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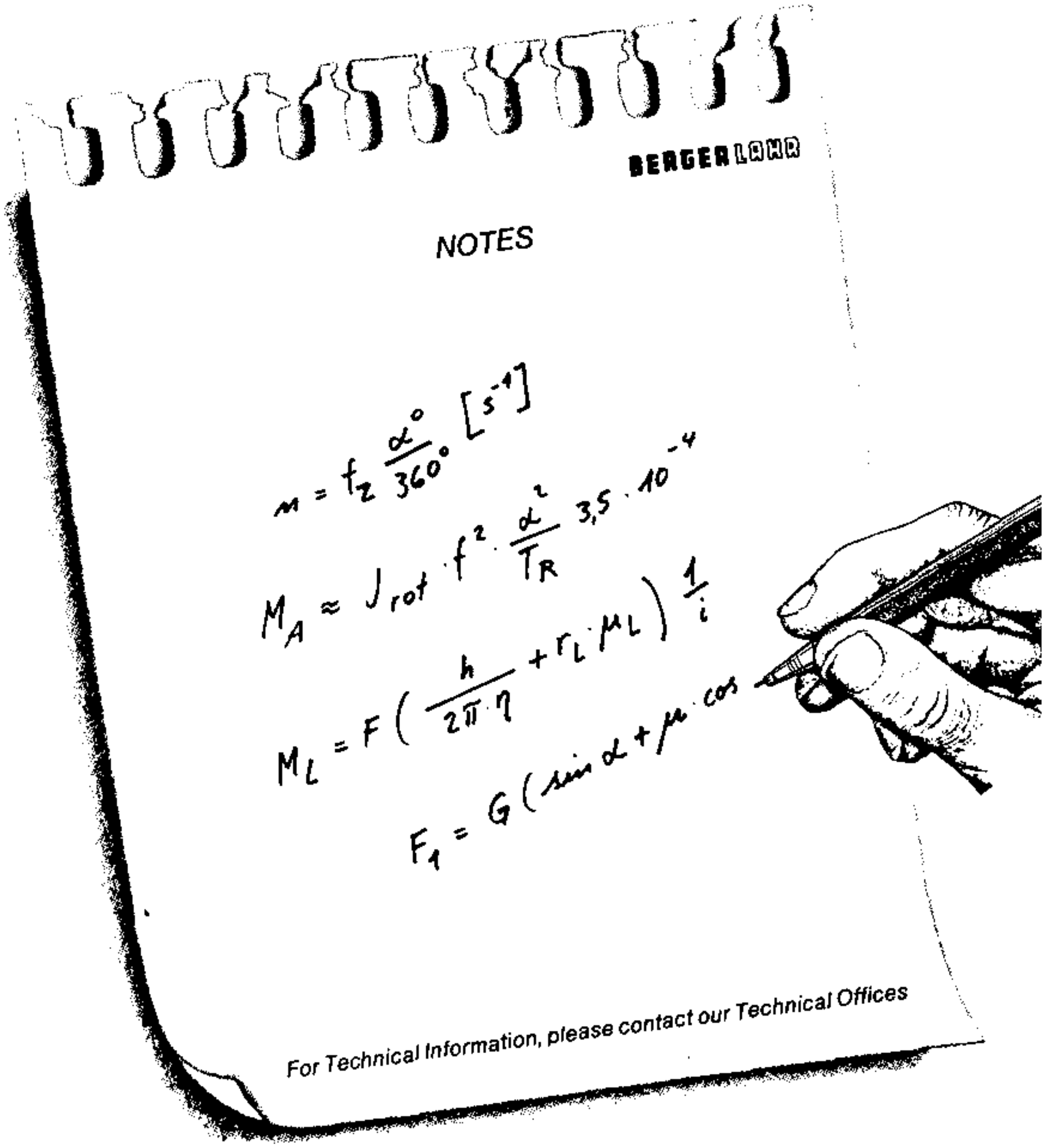
Formulas + Calculations for Optimum Selection of a Stepmotor



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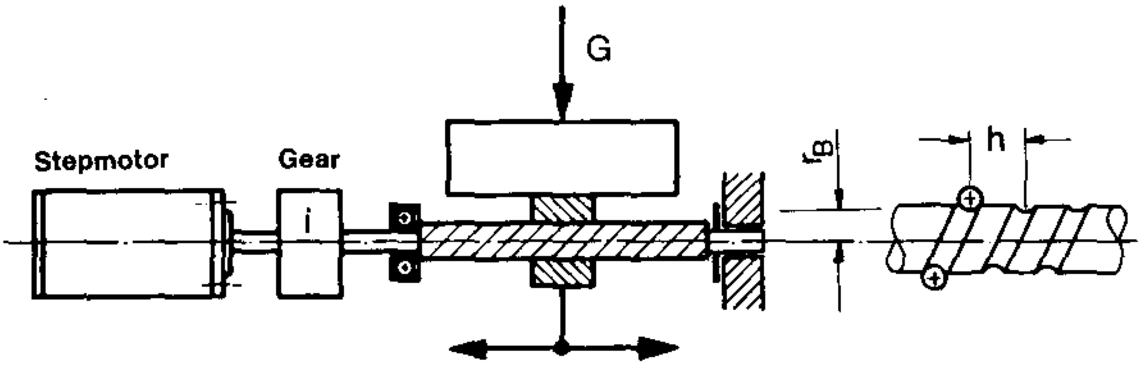
1. General Formulas

Visměre

1.1 Spindle Drive

1.1.1 Determination of Load Torque M_{Load}



$$F = F_{Table} + F_{Working\,Load} + F_{Prestress} + F_{Moving\,Force}$$

The required drive torque of a spindle drive is determined by the sum of the load torques and the required acceleration torque.

(1) $$M_{Motor} = M_{Load} + M_{Accel}$$ [Ncm]

(2) $$M_{Load} = F\left(\frac{h}{2\pi \cdot \eta} + r_B \mu_B\right)\frac{1}{i}$$ [Ncm]

F = Total force on nut [N]
h = Spindle pitch [cm]
r_B = Spindle bearing mean radius [cm]
μ_B = Spindle bearing friction coefficient
i = Gear ratio = $n_{Motor}/n_{Spindle}$

$\eta = \dfrac{\tan\alpha}{\tan(\alpha + \varrho)}$ = Efficiency coefficient of converting M into an axial force

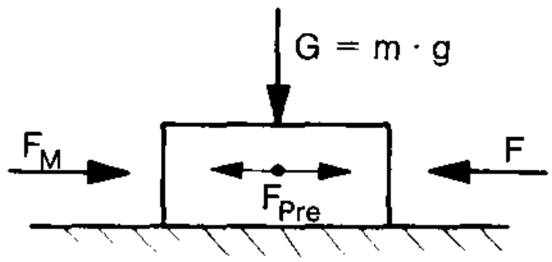
1.1.2 Experience Values

η = 0.9 for ball bearing spindles (see figure)
η = 0.3 for steel spindles with bronze nut
$r_B \cdot \mu_B$ = 0.015 cm for roller bearing
$r_B \cdot \mu_B$ = 0.15 cm for steel/bronze friction bearings

$F_{Prestress}$
At 10% Prestress and h = 5 mm: approx. 11 to 15 N
At 20% Prestress and h = 5 mm: approx. 22 to 30 N
At 10% Prestress and h = 10 mm: approx. 40 to 60 N
At 20% Prestress and h = 10 mm: approx. 80 to 120 N

1.1.3 Determination of Total Load F on Spindle Nut

a) Vertically Acting Forces

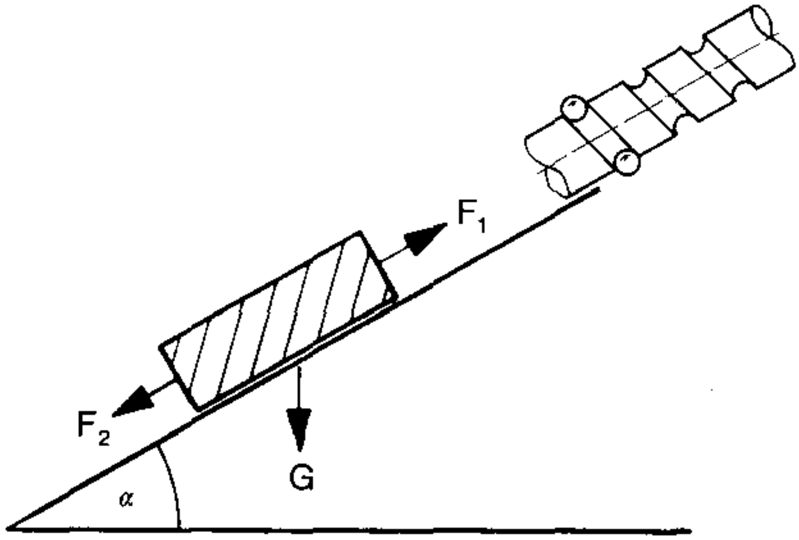


(3) $$F = \mu \cdot G + F_M + F_{Pre} \quad [N]$$

G = Weight of carriage and structure [kg]
F_M = Moving Force [N]
F_{Pre} = Prestress when using springloaded counter nut
μ = Friction coefficient
G ≈ 10 · m [N]
m = Mass [kg]

Values for μ	Dry	Lubricated
Steel on steel	0,18	0,12
Steel on cast iron	0,19	0,10
Steel on bronze	0,11	0,10
Axial Guide		
Rolling friction, Rollers	–	0,005

b) „Non-vertical" Spindle



(4)
$$F = F_{Pre} + F_M + F_{1,2} \quad [N]$$

(4a) $F_1 = G\,(\sin\alpha + \mu \cdot \cos\alpha)$ if moving up [N]

(4b) $F_2 = G\,(\sin\alpha - \mu \cdot \cos\alpha)$ if moving down [N]

For upward motion

(4c)
$$F = F_{Pre} + F_M + G\,(\sin\alpha + \mu \cdot \cos\alpha) \quad [N]$$

1.1.4 Determination of Moments of Inertia

The total moment of inertia J_{tot} is the sum of the moments of inertia of all masses in rotatory and translatory motion.

(5) $$J_{ext} = J_{rot} + J_{trans} \quad [kgcm^2]$$

J_{ext} = Total external J referenced to motor shaft

J_{rot} = Rotatory moment of inertia (full cylinder)

$J_{trans.}$ = Translatory moment of inertia

(5a) $$J_{tot} = J_{ext} + J_{Mot.} \quad [kgcm^2]$$

a) Rotatory Moment of Inertia J_{rot} – Full Cylinder

(6) $$J_{rot} = \frac{1}{2}\pi \cdot r^4 \cdot L \cdot \gamma \quad [kgcm^2]$$

	r	=	Radius of spindle	cm
	L	=	Length	cm
	γ	=	Specific weight	kg/cm^3
Steel	γ	=	$7{,}85 \cdot 10^{-3}\ kg/cm^3$	
Aluminum	γ	=	$2{,}7 \cdot 10^{-3}\ kg/cm^3$	
Brass	γ	=	$8{,}4 \cdot 10^{-3}\ kg/cm^3$	

For Steel

(7) $$J_{rot} = 7{,}72 \cdot 10^{-4} \cdot d^4 \cdot L \quad [kgcm^2]$$

For Aluminum

(7a) $$J_{rot} = 2{,}7 \cdot 10^{-4} \cdot d^4 \cdot L \quad [kgcm^2]$$

b) Translatory Moment of Inertia J_{trans}

(8) $$J_{trans} = m \left(\frac{h}{2\pi}\right)^2 \quad [kgcm^2]$$

m = Moved mass in kg

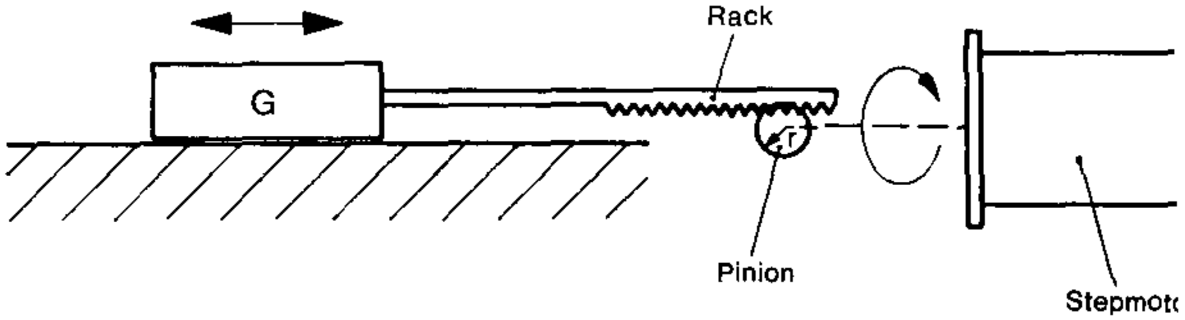
h = Spindle pitch in cm

If a reduction gear is used, the external moment of inertia J_{ext} is reduced by the square of the gear ratio.

(9) $$J_{ext} = (J_{rot} + J_{trans}) \frac{1}{i^2} \quad [kgcm^2]$$

1.2 Rack and Pinion Drive

Horizontally moved mass driven by rack and pinion.



1.2.1 Total Torques

The motor must provide the following total torques:

a) Acceleration of weight G, including rack
b) Acceleration of pinion
c) Acceleration of rotor
d) Overcoming the friction

1.2.1.1 Moments of Inertia

The following formula is used to calculate the rotatory moment of inertia equivalent to the weigh

(19) $J_{eq} = G \cdot r^2$ [kgcm²]

G = Weight in kg
r = Radius in cm

(6) $J_{rot} = \frac{1}{2} \cdot \pi \cdot r^4 \cdot L \cdot \gamma$ [kgcm²] $J_{rot} = J_{Pin}$

(20) $J_{tot} = J_{eq} + J_{Pin} + J_{rot}$ [kgcm²]

1.2.1.2 Acceleration and Load Torques

(18) $$M_A = J_{tot} \cdot \frac{f \cdot 2 \cdot \pi \cdot \alpha}{t_A \cdot 360° \cdot 10^2}$$ [Ncm]

(21) $M_{tot} = M_A + M_L$ [Ncm]

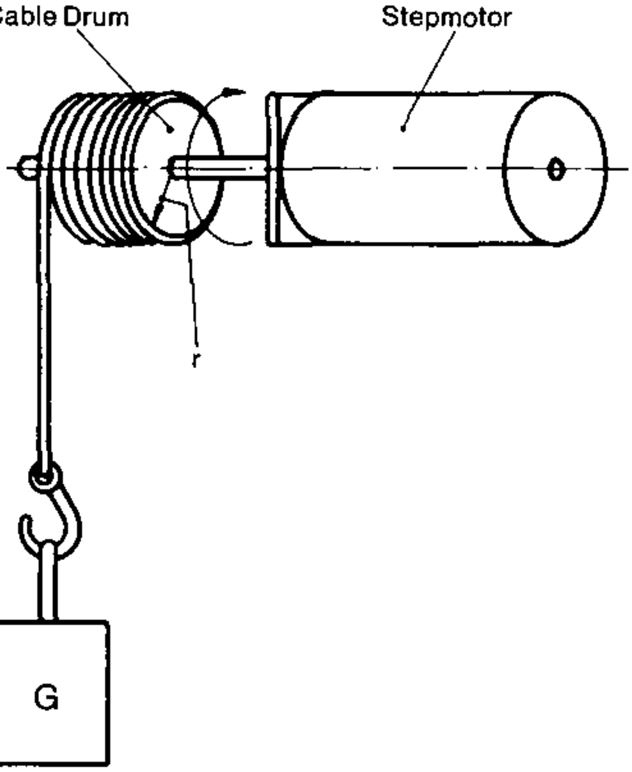
(22) $M_L \approx G \cdot \mu \cdot r$ [Ncm]

1.3 Drum Drive

Lifting a Weight by Cable and Drum

1.3.1 Total Torques

a) Acceleration of the weight
b) Acceleration of the drum
c) Lifting of the Weight G



1.3.1.1 Moments of Inertia

J_{eq} = Equivalent moment of inertia

The same formulas as used for the rack and pinion drive apply.

(19) $J_{eq} = G \cdot r^2$ [kgcm²]

(6) $J_{Drum} = \frac{1}{2} \cdot \pi \cdot r^4 \cdot L \cdot \gamma$ [kgcm²]

1.3.1.2 Acceleration and Load Torques

(18) $M_A = J_{tot} \cdot \frac{f \cdot 2 \cdot \pi \cdot \alpha}{t_A \cdot 360° \cdot 10^2}$ [Ncm]

M_A = Torque required for accelerating the system

(23) $M_L = G \cdot r$ [Ncm]

M_L = Torque required for lifting the weight

(21) $M_{tot} = M_A + M_L$ [Ncm]

M_{tot} = Total torque required for lifting the weight

1.4 Additional Formulas

1.4.1 Start-Stop Operation

(10) $$M_A \approx J_{tot} \cdot f^2 \cdot \frac{\alpha^2}{T_R} 3{,}5 \cdot 10^{-4} \qquad [\text{Ncm}]$$

(10a) $$f_{Start} \approx 199 \cdot \sqrt{\frac{M_A}{J_{tot}}} \qquad \left[\frac{1}{s}\right]$$

J_{tot} = Total Moment of Inertia [kgcm²] consisting of $J_{ext} + J_{Motor}$

f = Step frequency [Hz]

α = Step angle [Degrees]

T_R = Division angle of rotor teeth (for 5-phase motors: 7.2°)

M_A = $M_{Mot} - M_L$ [Ncm]

M_{Mot} = M at actual step frequency used

1.4.2 Calculation of Time for a Linear Acceleration (t_A)

(11) $$t_A = J_{tot} \cdot \frac{2 \cdot \pi \cdot \alpha \cdot f}{360° \cdot M_A \cdot 10^2} \qquad [\text{s}]$$

J_{tot} = Total moment of inertia consisting of $J_{ext} + J_{Mot}$ [kgcm²]
α = Step angle [Degrees]
f = Desired operating frequency [Hz]
M_A = Acceleration torque [Ncm]

(11a) $$M_A = M_{Mot} (\text{at } f) - M_L \qquad [\text{Ncm}]$$

1.4.3 Torques

(2) $M_L = F \left(\frac{h}{2 \cdot \pi \cdot \eta} + r_B + \mu_B\right) \frac{1}{i}$ [Ncm] Spindle drive

(22) $M_L \sim G \cdot \mu \cdot r$ [Ncm] Rack and pinion drive

(23) $M_L = G \cdot r$ [Ncm] Drum drive

M_L = Load torque

1.4.4 Advance, Speed and Power

Distance Increment

(12) $$\Delta s = \frac{h}{Z \cdot i} \quad [cm]$$

h = Spindle pitch in cm
Z = Number of steps per revolution
i = Gear ratio

Advance Speed

(13) $$v = \Delta s \cdot f = \frac{h}{Z \cdot i} f \quad [cm/s]$$ (for spindle drives; v = rate of feed)

f = Step frequency [s^{-1}]

(13a) $$f = \frac{v \cdot Z \cdot i}{2 \cdot \pi \cdot r} \quad [s^{-1}]$$ (for rotatory drives; v = peripheral speed)

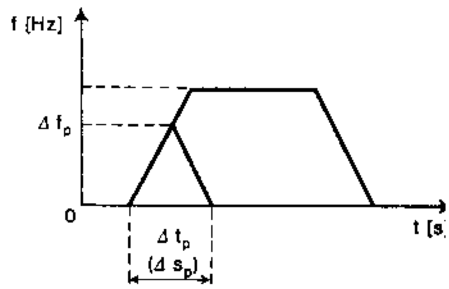
Advance in a defined time t

(14) $$s = \Delta s \cdot f \cdot t \quad [cm]$$

t = time in s

Motor RPM

(15) $$n = \frac{60 \cdot f}{Z \cdot i} \quad [min^{-1}]$$



Power for rotation

(16) $$P = 0{,}00105 \; M \cdot n \quad [W]$$

M in Ncm
n in min^{-1}

Positioning time for short distances

(24) $$\Delta t_p = \frac{t_A \cdot \Delta s_p}{s_A} \quad [s]$$

Positioning frequency for short distances

(25) $$\Delta f_p = \frac{f \cdot \Delta t_p}{t_A} \quad [s^{-1}]$$

(26) $$s_{A\,in\,cm} = s_{A\,in\,steps} \cdot \Delta s \quad [cm]$$

Δt_p = Positioning time [s]
Δs_p = Positioning distance [cr
Δf_p = Max. positioning freq. [s
$s_{A\,in\,cm}$ = Acceleration distance [
s_A = Acceleration distance ir

1.4.5 Determination of the Moment of Inertia J for Arbitary Bodies by Means of Measurement

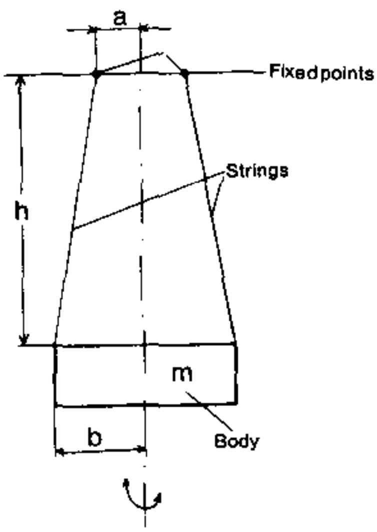
Procedure

The body is freely suspended by two strings attached to two fixes points. Then it is brought into rotational oscillation about the sketched center line. The moment of inertia is found using the previously determined mass m of the body and the distances a, b and h in the following formula.

(17) $$J = 25 \cdot T^2 m \cdot \frac{a \cdot b}{h} \quad [gcm^2]$$

J = Moment of inertia in gcm^2

T = Duration of period in sec.

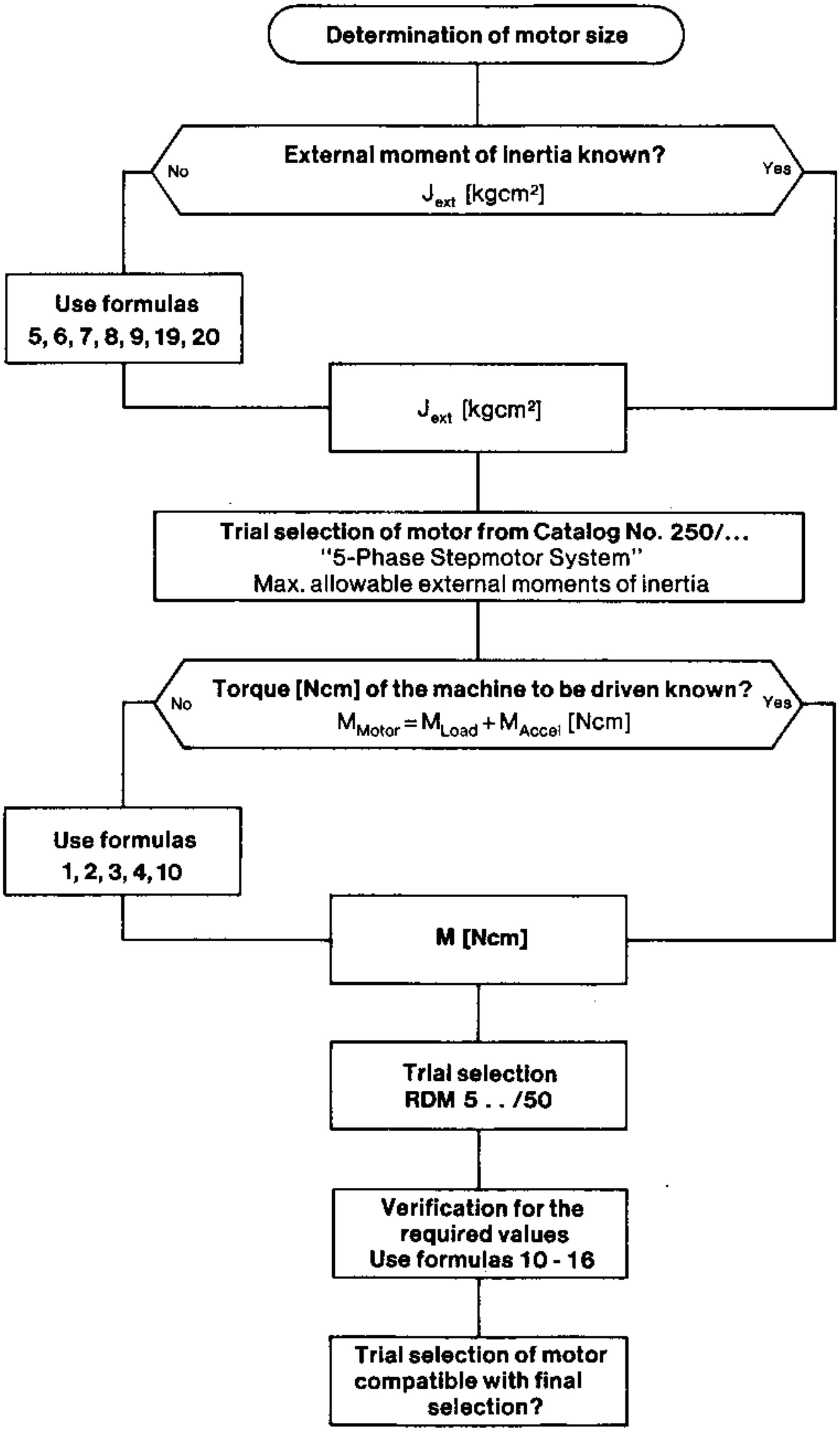


a, b, h = Distances in cm

1.4.6 How to Find the Optimum Stepmotor

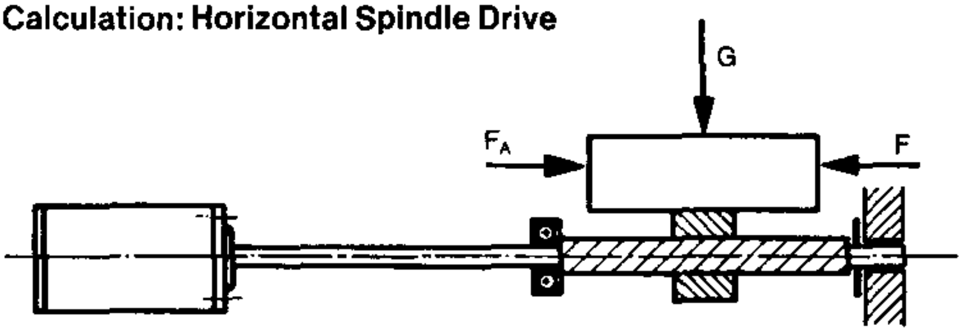
Aids: 1. "Formulas and Calculations for Optimum Selection of a Stepmotor" (this brochure)

2. BERGER Catalog "5-Phase Stepmotor System"



2. Calculation Examples

2.1 Calculation: Horizontal Spindle Drive



2.1.1 Known and Required Values

Known Values

$G = 1000\ N$

$F_A = 250\ N$

$\mu = 0{,}1$

$\eta = 0{,}9$

Required Values

$v_{Slew} = 12\ m/min = 20\ cm/s$

Positioning time for 10 mm = 0.5 s

Resolution: 0.01 mm

Spindle diameter	=	35 mm
Spindle length	=	800 mm
Spindle pitch h	=	5 mm
Travel distance	=	700 mm

Sought: the correct stepmotor

2.1.2 Required Torque

(2) $$M_L = F\left(\frac{h}{2\,\pi \cdot \eta} + r_B \cdot \mu_B\right)\ \frac{1}{i} \quad [Ncm]$$

(3) $$F = \mu \cdot G + F_A + F_{Pre} \quad [N]$$

$$F = 0{,}1 \cdot 1000\ N + 250\ N = 350\ N$$

$$M_L = 350\ N\left(\frac{0{,}5\ cm}{2 \cdot 3{,}14 \cdot 0{,}9} + 0{,}015\ cm\right) = 36\ Ncm$$

$\mathbf{M_L = 36\ Ncm}$

The calculation example does not include gear ratio $\left(\frac{1}{i}\right)$ and F_{Pre}

2.1.3 Existing Moments of Inertia

(5) $J_{ext} = J_{rot} + J_{trans.}$ [kgcm²]

(6) $J_{rot} = 0{,}5 \cdot \pi \cdot r^4 \cdot L \cdot \gamma$ [kgcm²]

$$J_{rot} = 0{,}5 \cdot 3{,}14 \cdot (1{,}75\ \text{cm})^4 \cdot 80\ \text{cm} \cdot \frac{7{,}85\ \text{kg}}{\text{cm}^3} \cdot 10^{-3}$$

$\mathbf{J_{rot} = 9{,}25\ kgcm^2}$

(8) $J_{trans} = m \left(\frac{h}{2\pi}\right)^2$ [kgcm²]

$$J_{trans} = 100\ \text{kg} \left(\frac{0{,}5}{2 \cdot 3{,}14}\right)^2 \quad [\text{kgcm}^2]$$

$\mathbf{J_{trans} = 0{,}63\ kgcm^2}$

(5) $J_{ext} = J_{rot} + J_{trans}$

$J_{ext} = 9{,}25\ \text{kgcm}^2 + 0{,}63\ \text{kgcm}^2 = 9{,}88\ \text{kgcm}^2 \approx 10\ \text{kgcm}^2$

$\mathbf{J_{ext} = 10\ kgcm^2}$

2.1.4 Required Operating Frequency

(13) $v = \frac{h}{Z \cdot i} \cdot f$ [cm/s]

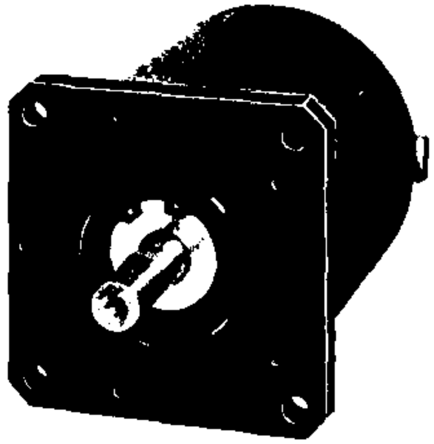
$$f = \frac{v \cdot Z \cdot i}{h} = \frac{20\text{cm/s} \cdot 500\ \text{Steps/Rev.}}{0{,}5\ \text{cm}} \quad [s^{-1}]$$

$f = 20000\ s^{-1}$

2.1.5 Values Determining the Motor Size

1. M_L = 36 Ncm
2. J_{ext} = 10 kgcm²
3. f = 20 000 Hz

2.1.6 Determination of Motor Size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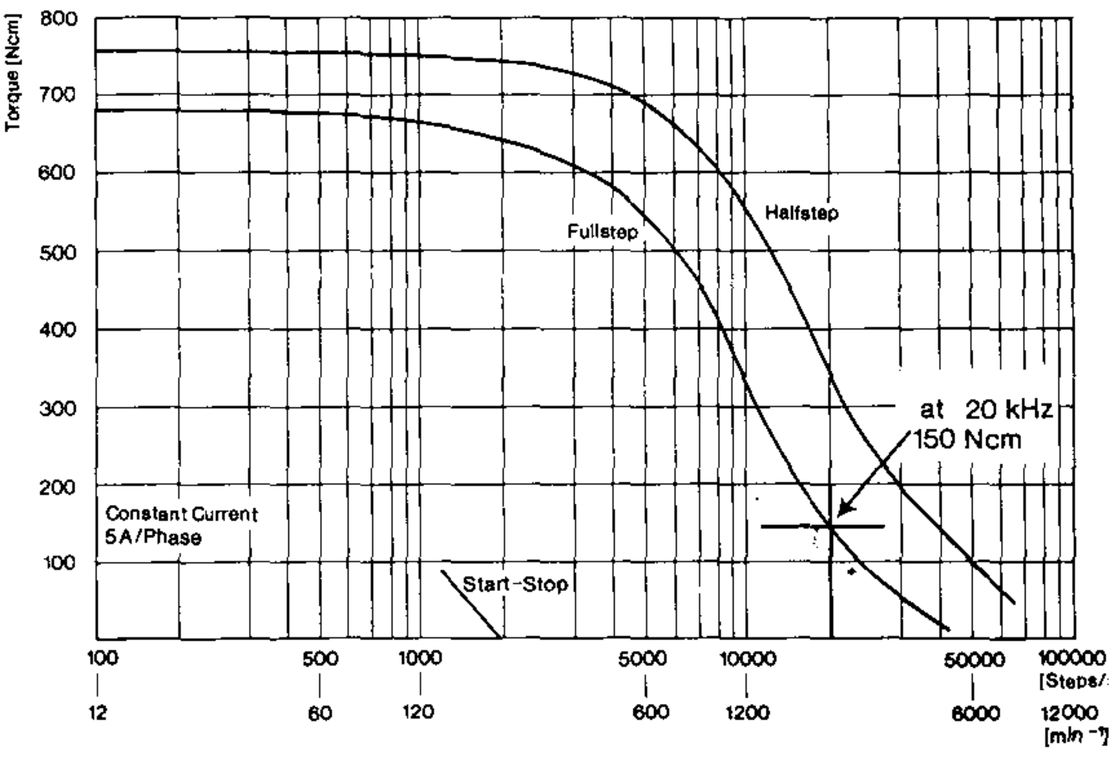
5-Phase Stepmotor Data Overview

The motor data are contained in our Catalog No. 250/... »5-Phase Stepmotor System« in the following arrangement.

MOTOR MODEL ►	RDM 51117/50	RDM 51122/50
Step angle [Degrees]	0,72	0,72
Maximum torque [Ncm]	700	1000
Holding Torque, excited [Ncm]	750	1100
Max. Power [W] at .... Hz	430 15	465 5
Moment of inertia of rotor [kgcm²]	7,5	11,5

Motor Characteristics (Constant-Current Operation / Standard Winding)

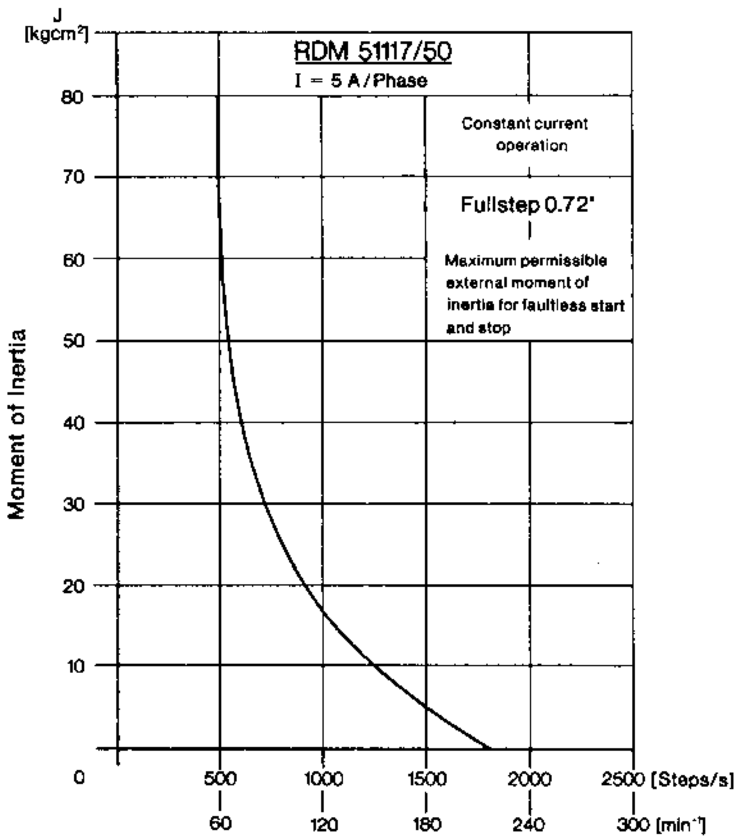
Motor Model **RDM 51117/50**
$R_W = 0{,}3\,\Omega$ $I_W = 5\,A$



* For fullstep of 0.72°

Maximum Permissible External Moments of Inertia

Motors of Series 511 . . /50



Motor size determined form curves: RDM 51117/50
Motor data see Catalog 250 "5-Phase Stepmotor System"

J_{Motor} = 7,5 kgcm²

M_A = M_{Mot} (at 20 kHz) – M_L [Ncm]

M_A = 150 Ncm – 36 Ncm = 114 Ncm

2.1.7 Determination of Acceleration Time

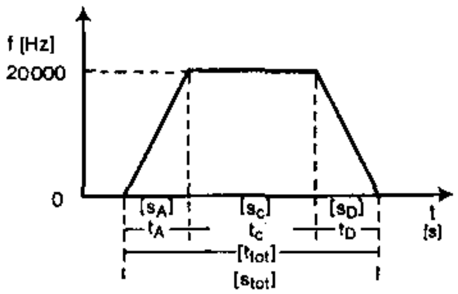
For linear acceleration and deceleration, the acceleration and deceleration times are equal.

(5a) $J_{tot} = J_{Rot} + J_{trans} + J_{Mot} = 17{,}5 \text{ kgcm}^2$

(11) $t_A = J_{tot} \cdot \dfrac{2\pi \cdot \alpha \cdot f}{360° \cdot M_A \cdot 10^2}$ [s]

$$t_A = 17{,}5 \text{ kgcm}^2 \cdot \frac{2 \cdot 3{,}14 \cdot 0{,}72° \cdot 20000 \text{ Hz}}{360° \cdot 114 \text{ Ncm} \cdot 10^2}$$

$$t_A = 0{,}386 \text{ s} \sim 0{,}39 \text{ s}$$



t_A = Time for acceleration
t_C = Time for constant speed
t_D = Time for deceleration
t_{tot} = Total travel time

s_A = Steps for acceleration
s_C = Steps for constant speed
s_D = Steps for deceleration

2.1.8 Distance Traveled in Total Travel Time

(27) $s_A = \dfrac{f \cdot t_A}{2}$ [Distance in steps]

$$s_A = \frac{20000 \cdot 0{,}39 \text{ s}}{\text{s} \cdot 2} = 3900 \text{ Steps}$$

During acceleration phase	=	3900 Steps	=	s_A
During deceleration phase	=	3900 Steps	=	s_D
Sum for acceleration and deceleration	=	7800 Steps		

Total distance traveled s_{tot} = 700 mm ≙ 70 000 Steps

2.1.9 Total Travel Time

$$t_{tot} = t_A + t_c + t_D \quad \text{[s]}$$

$$t_c = \frac{s_{tot} - (s_A + s_D)}{f} \quad \text{[s]}$$

$$t_c = \frac{70000 - (3900 + 3900)}{20000}$$

$$t_c = \mathbf{3{,}11\ s}$$

$$t_{tot} = t_A + t_c + t_D \quad \text{[s]}$$

$$t_{tot} = 0{,}39 + 3{,}11 + 0{,}39$$

$$t_{tot} = \mathbf{3{,}89\ s}$$

2.1.10 Verification of Required Values

2.1.10.1 Positioning Time Δt_p [s]

Δt_p required 0.5 s

(24) $$\Delta t_p = \frac{t_{A[s]} \cdot \Delta s_{p\,[cm]}}{s_{A\,[cm]}} \quad [s]$$

$$\Delta s_p = 10 \text{ mm} = 1 \text{ cm}$$

(26) $$s_{A\,[cm]} = s_A \,[\text{Steps}] \cdot \Delta s = s_A \cdot \frac{h}{Z}$$

$$s_{A\,[cm]} = 3900 \text{ Steps} \cdot \frac{0{,}5 \text{ cm}}{500 \text{ Steps}} = 3{,}9 \text{ cm}$$

$$\Delta t_p = \frac{0{,}39 \text{ s} \cdot 1 \text{ cm}}{3{,}9 \text{ cm}} = 0{,}1 \text{ s}$$

2.1.10.2 Smallest Distance Increment per Step

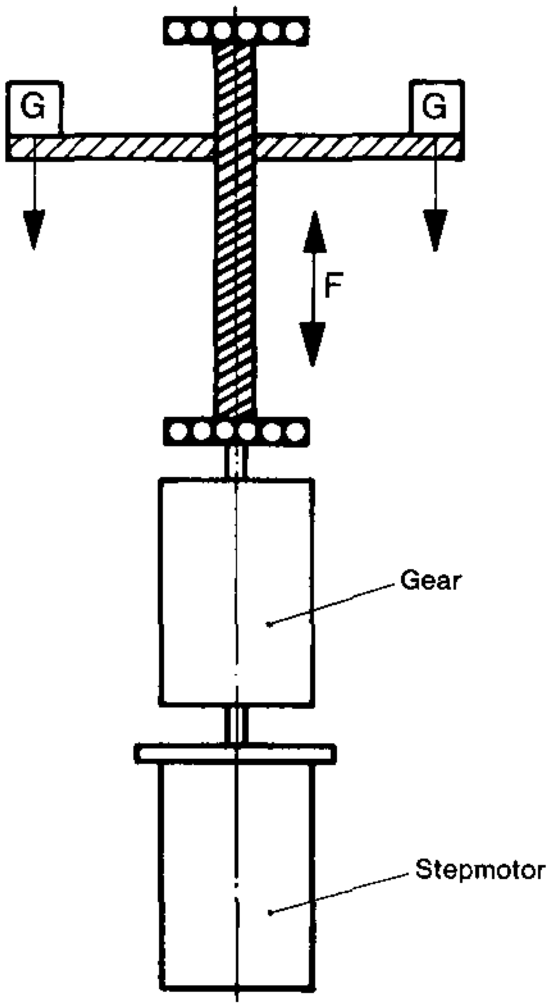
Δs required 0.01 mm

(12) $$\Delta s = \frac{h}{Z \cdot i} \quad [cm]$$

$$\Delta s = \frac{0{,}5}{500 \cdot 1} = 0{,}001 \text{ cm} = 0{,}01 \text{ mm}$$

2.2 Calculation: Vertical Spindle Drive (Lifting Force)

2.2.1 Known and Required Values



Known Values

$G = 150$ kg
$\eta = 0{,}9$
$\mu = 0{,}1$

Spindle diameter		63 mm
	length	10 m
	pitch	10 mm
	Gear ratio	$i = 20:1$

Required Values

Positioning time 10 mm in 1 s
Resolution < 0.01 mm

2.2.2 Required Torque

(2) $$M_L = F \left(\frac{h}{2\pi \cdot \eta} + r_B \, \mu_B \right) \cdot \frac{1}{i} \quad [\text{Ncm}]$$

(4c) $$F = G \cdot (\sin\alpha + \mu \cdot \cos\alpha) \quad [\text{N}]$$

at $\alpha = 90°$
$\sin\alpha = 1$
$\cos\alpha = 0$

$$F = 1500\ N\ (1 + 0{,}1 \cdot 0)$$

$$F = 1500\ N$$

$$M_L = 1500\ N \left(\frac{1\ cm}{2\pi \cdot \eta} + r_B \cdot \mu_B\right) \cdot \frac{1}{i} \quad [Ncm]$$

$$M_L = 1500\ N\ (0{,}177 + 0{,}015)\ \frac{1}{20} = 14{,}4\ Ncm$$

2.2.3 Existing Moments of Inertia

(9) $$J_{ext} = \left(J_{rot} + J_{trans}\right) \cdot \frac{1}{i^2}$$

(6) $$J_{rot} = 0{,}5 \cdot \pi \cdot r^4 \cdot L \cdot \gamma \quad [kgcm^2]$$

Moment of Inertia of Spindle

$$J_{rot} = 0{,}5 \cdot 3{,}14\ (3{,}15\ cm)^4 \cdot 1000\ cm \cdot 7{,}85\ kg/cm^2 \cdot 10^{-3}$$

$$J_{rot} = 1213{,}42\ kgcm^2$$

(8) $$J_{trans} = m \left(\frac{h}{2\pi}\right)^2 \quad [kgcm^2]$$

(equivalent moment of inertia of weight G)

$$J_{trans} = 150\ kg \left(\frac{1\ cm}{2 \cdot 3{,}14}\right) = 3{,}8\ kgcm^2$$

$$J_{ext} = (J_{rot} + J_{trans}) \cdot \frac{1}{i^2} \quad [kgcm^2]$$

$$J_{ext} = \left(1213{,}42\ kgcm^2 + 3{,}8\ kgcm^2\right) \cdot \frac{1}{20^2}$$

$$J_{ext} = 3{,}043\ kgcm^2$$

2.2.4 Required Speed

In order to determine the exact motor data, the speed must be determined.

Required: 10 mm in 1 s $\triangleq 1\ s^{-1}$
at $i = 20 : 1 \triangleq n_{Mot} \triangleq 1200\ min^{-1} \triangleq 10\ kHz$

Hence, the motor torques have to be determined for a step frequency of 10 kHz.

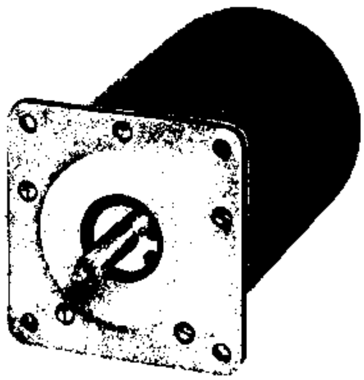
2.2.5 Values Determining the Motor Size

1) M_L = 14,4 Ncm

2) J_{ext} = 3,043 $kgcm^2$

3) f = 10000 Hz

2.2.6 Determination of Motor Size



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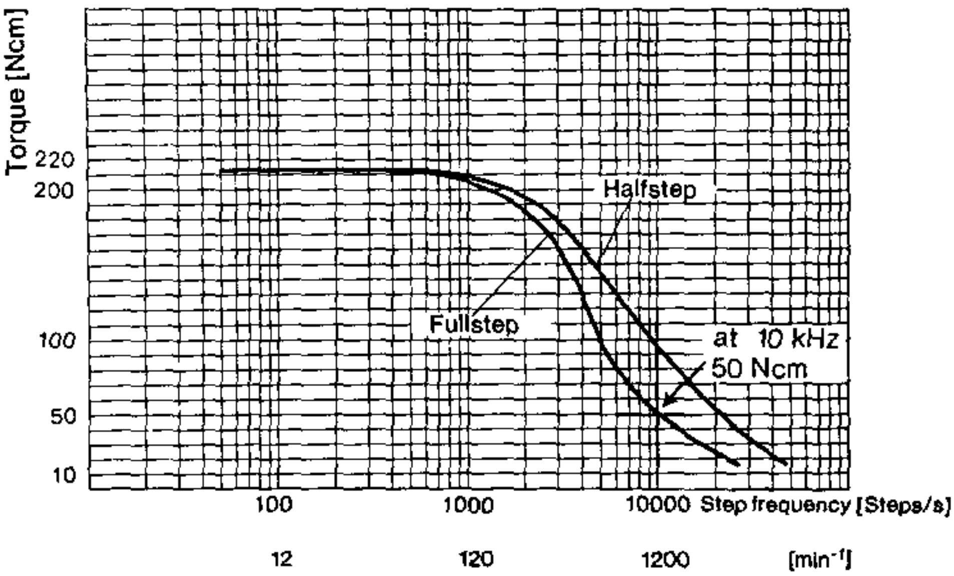
Data Overview
5-Phase Stepmotor

MOTOR MODEL ►	RDM 596/50	RDM 599/50	RDM 5913/50
Step angle [Degrees]	0,72	0,72	0,72
Maximum torque [Ncm]	115	210	310
Holding Torque, excited [Ncm]	125	220	400
Max. Power [W] at ... Hz	48 10	60 10	160 8
Moment of inertia of rotor [$kgcm^2$]	0,7	1,2	1,8

Constant Current Operation (70 V)

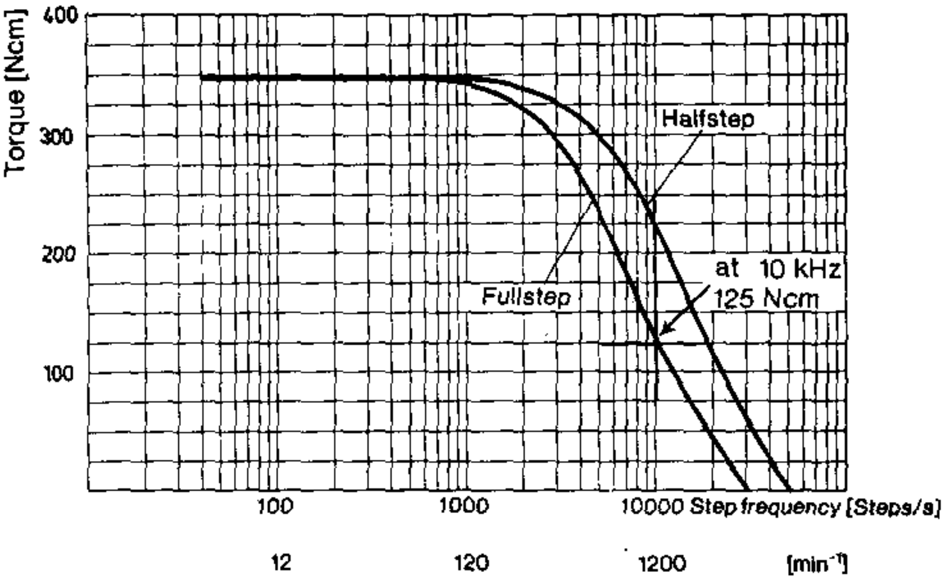
Motor Model **RDM 599/50**

R_W = 3.25 Ω I_W = 1.15 A



Motor Model **RDM 5913/50**

R_W = 1 Ω I_W = 2.8 A



For these two motor models:

a) RDM 599/50

J_{Mot} = 1,2 kgcm²

M_A = M_{Mot} (at 10 kHz) – M_L

M_A = 50 Ncm – 14,4 Ncm

b) RDM 5913/50

J_{Mot} = 1,8 kgcm²

M_A = M_{Mot} (at 10 kHz) – M_L

M_A = 125 Ncm – 14,4 Ncm

2.2.7 Calculation of Acceleration Time

For linear acceleration:

Acceleration Time = Deceleration Time

(11) $t_A = J_{tot} \cdot \frac{2 \cdot \pi \cdot \alpha \cdot f}{360° \cdot M_A \cdot 10^2}$ [s]

(5a) $J_{tot} = J_{ext} + J_{Mot.}$ [kgcm²]

J_{tot} = 3,043 kgcm² + 1,2 kgcm² = 4,243 kgcm² for RDM 599/50

J_{tot} = 3,043 kgcm² + 1,8 kgcm² = 4,843 kgcm² for RDM 5913/50

(11a) $M_A = M_{Mot}$ (at 10 kHz) $- M_L$ [Ncm]

M_A = 50 Ncm – 14,4 Ncm = 35,6 Ncm for RDM 599/50

M_A = 125 Ncm – 14,4 Ncm = 110,6 Ncm for RDM 5913/50

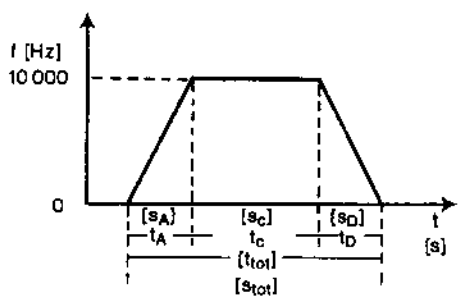
$t_A = 4{,}243 \text{ kgcm}^2 \cdot \frac{2 \cdot 3{,}14 \cdot 0{,}72° \cdot 10000 \text{ Hz}}{360° \cdot 35{,}6 \text{ Ncm} \cdot 10^2}$

t_A = **0,148 s** for RDM 599/50

$t_A = 4{,}843 \text{ kgcm}^2 \cdot \frac{2 \cdot 3{,}14 \cdot 0{,}72° \cdot 10000 \text{ Hz}}{360° \cdot 110{,}6 \text{ Ncm} \cdot 10^2}$

t_A = **0,0548 s** ~ for RDM 5913/50

$t_A \approx$ **0,055 s**



t_A = Time for acceleration
t_C = Time for constant speed
t_D = Time for deceleration

2.2.8 Distance Traveled

(27) $s_A = \frac{f \cdot t_A}{2}$ [Distance in Steps]

$s_D = \frac{10000 \cdot 0{,}055}{2}$ = 275 Steps for RDM 5913/50

During acceleration phase = 275 Steps = s_A
During deceleration phase = 275 Steps = s_D
550 Steps

2.2.9 Total Travel Time

Distance of 10 mm ≙ 20 · 1 Revolution = 10000 Steps

Spindle pitch h ≙ 10 = 10 mm Advance
at 1 Revolution ≙ 500 Steps
i = 20 : 1

$$t_{tot} = t_A + t_C + t_D \quad [s]$$

$$t_C = \frac{s_{tot} - (s_A + s_D)}{f} = \frac{10000 - 550}{10000} = \mathbf{0,945\ s}$$

$$t_{tot} = 0,055 + 0,945 + 0,055 = 1,055\ s$$

Therefore, if a distance of 10 mm is to be traversed in 1 second, the frequency must be increased, in this example to about 11000 Hz.

If the RDM 599/50 had been selected instead of the RDM 5913/50, the total time would be longer and the frequency would have to be increased even further.

2.2.10 Frequency Increase to 11 kHz (arbitrarily chosen)

(11a) $$M_A = M_{Mot}\,(\text{at } 11\ \text{kHz}) - M_L \quad [\text{Ncm}]$$

$$M_A = 120\ \text{Ncm} - 14,4\ \text{Ncm} = 105,6\ \text{Ncm}$$

$$t_A = 4,843\ \text{kgcm}^2\ \frac{2 \cdot 3,14 \cdot 0,72° \cdot 11000\ \text{Hz}}{360° \cdot 105,6\ \text{Ncm} \cdot 10^2}$$

$$t_A = 0,0634\ s$$

(27) $$s_A = \frac{f \cdot t_A}{2} \quad [\text{Distance in Steps}]$$

$$s_A = \frac{11000\ \text{Hz} \cdot 0,0568\ s}{2} = 349\ \text{Steps}$$

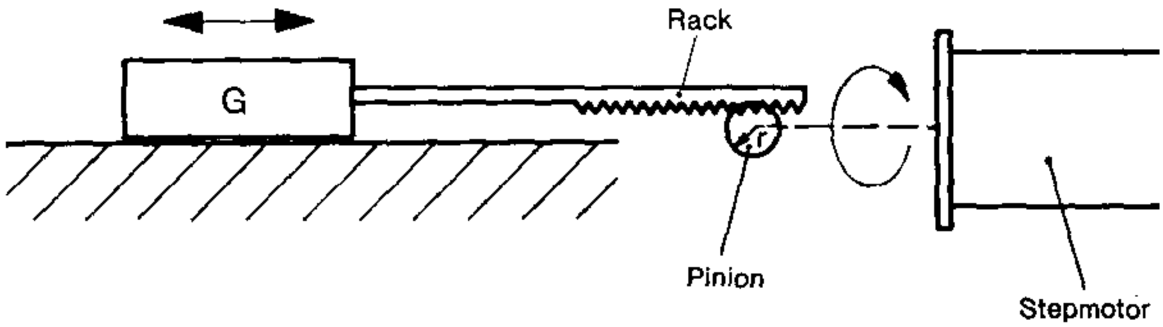
$$s_A + s_D = 698\ \text{Steps}$$

$$t_C = \frac{s_{tot} - (s_A + s_D)}{f} = \frac{10000 - 698}{11000} = 0,8456\ s$$

$$t_{tot} = 0,0634 + 0,8456 + 0,0634 = 0,9724\ s$$

2.3 Calculation: Rack and Pinion Drive

Example: Horizontally moved mass, driven by rack and pinion.



2.3.1 Known and Required Values

Given:

Weight	$G =$	4 kg
Radius	$r =$	3 cm
Pinion width	$L =$	1,5 cm
Material: Steel	$\gamma =$	$7{,}85 \cdot 10^{-3}$ kg/cm³
Speed	$v =$	400 cm/s
Acceleration Time	$t =$	0,5 s

2.3.2 Existing Moments of Inertia

(19) $J_{eq} = G \cdot r^2$ [kgcm²]

$J_{eq} = 4 \cdot (3)^2 = 36$ kgcm²

$J_{Pin} = \frac{1}{2} \cdot \pi \cdot r^4 \cdot L \cdot \gamma = \frac{1}{2} \cdot \pi \cdot 3^4 \cdot 1{,}5 \cdot 7{,}85 \cdot 10^{-3}$

$J_{Pin} = 1{,}5$ kgcm²

Assumed motor model: RDM 5913/50

$J_{Mot} = 1{,}8$ kgcm²

Rotor moment of inertia see catalog data.

(5a) $J_{tot} = J_{eq} + J_{Pin} + J_{Mot}$ [kgcm²]

$J_{tot} = 36 + 1{,}5 + 1{,}8 = 39{,}3$

$J_{tot} \sim 40$ kgcm²

2.3.3 Step Frequency

(13a) $$f = \frac{v \cdot Z \cdot i}{2 \cdot \pi \cdot r} \quad [s^{-1}]$$

$$f = \frac{400\ cm/s \cdot 500 \cdot 1}{2 \cdot \pi \cdot 3\ cm} \approx 10615\ Steps/s$$

2.3.4 Acceleration and Load Torque

$$M_A = J_{tot} \cdot \frac{f}{t_A} \cdot \frac{2\pi \cdot \alpha}{360° \cdot 10^2}$$

$$M_A = 40 \cdot \frac{10610}{0{,}5} \cdot \frac{2 \cdot 3{,}14 \cdot 0{,}72}{360° \cdot 10^2} = 107\ Ncm$$

$$M_A = 107\ Ncm$$

(21) $$M_{tot} = M_A + M_L \quad [Ncm]$$

$$M_{tot} = 107 + 0{,}6 = 107{,}6 \sim 108\ Ncm$$

(22) $$M_L \sim G \cdot \mu \cdot r \quad [Ncm]$$

$$M_L \sim 40 \cdot 0{,}005 \cdot 3 = 0{,}6\ Ncm$$

2.3.5 Verification of Data

Model RDM 5913/50 is too weak, it would operate at its very performance limit (100%).

M = 120 Ncm at 10.6 kHz

This can be remedied in the following ways:

a) Increase acceleration time by about 20%, this would reduce M to about 95 Ncm

or

b) Reduce speed v = 400 cm/s by about 20%, this would reduce M to about 92 Ncm

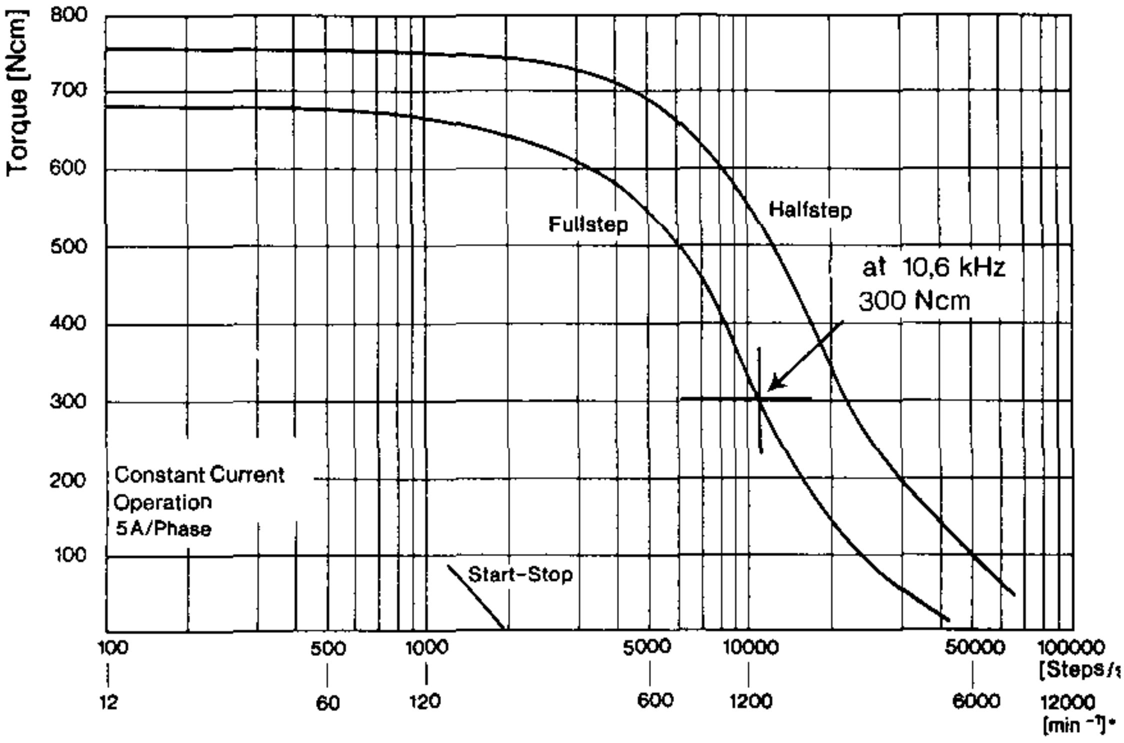
or

c) Use next larger motor model (RDM 51117/50). This model would provide a torque M_{Mot} of about 300 Ncm at 10.6 kHz.

2.3.6 Torque Curves

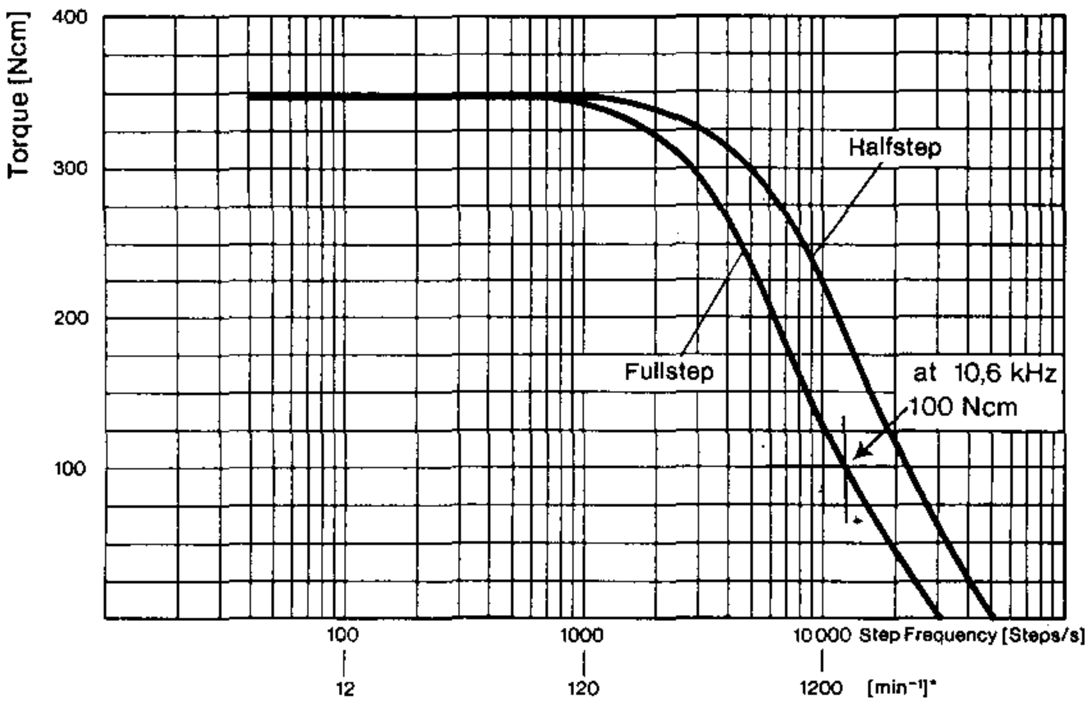
Motor Model **RDM 51117/50**

$R_w = 0.3\ \Omega \quad I_w = 5\ A$



Motor Model **RDM 5913/50**

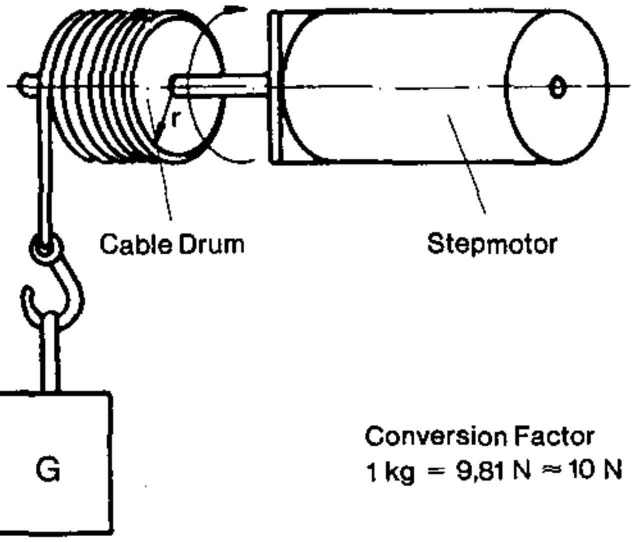
$R_w = 1\ \Omega \quad I_w = 2.8\ A$



* For fullstep 0.72°

2.4 Calculation: Drum Drive

Lifting a Weight by Cable and Drum



Conversion Factor
1 kg = 9,81 N ≈ 10 N

2.4.1 Known and Required Values

Weight	G	=	4 kg
Drum radius	r	=	3 cm
Lifting speed	v	=	400 cm/s
Acceleration time	t_A	=	0,5 s
Drum moment of inertia	J_{Dr}	=	10 kgcm²

2.4.2 Existing Moments of Inertia

$J_{eq} = G \cdot r^2$ [kgcm²]

$J_{eq} = 4\text{ kg} \cdot (3\text{ cm})^2 = 36\text{ kgcm}^2$

$J_{Dr} = 10\text{ kgcm}^2$

$J_{ext} = 46\text{ kgcm}^2$

2.4.3 Existing Load Torque

(23) $M_L = G \cdot r$ [Ncm]

$M_L = 4\text{ kg} \cdot 3\text{ cm} = 12\text{ kgcm} \mathrel{\hat=} 120\text{ Ncm}$

2.4.4 Operating Frequency

(13) $$v = \frac{h}{Z \cdot i} \cdot f \quad [\text{cm/s}]$$

(13a) $$f = \frac{v \cdot Z \cdot i}{2 \cdot \pi \cdot r} \quad [\text{s}^{-1}]$$

$$f = \frac{400\text{ cm/s} \cdot 500\text{ Steps} \cdot 1}{2 \cdot 3{,}14 \cdot 3\text{ cm}} = 10\,615\text{ Steps/s} \quad \hat=\ [\text{s}^{-1}]$$

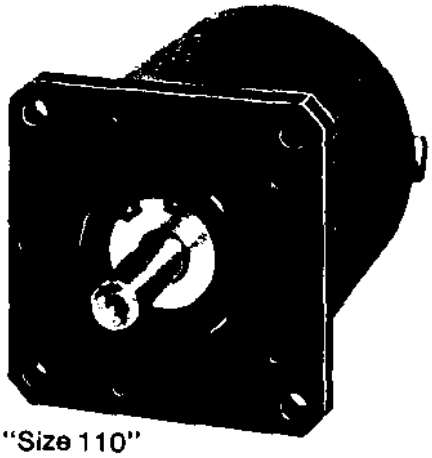
2.4.5 Values Determining the Motor Size

1) M_L = 120 Ncm

2) J_{ext} = 46 kgcm²

3) f = 10615 s^{-1}

2.4.6 Determination of Motor Size

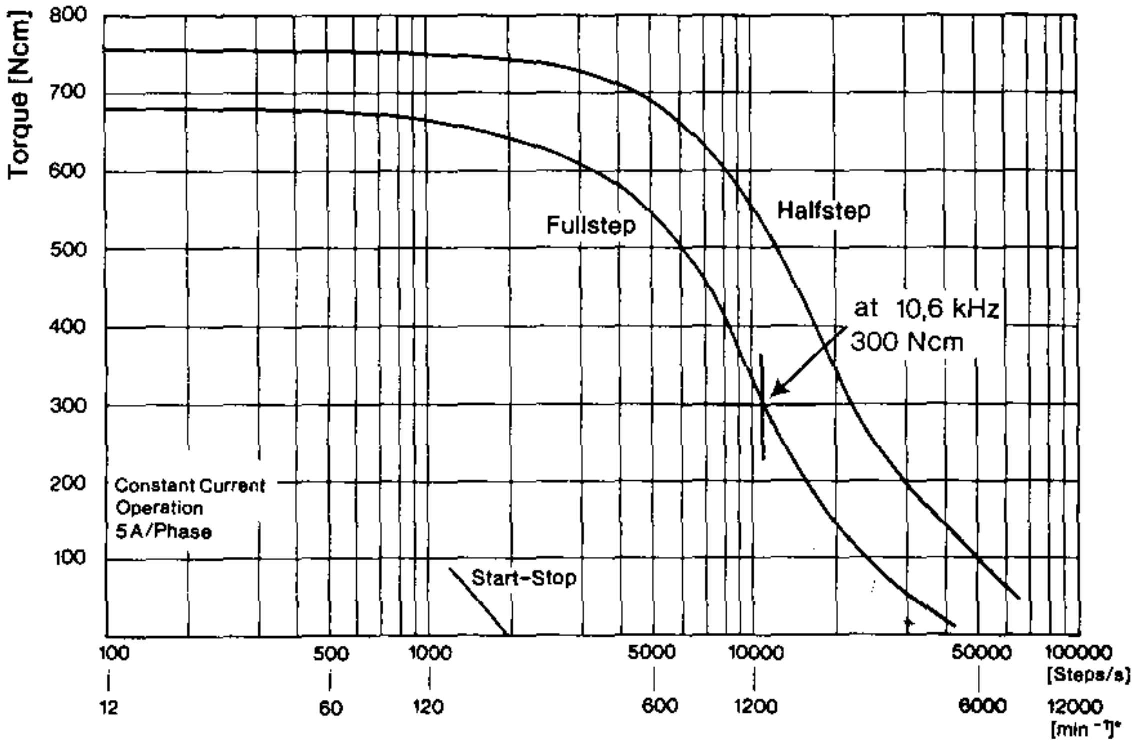


"Size 110"

5-Phase Stepmotor Data Overview
The motor data are contained in our Catalog No. 250/... "5-Phase Stepmotor System" in the following arrangement

MOTOR MODEL ►	RDM 51117/50	RDM 51122/50
Step angle [Degrees]	0,72	0,72
Maximum torque [Ncm]	700	1000
Holding Torque, excited [Ncm]	750	1100
Max. Power [W] at ... Hz	430 15	465 5
Moment of inertia of rotor [kgcm²]	7,5	11,5

Motor Model: **RDM 51117/50 Constant Current Operation (90 V)**
$R_w = 0{,}3\ \Omega \quad I_w = 5\ A$



* For fullstep 0.72°

Based on this data, the RDM 51117/50 was selected M_{Mot} at 10,6 kHz 300 Ncm
J_{Mot} 7,5 kgcm²

2.4.7 Acceleration Torque

(18) $$M_A = J_{tot} \cdot \frac{f \cdot 2 \cdot \pi \cdot \alpha}{t_A \cdot 360° \cdot 10^2} \quad [Ncm]$$

(5a) $$J_{tot} = J_{ext} + J_{Mot} \quad [kgcm^2]$$

$$J_{tot} = 46\ kgcm^2 + 7{,}5\ kgcm^2 = 53{,}5\ kgcm^2$$

$$M_A = 53{,}5 \cdot \frac{10615 \cdot 2 \cdot \pi \cdot 0{,}72}{0{,}5 \cdot 360 \cdot 10^2} = 142{,}66\ Ncm$$

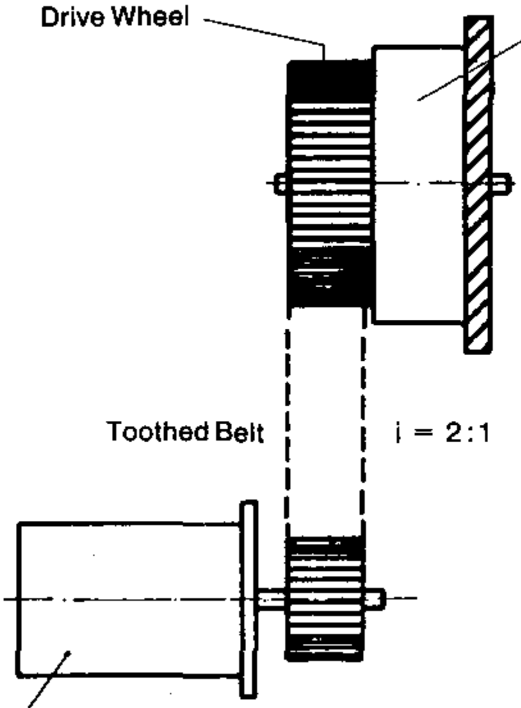
2.4.8 Total Torque to be Gerated

(21) $$M_{tot} = M_L + M_A \quad [Ncm]$$

$$M_{tot} = 120\ Ncm + 142{,}66\ Ncm = 262{,}66\ Ncm$$

i.e. *Model RDM 51117/50 with 300 Ncm is sufficient,*
it provides a reserve of 37.3 Ncm = 13%

2.5 Calculation: Flywheel Drive



2.5.1 Data

Printing Wheel		Drive Wheel		Motor Pinion	
Diameter	140 mm	Diameter	90 mm	Diameter	45 mm
Width (L)	90 mm	Width (L)	25 mm	Width (L)	25 mm
Material	Steel	Material	Aluminum	Material	Aluminum
		Number of Teeth	24	Number of Teeth	12

Reduction ratio 2 : 1 by toothed belt.

Printing wheel setting time 0.3 s for 180°.

2.5.2 Moments of Inertia

(6) $J_{rot} = \frac{1}{2} \pi \cdot r^4 \cdot L \cdot \gamma$ [kgcm²]

For steel

(7) $J_{rot} = 7{,}72 \cdot 10^{-4} \cdot d^4 \cdot L$ [kgcm²]

For Aluminum:

(7a) $J_{rot} = 2{,}7 \cdot 10^{-4} \cdot d^4 \cdot L$ [kgcm²]

If a transmission is used, Formulas 6 - 7 a must be multiplied by $\frac{1}{i^2}$.

The formulas then become:

$$J_{ext} = \left(J_{Prin} + J_{Driv}\right) \cdot \frac{1}{i^2} + J_{Pinion}$$

$$J_{Print\,Wheel} = 7{,}72 \cdot 10^{-4} \cdot (14\ cm)^4 \cdot 9 = 267 \quad kgcm^2$$

$$J_{Drive\,Wheel} = 2{,}7 \cdot 10^{-4} \cdot 9^4 \cdot 2{,}5 = 4{,}43 \quad kgcm^2$$

$$J_{Pinion} = 2{,}7 \cdot 10^{-4} \cdot 4{,}5^{-4} \cdot 2{,}5 = 0{,}28 \quad kgcm^2$$

$$J_{ext} = (267 + 4{,}43) \cdot \frac{1}{2^2} + 0{,}28 = 68{,}13 \approx 70\ kgcm^2$$

(5a) $J_{tot} = J_{ext} + J_{Mot}$ [kgcm²]

2.5.3 Acceleration Torque

(18) $M_A = J_{tot} \cdot \frac{f \cdot 2 \cdot \pi \cdot \alpha}{t_A \cdot 360° \cdot 10^2}$ [Ncm]

2.5.4 Acceleration Time

(11) $t_A = J_{tot} \cdot \frac{2\pi \cdot \alpha \cdot f}{360° \cdot M_A \cdot 10^2}$ [s]

f is calculated from the requirement i = 2 : 1 and t = 0.3 s for a 180 ° rotation of the printing wheel, i. e. the motor must execute a rotation of 360° in 0.3 s. For a 5-phase motor operating in the fullstep mode, this means 500 steps.

The frequency is then $\frac{500\ \text{Steps}}{0{,}3\ s} = 1667$ Hz

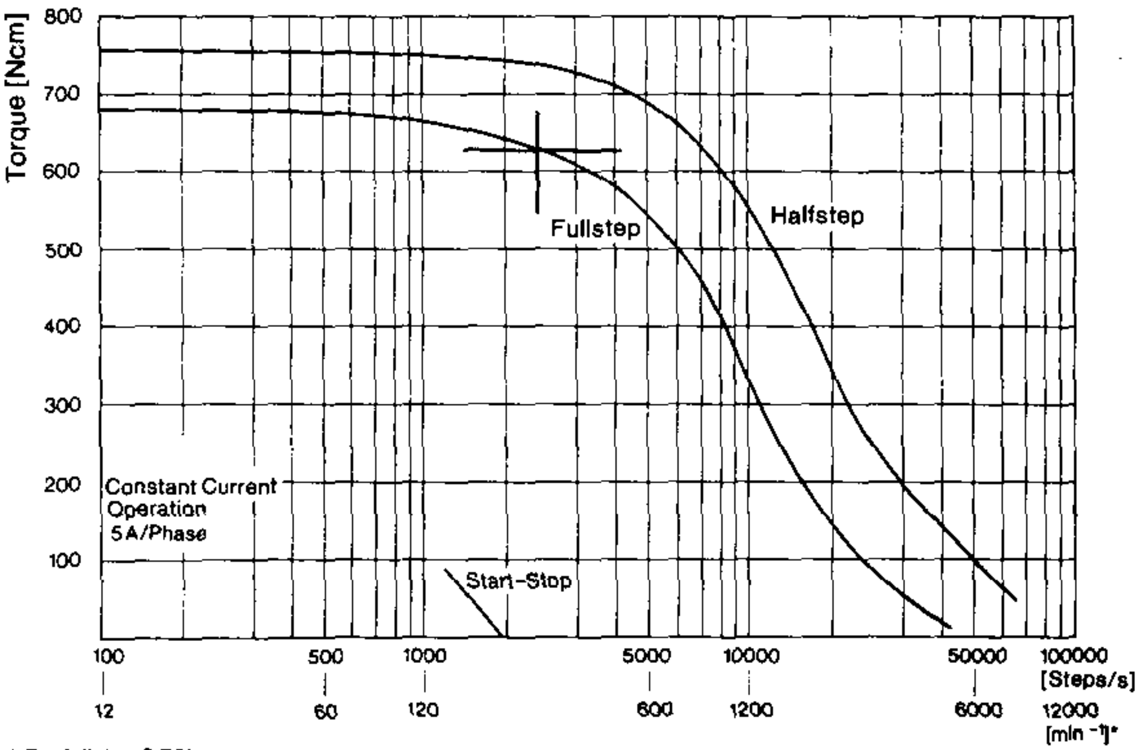
However, as the motor must accelerate and decelerate, a higher frequency must be *chosen. We assume here f = 2500 Hz.*

The RDM 51117/50 is selected because it is the only motor capable of accelerating the 70 kgcm²

$J_{tot} = J_{ext} + J_{Mot} = 70\ \text{kgcm}^2 + 7{,}5\ \text{kgcm}^2 = 77{,}5\ \text{kgcm}^2$

M_{Mot} = the available torque at 2500 Hz according curve approx. 600 Ncm

Motor Model: **RDM 51117/50**
$R_W = 0{,}3\ \Omega \quad I_W = 5\ A$



* For fullstep 0.72°

$$t_A = 77{,}5\ \text{kgcm}^2 \cdot \frac{2 \cdot 3{,}14 \cdot 0{,}72^\circ \cdot 2500\ s^{-1}}{360^\circ \cdot 600\ \text{Ncm} \cdot 10^2} = \underline{\underline{0{,}04\ s}}$$

(27) $$s_A = \frac{f \cdot t_A}{2}\ \text{[Steps]}$$

$$s_A = \frac{2500 \cdot 0{,}04}{2} = 50\ \text{Steps}$$

2.5.5 Total Time

As acceleration = deceleration, $s_A = s_D = 2 \times 50 = 100$ Steps

Total distance s_{tot} = 180° at i = 2 : 1, 500 Steps

$$t_{tot} = t_A + t_c + t_D\ \text{[s]}$$

$$t_c = \frac{s_{tot} - (s_A + s_D)}{f} = \frac{500 - 100}{2500} = 0{,}16\ s$$

$$t_{tot} = 0{,}04 + 0{,}16 + 0{,}04 = 0{,}24\ s$$