]	desired output shaft torque
	22°C	[T _{amb}]	ambient temperature
	Continuous operation		
Motor dimensions:	80 mm		maximum allowable length
	∅ 25 mm		maximum allowable diameter

The specification page for the R22 gearhead shows a maximum continuous torque of 600 mNm, so the required 500 mNm can be handled by this planetary gearhead. When choosing the reduction ratio we should keep in mind that the recommended maximum input speed of the R22 gearhead is 5,000 rpm. We should keep the input speed below this value in order to assure low wear and low audible noise.

$$i = n_{\max} / n_{\text{load}}$$

$$i = 5,000 \text{ rpm} / 30 \text{ rpm} = 166.7$$

The catalog indicates that the closest ratio to the desired value calculated above is 159:1. The efficiency for this ratio is $\eta = 0.6$ (or 60%). We may now calculate the motor speed (n_m) and the reflected torque (τ_m) on the motor shaft.

$$\tau_m = \tau / (i \times \eta) \quad [\text{mNm}]$$

$$\tau_m = 500 \text{ mNm} / (159 \times 0.6) = 5.24 \text{ mNm}$$

$$n_m = n_{\text{load}} \times i = 30 \text{ rpm} \times 159 = 4,770 \text{ rpm}$$

The motor data sheet shows the 22V28 family of motors can easily deliver a torque of 5.24 mNm continuously. The 22V28 is available as a standard combination with the planetary gearhead R22. Based on the available voltage we choose the -213E winding (12 V measuring voltage) and calculate the motor current and voltage the same way as in the previous example.

The motor is required to be driven at a speed of 4,770 rpm under a load of 5.24 mNm. The ambient temperature (T_{amb}) is 22° and the available voltage in the application is 15 V_{dc}. The characteristics we are most interested in are the torque constant (k) of 14.9 mNm/A, and the terminal resistance of 11.9 Ω. Neglecting the no-load current (I_o), for a torque load of 5.24 mNm the motor current is:

$$I = \tau / k = 5.24 \text{ mNm} / 14.9 \text{ mNm/A} = 0.35 \text{ A}$$

Now we can calculate the drive voltage required to run the motor at 22° C, for a desired speed of 4,770 rpm with a load torque of 5.24 mNm:

$$U = R \times I + k \times \omega \quad [V_{dc}]$$

$$\omega = 2\pi/60 \times n = 2\pi/60 \text{ rad/rpm-s} \times 4,770 \text{ rpm} = 499.51 \text{ rad/s}$$

$$U = 11.9 \Omega \times 0.35 \text{ A} + (14.9 \times 10^{-3} \text{ Nm/A}) \times 499.51 \text{ rad/s} = 11.61 V_{dc}$$

We note the current of the motor under load is 0.35 A, which is well under the rated continuous current of 0.58 A. We therefore can safely assume that the final rotor temperature (T_f) will stay below the maximum rated coil temperature of 100 °C. We can also be sure that the voltage will remain within the 15 V_{dc} available because the relatively small coil temperature increase will correspond to a negligible increase in the coil resistance. (If for good measure the calculations are done, the final temperature of the coil would be 50 °C and the required voltage would be 12.09 V_{dc} . Both are well within the limits and our assumptions are justified.)

The problem is now solved. The gearmotor 22V28-213E.202 R22 0 159 would be a good choice for the application. If the application requires particularly long motor life, the next largest motor (23V) could also be considered. If this were a battery application the 22N78 could also be used to increase efficiency and extend battery life.

Examples of DC Motor calculations

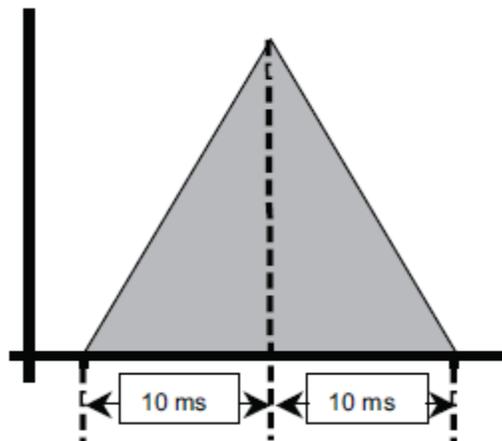
Example: Positioning with a DC Coreless Motor.

In this application we are looking for a DC Coreless Motor to move an inertial load (J_{load}) of $40 \times 10^{-7} \text{ kgm}^2$ by an angle of 1 rad in 20 msec.

The application requirements are:

Available voltage:	48 V _{dc}
Available current:	4 Amp
Motor operating point:	1 rad [θ] desired motor movement
	$40 \times 10^{-7} \text{ kgm}^2$ [J_{load}] motor load inertia on output shaft
	20 msec [Δt] desired move time
	40 °C [T_{amb}] ambient temperature
	Intermittent operation
Motor dimensions:	68 mm maximum allowable length
	Ø 35 mm maximum allowable diameter

Friction is negligible. With this incremental application we consider a duty cycle of 100% and a triangular speed profile.



The motor must rotate 0.5 rad ($\theta/2$) in 10 msec ($\Delta t/2$) while accelerating, then another 0.5 rad (also $\theta/2$) in 10 msec (also $\Delta t/2$) while decelerating. First let us calculate the angular acceleration α .

$$\alpha = (2 \times \theta/2) / (\Delta t/2)^2 \quad [\text{rad/s}^2]$$

$$\alpha = 2 \times .5 \text{ rad} / (.01 \text{ s})^2 = 10,000 \text{ rad/s}^2$$

The torque necessary to accelerate the load is:

$$\tau_{load} = J_{load} \times \alpha \quad [\text{mNm}]$$

$$\tau_{load} = 40 \times 10^{-7} \text{ kgm}^2 \times 10,000 \text{ rad/s}^2 = .040 \text{ Nm} = 40 \text{ mNm}$$

When selecting a motor for incremental motion, it is best if the inertia of the rotor is equal to the inertia of the load. If the rotor inertia is much larger, then a large portion of the mechanical power is used just to move the rotor. The rotor inertia should also not be less than half the load inertia. If it is, then a gearbox should be used to reduce the load inertia felt by the motor. This process is referred to as matching inertias. We will thus select a motor that has a rotor inertia close to $40 \times 10^{-7} \text{ kgm}^2$.

According to the motor specification page, the 30GT2R82-234P.4 has a rotor inertia of $33 \times 10^{-7} \text{ kgm}^2$ and has a torque constant of 20.1 mNm/A. It can deliver enough continuous torque (87 mNm) to handle the combined load calculated below.

$$\tau_{\text{rotor+load}} = (40 \times 10^{-7} \text{ kgm}^2 + 33 \times 10^{-7} \text{ kgm}^2) \times 10,000 \text{ rad/s}^2 = .073 \text{ Nm} = 73 \text{ mNm}$$

$$I = \tau / k = 73 \text{ mNm} / (20.1 \text{ mNm/A}) = 3.63 \text{ A}$$

The coil resistance (at 22°C) is 0.48 Ω, and the thermal resistance is 4.5 °C/W + 9 °C/W / 2 = 9 °C/W. By using the equation from the first example we find:

$$T_f = 113.2 \text{ °C} \quad R_{Tr} = .62 \text{ Ω}$$

Since we are using a triangular speed profile, we must determine the maximum speed of the motor during the move and then calculate the required voltage at that speed for the above coil resistance at operating temperature. This maximum speed will occur at the peak of the triangle (after 10 msec).

$$\omega_{\text{max}} = \alpha \times \Delta t \quad [\text{rad/s}]$$

$$\omega_{\text{max}} = 10,000 \text{ rad/s}^2 \times 0.010 \text{ sec} = 100 \text{ rad/s}$$

$$U = R \times I + K \times \omega = .62 \text{ Ω} \times 3.63 \text{ A} + (20.1 \times 10^{-3} \text{ Nm/A}) \times 100 \text{ rad/s} = 4.25 \text{ V}_{\text{dc}}$$

The problem is now solved. Since the maximum permissible coil temperature of the 35NT is 155 °C, and the available voltage in the application is 48 V, this motor is perfectly capable of performing the required movement.

It is interesting to note here that, had we chosen the larger motor 35NT2R82, the coil temperature would be calculated at over 300 °C! Even though the motor is capable of providing more torque, the higher rotor inertia requires it to supply much more power just to move its rotor at the desired speed. This demonstrates the importance of inertia matching.

Examples of BLDC Slotless Motor calculations

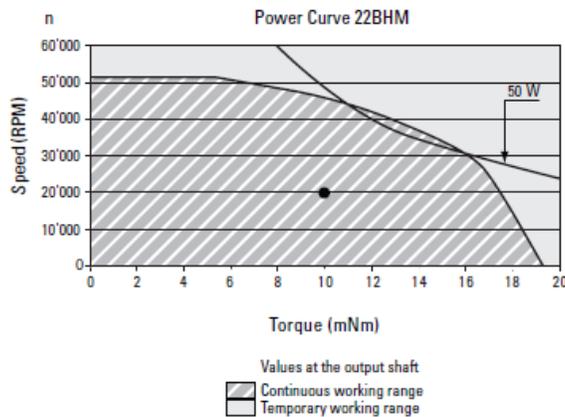
This chapter aims to provide all the information necessary to select a BLDC Slotless motor and to calculate the values at the desired operating point. The following examples are for motor applications running in continuous operation.

1) Example: Brushless application requirements

For this application we are looking for a BLDC motor with high speed capabilities in a continuous duty operation. The motor will be controlled by an amplifier for a motor with Hall Effect sensors.

Available voltage:	30 V _{dc}		
Available current:	3 Amps		
Motor operating point:	20,000 rpm	[ω]	desired motor speed
	10 mNm	[τ]	motor shaft output torque
	22°C	[T _{amb}]	ambient temperature
	Continuous operation		
Motor physical dimensions:	60 mm		maximum allowable length
	Ø 25 mm		maximum allowable diameter

Using the speed-torque curve and maximum allowable operating specifications from the data sheet, it is possible to select the correct motor solution. Here we find the BLDC motor 22BHM 8B capable of operating at the desired working point. (The 8B refers to the option with Hall Effect Sensors.)



The motor 22BHM 8B is available in 3 different 24 V_{dc} windings. The differences between the windings are the amount of torque and the speeds of the motor. Since the desired motor speed is 20,000 rpm we will investigate the -H winding with a no load speed of 28,300 rpm. The torque constant is 8.3 mNm/A and the resistance is .99 Ω.

Calculating for the motor current we find:

$$I = \tau / k = 10 \text{ mNm} / 8.3 \text{ mNm/A} = 1.20 \text{ A}$$

The supply current of the system is 3 Amps and therefore current draw is not an issue.

Calculating the voltage required to run the motor at 20,000 rpm:

$$U = R \times I + k \times \omega$$

$$\omega = 2\pi/60 \times n = 2\pi/60 \text{ rad/rpm-s} \times 20,000 \text{ rpm} = 2094.40 \text{ rad/s}$$

$$U = 0.99 \Omega \times 1.20 \text{ A} + (8.3 \times 10^{-3} \text{ Nm/A}) \times 2094.40 \text{ rad/s} = 18.57 \text{ V}_{dc}$$

The problem is now solved. Since the voltage required is less than the available voltage, it is possible to reach the operating point with the BLDC Slotless motor 22BHM 8B H.01.

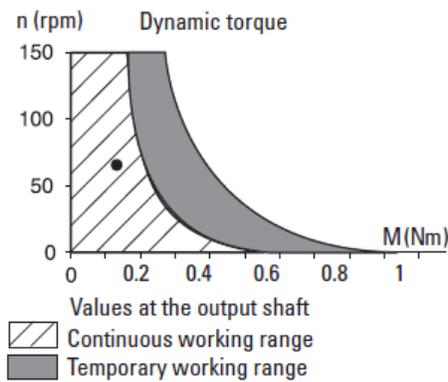
2) Example: Brushless motor with a Gearhead

For this application we want to drive a load at an extremely low constant speed. The customer needs a combination of a Brushless DC motor with a gearhead.

Available voltage:	20 V _{dc}		
Available current:	2 Amps		
Gearmotor operating point:	60 rpm	[ω]	desired gearmotor speed
	150 mNm	[τ]	gearmotor shaft output torque
	22 °C	[T _{amb}]	ambient temperature
	Continuous operation		
Motor physical dimensions:	120 mm		maximum allowable length
	∅ 20 mm		maximum allowable diameter

Before selecting a motor we must first determine which gearhead is suitable for the application. The important parameters are the specifications relating to the operating point at the shaft of the gearhead. Once an appropriate gearhead has been determined, the working point at the motor shaft can be calculated. From here the motor type can be defined using the same procedure as in the previous example for motor only.

We start the elimination process by comparing the desired gearhead output torque with the data of the various gearheads in continuous operation as listed in the catalog specification pages. We find the R16 planetary gearhead (16 mm diameter) capable of operating at the desired working point.



For continuous operation, one of the most important gearhead parameters to be considered is the maximum recommended input speed into the gearhead ($n_{\text{max input-gearhead}}$). This specification allows us to calculate the maximum reduction ratio (i_{max}) to use for the application.

$$i_{\text{max}} = n_{\text{max input-gearhead}} / n_{\text{output-gearhead}} = 7,500 \text{ rpm} / 60 \text{ rpm} = 125$$

The gearhead can be chosen by selecting the largest available ratio that is below the above result. By reviewing the catalog we choose the 121:1 ratio R16 gearhead.

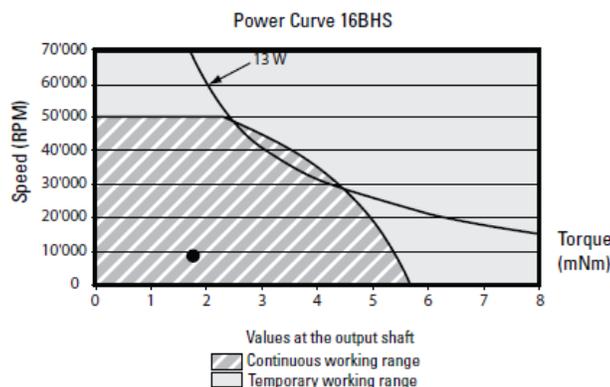
Motor speed at the shaft:

$$n_{\text{motor}} = i \times n_{\text{output-gearhead}} = 121 \times 60 \text{ rpm} = 7,260 \text{ rpm}$$

Motor torque at the shaft:

$$\eta = .65 \quad (\text{gearhead efficiency})$$

$$\tau_{\text{motor}} = \tau_{\text{gearhead}} / i \times \eta = 150 \text{ mNm} / (121 \times .65) = 1.91 \text{ mNm}$$



Since the gearhead has a diameter of 16mm we will be looking at 16 mm Brushless DC motors. Based on the load torque (τ_m) the motor will be required to turn, we select the 16BHS 8B (the 8B refers to the option for Hall Effect Sensors).

The 16BHS 8B is available in 4 different 12 V_{dc} windings. The differences between the windings are the amount of torque and the speed of the motors. Since the desired motor speed is 7,260 rpm we will investigate the -E winding with a no load speed of 8,150 rpm. The torque constant is 13.5 mNm/A and the phase resistance is 19.4 Ω.

Calculating for the motor current we find:

$$I = \tau / k = 1.91 \text{ mNm} / (13.5 \text{ mNm/A}) = 0.14 \text{ A}$$

There are no issues with the current because the system is able to supply 2 amps and the maximum recommended continuous current is .41 Amps. The voltage required to run the motor at 7,260 rpm is determined by the following formula:

$$U = R \times I + k \times \omega$$

$$\omega = 2\pi/60 \times n = 2\pi/60 \text{ rad/rpm-s} \times 7,260 \text{ rpm} = 760.3 \text{ rad/s}$$

$$U = 19.4 \Omega \times .14 \text{ A} + (13.5 \times 10^{-3} \text{ Nm/A}) \times 760.3 \text{ rad/s} = 12.98 \text{ V}_{dc}$$

The problem is now solved. The voltage required is less than the available voltage, therefore the motor 16BHS 8B E.01 with the planetary gearhead R16 0 121 can achieve the desired working point.

Examples of BLDC Slotted Motor Calculations

This chapter aims to provide all the information necessary to select a Slotted BLDC motor and to calculate the values at the desired operating point. The following examples are for motor applications running in continuous operation.

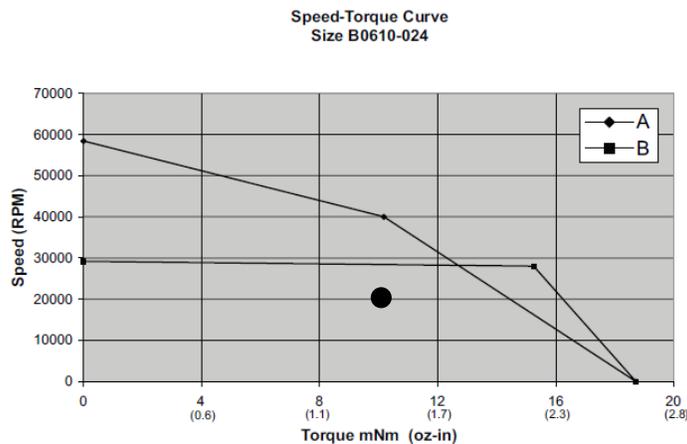
1) Example: Brushless application requirements

For this application we are looking for a BLDC motor with high speed capabilities in a continuous duty operation. The motor will be controlled by an amplifier for a motor with Hall Effect sensors. We will consider the same example as discussed for slotless design, and select a slotted motor that meets the requirements below.

Available voltage:	30 V _{dc}		
Available current:	3 Amps		
Motor operating point:	20,000 rpm	[ω]	desired motor speed
	10 mNm (1.42 oz-in)	[τ]	motor shaft output torque
	22 °C	[T _{amb}]	ambient temperature
	Continuous operation		
Motor physical dimensions:	60 mm (2.36 in)		maximum allowable length
	∅ 25 mm (0.98 in)		maximum allowable diameter

Motor pre-selection: Since the maximum allowable diameter is 25 mm (0.98 in), we will look at motor sizes 9 (0.9 inch diameter) and smaller that meet the operating point by comparing the speed-torque curves.

By referring to the speed-torque curve below we find the motor B0610-024B capable of reaching the desired operating point with a continuous operating. This is the smallest motor capable of meeting the above requirements. However a customized motor can be made even smaller for these same requirements.



The motor B0610-024 is available in 2 different 24 V_{dc} windings. The differences between the windings are the amount of torque and the speed of the motors. Since the desired motor speed is 20,000 rpm we will investigate the B0610-024B motor with a no load speed of 29,197 rpm. The torque constant is 7.84 mNm/A and the phase resistance is 1.57 Ω.

Calculating for the motor current we find:

$$I = \tau / k = 10 \text{ mNm} / 7.84 \text{ mNm/A} = 1.28 \text{ A}$$

Current draw is not an issue because the supply current of the system is 3 A and maximum recommended continuous current is 2.4 A. The voltage required to run the motor at 20,000 rpm is calculated using the following formula:

$$U = R \times I + k \times \omega$$

$$\omega = 2\pi/60 \times n = 2\pi/60 \text{ rad/rpm-s} \times 20,000 \text{ rpm} = 2,094.39 \text{ rad/s}$$

$$U = 1.57 \Omega \times 1.28 \text{ A} + (7.84 \times 10^{-3} \text{ Nm/A}) \times 2,094.39 \text{ rad/s} = 18.43 \text{ V}_{dc}$$

The problem is now solved. Since the voltage required is less than the available voltage, it is possible to reach the operating point with the Slotted BLDC motor B0610-024B.

2) Example: Slotted Brushless motor with a Gearhead

For this application we want to drive a load at a low constant speed. The customer needs a combination of a Slotted Brushless motor with a gearhead.

Available voltage:	50 V _{dc}		
Available current:	1 Amp		
Gearmotor operating point:	2,500 rpm	[n]	desired gearmotor speed
	40 mNm	[τ]	gearmotor shaft output torque
	10.5 Watts	[P]	output power at the gearhead
	22°C	[T _{amb.}]	ambient temperature
	Continuous operation		
Motor physical dimensions:	70 mm		maximum allowable length
	∅ 15 mm		maximum allowable diameter

Gearhead pre-selection:

Before selecting a motor we must first determine which gearhead is suitable for the application. The important parameters are the specifications relating to the operating point at the shaft of the gearhead.

Once an appropriate gearhead has been determined, the working point at the motor shaft can be calculated. From here the motor type can be defined using the same procedure as in the previous example for motor only.

We start the elimination process by comparing the desired gearhead output torque and size requirements with the data of the various gearheads in continuous operation as listed in the catalog specification pages. We find the Size 5 planetary gearhead (12.7 mm diameter) to be the smallest gearhead capable of operating at the desired working point with a maximum continuous operating torque of 290 mNm.

For continuous operation, one of the most important gearhead parameters to consider is the maximum recommended input speed into the gearhead ($n_{\text{max input-gearhead}}$). This specification allows us to calculate the maximum reduction ratio (i_{max}) to use for the application.

$$i_{\text{max}} = n_{\text{max input-gearhead}} / n_{\text{output-gearhead}} = 80,000 \text{ rpm} / 2,500 \text{ rpm} = 32$$

The gearhead can be chosen by selecting the largest available ratio that is below the above result. By reviewing the catalog we choose the following gearhead and ratio.

$$\begin{aligned} \text{Size 5} &\rightarrow i = 25 \\ &\eta = 82.5\% \end{aligned}$$

Note: The efficiency for the gearhead is given as a range between 75% and 90%. For the purposes of this calculation we will assume an efficiency of 82.5%.

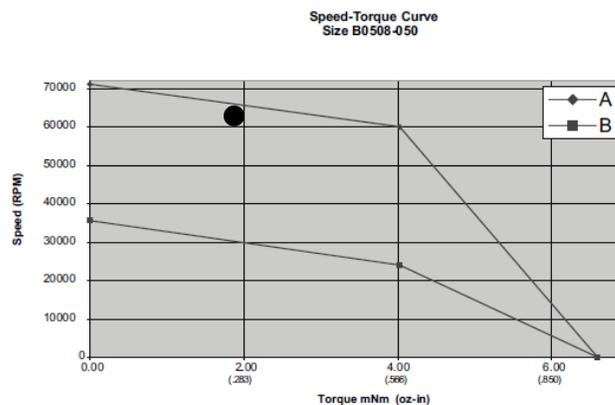
Motor speed at the shaft:

$$n_{\text{motor}} = i \times n_{\text{output-gearhead}} = 25 \times 2,500 \text{ rpm} = 62,500 \text{ rpm}$$

Motor torque at the shaft:

$$\tau_m = \tau_{\text{gearhead}} / (i \times \eta) = 40 \text{ mNm} / (25 \times .825) = 1.94 \text{ mNm}$$

Since the gearhead has a diameter of 12.7 mm we will be looking at a 12.7 mm or smaller BLDC motor. By examining the speed-torque curve below we can determine that the B0508-050A can run at 62,500 rpm under the load torque (τ_m) calculated above. The torque constant is 6.71 mNm/A and the phase resistance is 7.28 Ω .



Calculating for the motor current we find:

$$I = \tau / k = 1.94 \text{ mNm} / 6.71 \text{ mNm/A} = 0.29 \text{ A}$$

The current draw is not an issue because the system is able to supply 1 A, and the maximum recommended continuous current for the motor is .982 A. The voltage required to run the motor at 62,500 rpm is determined by the following formula:

$$U = R \times I + k \times \omega$$

$$\omega = 2\pi/60 \times n = 2\pi/60 \text{ rad/rev-s} \times 62,500 \text{ rpm} = 6,545 \text{ rad / s}$$

$$U = 7.28 \Omega \times .29 \text{ A} + (6.71 \times 10^{-3} \text{ Nm/A}) \times 6,545 \text{ rad/s} = 46.03 \text{ V}_{\text{dc}}$$

The voltage required is less than the available voltage. Therefore the B0508-050A with the Size 5 Planetary gearhead (25:1 Ratio) is capable of reaching the desired working point.

Examples of DMM Stepper Motor Calculations

Example: Positioning with a DMM Stepper Motor

For this application we are looking for a Stepper motor for an intermittent duty application. The application requirements are:

Available voltage:	45 V _{dc}	
Available current:	2 Amp	
Motor operating point:	0.5 rad	[θ] desired motor position
	20 × 10 ⁻⁷ kgm ²	[J _{load}] motor load inertia on the output shaft
	20 msec	[Δt] desired move time
	40 °C	[T _{amb}] operating temperature
	Intermittent operation	
Motor dimensions:	68 mm	maximum allowable length
	∅ 35 mm	maximum allowable diameter

L/R Driver - No Gearbox - No Ramping Acceleration

Let us first see whether the move can be accomplished with a simple L/R drive not featuring ramping acceleration. In this case we need to check whether the motor can start at the required speed and load inertia.

We consider the speed profile to be rectangular with constant speed:

$$\text{Speed} = \omega = 0.5 \text{ rad} / 0.02 \text{ sec} = 25 \text{ rad/s}$$

$$n_{\text{motor}} = 25 \text{ rad/s} \times 60 / 2\pi \text{ rpm-s/rad} = 239 \text{ rpm}$$

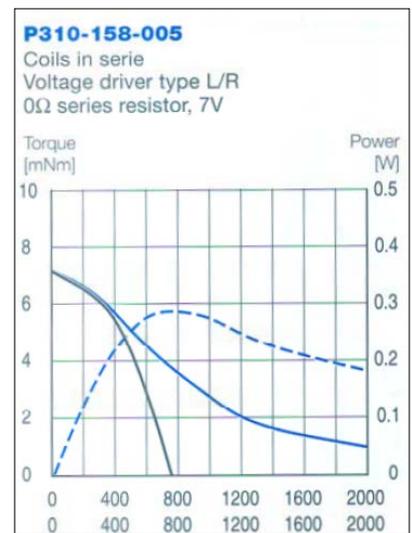
The figure shows the pull-in and pull-out torque curves for the P310 motor. We will use a simple L/R drive which provides 7 V_{dc} in full step mode. Since no ramping is provided (constant speed), the pull-in torque curve shows a maximum starting speed of 800 rpm when accelerating an inertia equal to the motor inertia and without any additional torque (friction torque is zero for example). With a safety factor of 75% the maximum starting frequency is f₀ = 600 steps/s.

The inertia of the P310 is 0.86 kg-m² but we need to accelerate 20 kg-m². Therefore the maximum starting frequency f₁ to move this load is:

$$f_1 = f_0 \times \sqrt{(2 \times J_m) / (J_m + J_{\text{load}})}$$

$$f_1 = 600 \text{ steps/s} \times \sqrt{(2 \times 0.86 \text{ kg-m}^2) / (20 \text{ kg-m}^2 + 0.86 \text{ kg-m}^2)} = 172 \text{ rpm}$$

As a result, P310 with a simple L/R drive would not be able to suit the requirements.



The stepper motor P430 makes 100 steps/rev. To move the load 0.50 rad with a stepper motor that has a 3.6° step angle, it will take the motor 8 steps to make this move.

$$0.50 \text{ rad} = 28.65^\circ$$

$$28.65^\circ / 3.6^\circ = 7.96 \rightarrow 8 \text{ steps of the motor needed}$$

The starting frequency equivalent to 25 rad/s is :

$$f = (25 \text{ rad/s} / 2\pi \text{ rad/rev}) \times 100 \text{ steps/rev} = 398 \text{ steps/s}$$

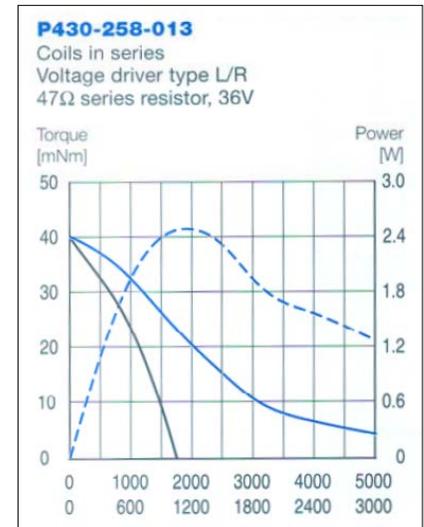
With 36 V_{dc} available in the L/R drive and 47 Ω resistors in series, the P430 can start at up to 1,700 steps/s while moving an inertial load equal to its own rotor inertia without any additional torque required. With 75% safety margin:

$$f_0 = 1,700 \times 0.75 = 1,275 \text{ steps/s}$$

With an inertial load of $20 \times 10^{-7} \text{ kg}\cdot\text{m}^2$ this pull-in frequency becomes:

$$f_1 = 1,275 \text{ steps/s} \times \sqrt{(2 \times 3 \text{ kgm}^2) / (20 \text{ kg}\cdot\text{m}^2 + 3 \text{ kgm}^2)} = 651 \text{ steps/s}$$

The problem is now solved. The working point of 398 steps/s is well below the pull-in torque curve of the P430, and no ramping is necessary to perform the desired operation.



The move could be made in an even shorter time if we use a starting frequency closer to the maximum allowed:

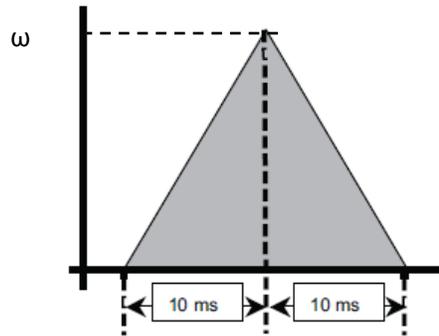
$$f = 600 \text{ steps/s}$$

$$\omega = (600 \text{ steps/s} / 100 \text{ steps/rev}) \times 2\pi \text{ rad/rev} = 38 \text{ rad/s}$$

$$\Delta t = 0.5 \text{ rad} / 38 \text{ rad/s} = 13 \text{ msec}$$

Chopper Driver – No Gearbox – With Ramping Acceleration

The load inertia of $20 \times 10^{-7} \text{ kg-m}^2$ has to be moved by an angle of $0.50 \text{ rad } (\theta)$ in 20 msec using an acceleration ramp. We will use a triangular speed profile with an acceleration time of 10 msec for a shaft movement of $.25 \text{ rad}$. The speed required is calculated as follows.



$$\text{Acceleration} = \alpha = 2 \times (\theta/\Delta t^2) = 2 \times .25 \text{ rad} / (0.01 \text{ sec})^2 = 5,000 \text{ rad/s}^2$$

$$\text{Speed} = \omega = (5,000 \text{ rad/s}^2) \times 0.01 \text{ sec} = 50 \text{ rad/s}$$

$$n_{\text{motor}} = 50 \text{ rad/s} \times 60/2\pi \text{ rpm-s/rad} = 477.5 \text{ rpm}$$

The torque necessary to accelerate the load is:

$$\tau_{\text{load}} = J_{\text{load}} \times \alpha \quad [\text{Nm}]$$

$$\tau_{\text{load}} = 20 \times 10^{-7} \text{ kg-m}^2 \times 5,000 \text{ rad/s}^2 = .010 \text{ Nm}$$

With a triangular speed profile this requires a peak speed up to 477.5 rpm , with a load torque of 10 mNm . Therefore the peak power required for the load alone is 0.50 W .

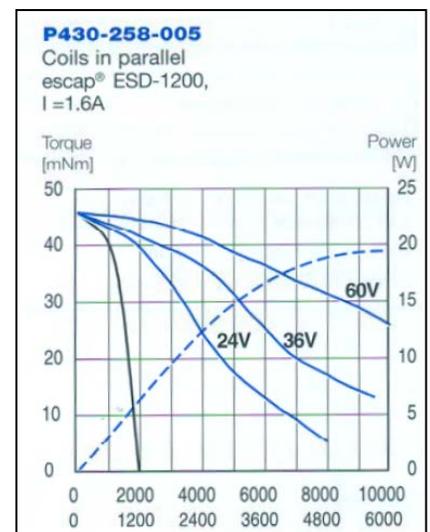
$$P = \tau \times \omega = .010 \text{ Nm} \times 50 \text{ rad/s} = .50 \text{ Watts}$$

Let us first consider the P430 with rotor inertia of $3 \times 10^{-7} \text{ kgm}^2$. We have:

$$J_{\text{total}} = J_{\text{load}} + J_{\text{motor}} = (20 \times 10^{-7} \text{ kg-m}^2) + (3 \times 10^{-7} \text{ kg-m}^2) = 23 \times 10^{-7} \text{ kg-m}^2$$

$$\tau_{\text{total}} = J_{\text{total}} \times \alpha = 23 \times 10^{-7} \text{ kg-m}^2 \times 5,000 \text{ rad/s}^2 = .0115 \text{ Nm} = 11.5 \text{ mNm}$$

The curve shows that P430-258-005 with current limit of 1.6 A and 24 V can easily do the job.



In fact, at around 500 rpm the motor can provide up to 43 mNm. With a safety factor of 75% we could easily provide 32 mNm with the P430 and the motion time could be reduced as followed:

$$\alpha_{\max} = \tau_{\max} / J_{\text{total}} = 32 \times 10^{-3} \text{ Nm} / 23 \times 10^{-7} \text{ kg-m}^2 = 13,913 \text{ rad/s}^2.$$

$$\Delta t = \sqrt{2 \times \theta / \alpha_{\max}} = \sqrt{2 \times 0.25 \text{ rad} / 13,913 \text{ rad/s}^2} = 6.0 \text{ msec}$$

Chopper Driver – With Gearbox – With Ramping Acceleration

The P310 has a holding torque 14 mNm at nominal current and would not be able to directly provide 10 mNm at 477 rpm for accelerating the load. However we could use a gearbox to achieve the work. A first choice consists of matching inertias, and then making sure that with the selected ratio the motor speed remains within a reasonable range and the necessary torque can be delivered. With incremental motion, an inertial match assures the shortest move time, with the motor providing constant torque over the speed range considered. In our example this calls for a desired ratio i_0 of:

$$i_0 = \sqrt{J_{\text{load}}/J_{\text{motor}}} = \sqrt{20 \text{ kg-m}^2/0.86 \text{ kg-m}^2} = 4.82 \quad [\text{no units}]$$

From the various gearhead models available for combination with the P310 stepper motor, we select the K24. This gearhead offers a ratio of 5:1 which is close enough to our target 4.82, and has an efficiency of 85%.

The load inertia reflected onto the motor shaft is calculated by:

$$J_{\text{load at motor}} = J_{\text{load at gearbox}} / (i^2 \times 0.85) = 20 \times 10^{-7} / (5^2 \times 0.85)$$

$$J_{\text{load at motor}} = 0.94 \times 10^{-7} \text{ kg-m}^2.$$

If we now consider the previous values reflected on the motor shaft, the required motor acceleration, angular speed, and step rate are:

$$\alpha_{\text{at motor}} = \alpha_{\text{at gearbox}} \times i = 5,000 \text{ rad/s}^2 \times 5 = 25,000 \text{ rad/s}^2$$

$$\omega_{\text{at motor}} = \omega_{\text{at gearbox}} \times i = 50 \text{ rad/s} \times 5 = 250 \text{ rad/s}$$

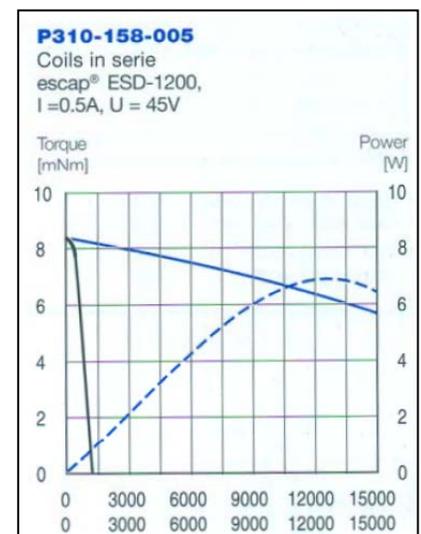
$$f = (250 \text{ rad/s}) / (2\pi \text{ rad/rev}) \times 60 \text{ steps/rev} = 2,387 \text{ steps/s}$$

$$\tau = (J_{\text{load at motor}} + J_{\text{motor}}) \times \alpha_{\text{at motor}} = (0.94 + 0.86) \times 10^{-7} \text{ kgm}^2 \times 25,000 \text{ rad/s}^2 = .0045 \text{ Nm} = 4.5 \text{ mNm}$$

The pull-out torque curve shows that at around 2,000 steps/s the P310-158-005 with coil in series, chopper drive, 45 V V_{dc} and a 0.5 A current limit can provide up to 8 mNm. With a safety factor of 75% we have up to 6 mNm available and the motor with gearhead can easily perform the job.

Here again, the shortest move time would be:

$$\tau_{\max} = 6 \text{ mNm}$$



$$\alpha_{\text{max at motor}} = \tau_{\text{max}} / (J_{\text{load at motor}} + J_{\text{motor}}) = .006 \text{ Nm} / 1.8 \times 10^{-7} \text{ kg-m}^2 = 33,333 \text{ rad/s}^2$$

$$\alpha_{\text{max at gearbox}} = \alpha_{\text{max at motor}} / 5 = 6,666 \text{ rad/s}^2$$

$$\Delta t = \sqrt{(2 \times \theta) / \alpha_{\text{max at gearbox}}} = \sqrt{(2 \times 0.25 \text{ rad} / 7,230 \text{ rad/s}^2)} = 8.7 \text{ msec}$$

The P310 with K24 0 5 is an excellent alternative to the P430 if a smaller diameter is required. DMM motors feature not only a low inertia rotor, but also a very strong magnetic design which enables use at high speed compared to other multi-pole stepper motors.

Examples of Can Stack Step Motor calculations

Example: Drive with a Can Stack Step Motor with a frictional torque load

For this application we will consider a Step Motor for an intermittent duty application. The application requirements are:

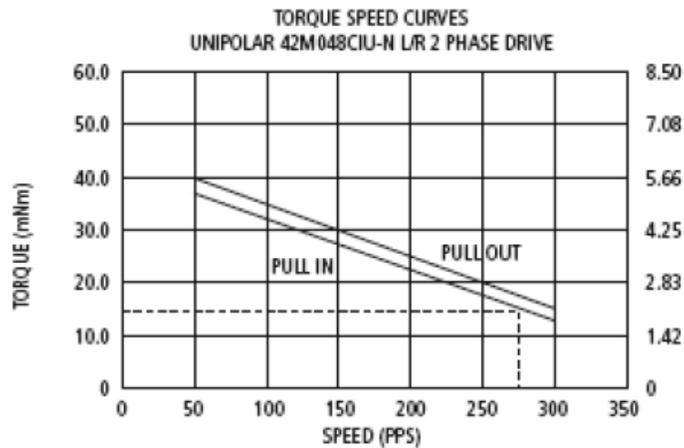
Available voltage:	24 V _{dc}		
Available current:	2 Amp		
Motor operating point:	67.5°	[θ]	desired motor position
	15 mNm	[τ]	desired motor torque
	0.06	[Δt]	desired move time
	Intermittent operation		

If a 7.5° per step motor is used, then the motor would have to take nine steps to move 67.5°.

$$67.5^\circ / 7.5^\circ = 9 \text{ steps}$$

$$f = \text{step rate} = 9 \text{ steps} / 0.06 \text{ sec} = 150 \text{ steps/s}$$

In the figure below the maximum pull-in rate with a torque of 15 mNm is 275 steps/s. We use the pull-in torque curve for this calculation because the control circuit does not provide any ramping. The maximum speed the motor can reach during operation is limited by the maximum speed the motor can start at without missing any steps. This is what the pull-in torque curve represents.



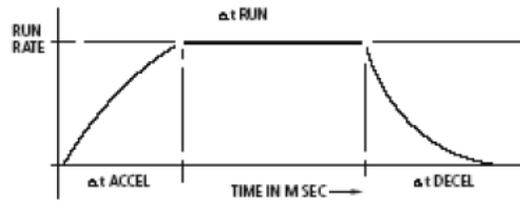
The problem is now solved. The Can Stack motor 42M048C1U motor could be used at 150 steps/s because this point falls well below the pull-in torque curve.

Use the pull-out torque curve in conjunction with a Torque = Inertia × Acceleration ($\tau = J \times \alpha$) analysis when the load is inertial and/or acceleration control is provided.

In this equation acceleration or ramping is in rad/s^2 $\alpha = \Delta\omega / \Delta t = \text{rad/s}^2$

Ramping:

Acceleration control or ramping is normally accomplished by gating on a voltage controlled oscillator (VCO) and the associated charging capacitor. Varying the RC time constant will give different ramping times. A typical VCO acceleration control frequency plot for an incremental movement with equal acceleration and deceleration time would be as shown below.



Acceleration also may be accomplished by changing the timing of the input pulses (frequency). For example, the frequency could start at a ¼ rate; go to ½ rate, ¾ rate and finally the running rate.

For applications where ramping acceleration or deceleration control time is allowed:

$$\tau_j = J_T \times \Delta\omega/\Delta t$$

Where J_T = rotor inertia (gm^2) + load inertia (gm^2)

Δf = step rate change

Δt = time allowed for acceleration in seconds

λ = steps per revolution (for Portescap Can Stacks this can be 20 steps/rev, 24 steps/rev, or 48 steps/rev)

$$\omega = f \text{ steps/s} \times 2\pi \text{ rad/rev} \times 1/(\lambda \text{ steps/rev}) \quad [\text{rad/s}]$$

Dividing by Δt :

$$\Delta\omega/\Delta t = \Delta f/\Delta t \text{ step/s}^2 \times 2\pi \text{ rad/rev} \times 1/(\lambda \text{ step/rev}) \quad [\text{rad/s}^2]$$

Plugging this definition of $\Delta\omega/\Delta t$ into the equation for τ_j yields:

$$\tau_j = J_T \times \Delta f/\Delta t \text{ step/s}^2 \times 2\pi \text{ rad/rev} \times 1/(\lambda \text{ step/rev}) \quad [\text{mNm}]$$

In order to solve an application problem using acceleration ramping, it is usually necessary to make several estimates to avoid needing a procedure similar to the one used in the following example.

Example: Frictional torque plus inertial load with acceleration control

For this application we are looking for Stepper Motor for an intermittent duty application. The application requirements are:

Available voltage:	24 V _{dc}	
Available current:	3 Amp	
Motor operating point:	67.5°	[θ] - desired motor position
	15 mNm	[τ _f] – frictional load
	< 0.5	[Δt] - desired move time
	Intermittent operation	
Motor dimensions:	60 mm	maximum allowable length
	∅ 60 mm	maximum allowable diameter

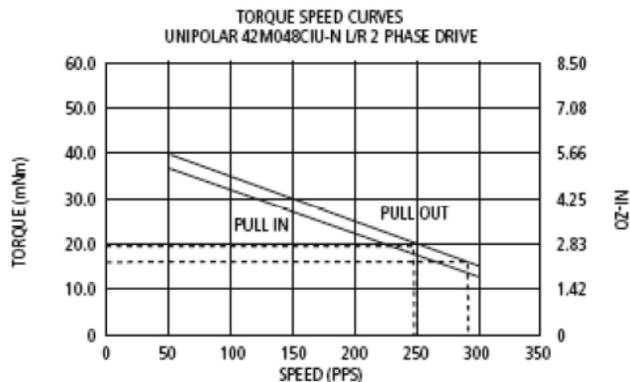
An assembly device must move 4 mm in less than 0.5 seconds. The motor will drive a lead screw through a gear reduction. The lead screw and gear ratio were selected so that 100 steps of a 7.5° per step motor results in 4 mm of linear motion.

The total inertial load (rotor + gear + screw) = $25 \times 10^{-4} \text{ gm}^2$. The frictional load is 15 mNm.

(1) Select a stepper motor pull-out torque curve which allows a torque in excess of 15 mNm at a step rate greater than:

$$f = 100 \text{ steps}/0.5 \text{ sec} = 200 \text{ steps/s}$$

At a step rate of 250 steps/s (safely over 200 steps/s) the 42M048C1U is capable of providing 20 mNm.



(2) Make a first an estimate of a working rate (a running rate less than the maximum) and determine the torque available to accelerate the inertia (excess over τ_f) τ_A = torque available.

$$\tau_A - \tau_f = 20 \text{ mNm} - 15 \text{ mNm} = 5 \text{ mNm}$$

(3) Using a 60% safety margin

5 mNm \times 0.6 = 3 mNm
Calculate Δt to accelerate.

From the equation:

$$\tau_j = J_T \times \Delta f / \Delta t \text{ steps/s}^2 \times 2\pi \text{ rad/rev} \times 1/(\lambda \text{ steps/rev})$$

$$\lambda = 48 \text{ steps/rev (from } 7.5^\circ \text{ per step)}$$

We rearrange to solve for Δt .

$$\Delta t = (25 \times 10^{-4} \text{ kgm}^2 \times 250 \text{ steps/s} \times 2\pi \text{ rad/rev} \times 1/(48 \text{ steps/rev})) / 3 \text{ mNm} = 0.027 \text{ sec}$$

Note: The same amount of time is allowed to decelerate the load

(4) Determine the number of steps used to accelerate and decelerate.

$$N_A + N_D = f/2 \times \Delta t \times 2$$

< OR >

$$N_A + N_D = f \times \Delta t = 250 \text{ steps/s} \times 0.027 \text{ sec} = 6.75 \text{ steps} \rightarrow 7 \text{ steps needed to complete the move}$$

(5) Calculate the time to move at the run rate.

$$N_T = \text{total steps/revolution} - \text{steps required to make the desired move}$$

$$N_T = 100 \text{ steps} - 7 \text{ steps} = 93 \text{ steps}$$

$$\Delta t_{\text{run}} = N_T / (N_A + N_D) = 93 \text{ steps} / (125 \text{ steps} + 125 \text{ steps}) = 0.37 \text{ sec}$$

(6) The total time to move is determined as follows:

$$\Delta t_{\text{run}} + \Delta t_{\text{accel}} + \Delta t_{\text{decel}} = \Delta t_{\text{total}}$$

$$0.37 \text{ sec} + 0.027 \text{ sec} + 0.027 \text{ sec} = 0.42 \text{ sec}$$

The problem is now solved. The Can Stack stepper motor 42M048C1U is a good first estimate. This motor can be moved slower if more of a safety factor is desired.

(1) Since no acceleration ramping will be provided, use the following equation:

$$\tau_j = J_T \times f^2 / 2 \times 2\pi / \lambda$$

$$\tau_j = 22.5 \times 10^{-4} \text{ gm}^2 \times (200 \text{ steps/s})^2 / 2 \times 2\pi / (48 \text{ steps/rev})$$

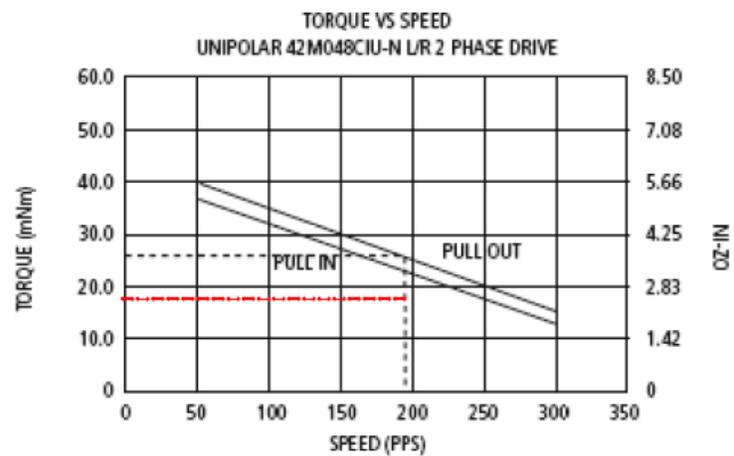
$$\tau_j = 5.85 \text{ mNm}$$

(2) Total torque

$$\tau_T = \tau_F + \tau_j$$

$$\tau_T = 12 \text{ mNm} + 5.85 \text{ mNm} = 17.85 \text{ mNm}$$

(3) Refer to the pull-out torque curve below at a speed of 200 steps/s, where the available torque is 26 mNm.



The problem is now solved. The Can Stack stepper motor 42M048C1U can perform in this application, with a safety factor.