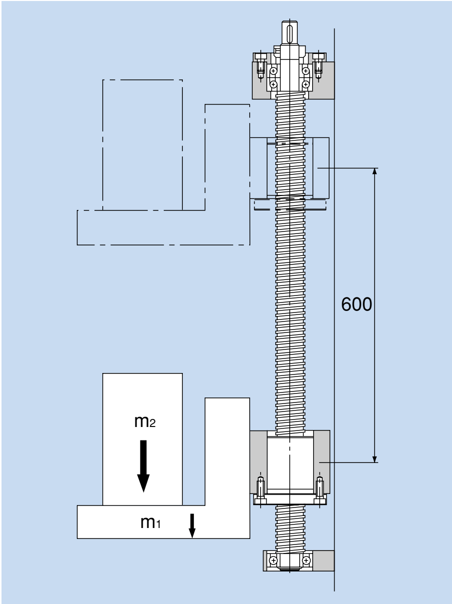
12.2. Vertical Conveyance System

12.2.1. Selection Conditions

Table mass	m_1 =40 kg
Workpiece mass	m_2 =10 kg
Stroke length	ℓ_s =600 mm
Maximum speed	V_{max} =0.3 m/s
Acceleration time	t_1 =0.2 s
Deceleration time	t_3 =0.2 s
Reciprocations per minute	n =5 min^{-1}
Backlash	0.1 mm
Positioning accuracy	±0.7 mm/600 mm
Positioning repeatability	±0.05 mm
Minimum feed distance	s =0.01 mm/pulse
Service life time	20000 h
Driving motor	AC servomotor Rated rotation speed:3000 min^{-1}
Inertial moment of the motor	J_m =5×10^{-5} kg•m²
Reduction mechanism	None (direct coupling)
Frictional coefficient of the guide surface	μ =0.003 (rolling)
Resistance of the guide surface	f =20 N (without load)



12.2.2. Selection Items

Screw shaft diameter
Lead
Nut model No.
Accuracy
Axial clearance
Screw shaft support method
Driving motor

12.2.3. Selecting Lead Accuracy and Axial Clearance

●Selecting lead accuracy

To achieve positioning accuracy of ±0.7 mm/600 mm:

$$\frac{\pm 0.7}{600} = \frac{\pm 0.35}{300}$$

The lead accuracy must be ±0.35 mm/300 mm or higher.

Therefore, the accuracy grade of the Ball Screw (see table 1 on page K-24) needs to be C10 (travel distance error: ±0.21 mm/300 mm).

Accuracy grade C10 is available for low-priced, Rolled Ball Screws. Assume that a Rolled Ball Screw is selected.

●Selecting axial clearance

The required backlashes is 0.1 mm or less. However, since an axial load is constantly applied in a single direction with vertical mount, the axial load does not serve as a backlash no matter how large it is.

Therefore, a low price, rolled Ball Screw is selected since there will not be a problem in axial clearance.

12.2.4. Selecting a Screw Shaft

●Assuming the screw shaft length

Assume the overall nut length to be 100 mm and the screw shaft end length to be 100 mm. Therefore, the overall length is determined as follows based on the stroke length of 600 mm.

$$600 + 200 = 800 \text{ mm}$$

Thus, the screw shaft length is assumed to be 800 mm.

●Selecting lead

With the driving motor's rated rotation speed being 3,000 min^{-1} and the maximum speed 0.3 m/s, the Ball Screw lead is obtained as follows:

$$\frac{0.3 \times 60 \times 1000}{3000} = 6 \text{ mm}$$

Therefore, it is necessary to select a type with a lead of 6 mm or longer.

In addition, the Ball Screw and the motor can be mounted in direct coupling without using a reduction gear. The minimum resolution per revolution of an AC servomotor is obtained based on the resolution of the encoder (1,000 p/rev; 1,500 p/rev) provided as a standard accessory for the AC servomotor, as indicated below.

1000 p/rev (without multiplication)
1500 p/rev (without multiplication)
2000 p/rev (doubled)
3000 p/rev (doubled)
4000 p/rev (quadrupled)
6000 p/rev (quadrupled)

To meet the minimum feed distance of 0.010 mm/pulse, which is the selection requirement, the following should apply.

Lead 6mm —— 3000 p/rev
8mm —— 4000 p/rev
10mm —— 1000 p/rev
20mm —— 2000 p/rev
40mm —— 2000 p/rev

However, with a lead being 6 mm or 8 mm, the feed distance is 0.002 mm/pulse, and the starting pulse of the controller that issues commands to the motor driver needs to be at least 150 kpps, and the cost of the controller may be higher.
In addition, if the lead of the Ball Screw is greater, the torque required for the motor is also greater, and thus the cost will be higher.
Therefore, select 10 mm for the Ball Screw lead.

●Selecting a screw shaft diameter

Those Ball Screw models that meet the lead being 10 mm as described in Section 12.2.3. and Section 12.2.4. (see table 4 on page K-40) are as follows.

Shaft diameter	Lead
15mm ——	10mm
20mm ——	10mm
25mm ——	10mm

Accordingly, the combination of a screw shaft diameter of 15 mm and a lead 10 mm is selected.

●Selecting a screw shaft support method

Since the assumed Ball Screw has a stroke length of 600 mm and operates at a maximum speed of 0.3 m/s (Ball Screw rotation speed: 1,800 min^{-1}), select the fixed-supported configuration for the screw shaft support.

●Studying the permissible axial load

■Calculating the maximum axial load

Guide surface resistance	f	=20 N(without load)
Table mass	m_1	=40 kg
Workpiece mass	m_2	=10 kg
Maximum speed	V_{max}	=0.3 m/s
Acceleration time	t_1	=0.2 s

Hence,

Acceleration:

$$\alpha = \frac{V_{max}}{t_1} = 1.5\ m/s^2$$

During upward acceleration:

$$Fa_1 = (m_1 + m_2) \cdot g + f + (m_1 + m_2) \cdot \alpha = 585\ N$$

During upward uniform motion:

$$Fa_2 = (m_1 + m_2) \cdot g + f = 510\ N$$

During upward deceleration:

$$Fa_3 = (m_1 + m_2) \cdot g + f - (m_1 + m_2) \cdot \alpha = 435\ N$$

During downward acceleration:

$$Fa_4 = (m_1 + m_2) \cdot g - f - (m_1 + m_2) \cdot \alpha = 395\ N$$

During downward backward motion:

$$Fa_5 = (m_1 + m_2) \cdot g - f = 470\ N$$

During downward deceleration:

$$Fa_6 = (m_1 + m_2) \cdot g - f + (m_1 + m_2) \cdot \alpha = 545\ N$$

Thus, the maximum axial load applied on the Ball Screw is as follows:

$$Fa_{max} = Fa_1 = 585\ N$$

Buckling load of the screw shaft

Coefficient determined by the mounting method: η_2=20 (see page K-43)

Since the mounting method for the section between the nut and the bearing, where buckling is to be considerd, is "fixed-fixed:"

Center distance: ℓ_a=700 mm (estimate)

Thread minor diameter: d_1=12.5 mm

$$P_1 = \eta_2 \cdot \frac{d_1^4}{\ell_a^2} \times 10^4 = 20 \times \frac{12.5^4}{700^2} \times 10^4 = 9960 \text{ N}$$

Permissible compressive and tensile load of the screw shaft

$P_2 = 116d_1^2 = 116 \times 12.5^2 = 18100$ N

Thus, the buckling load and the permissible compressive and tensile load of the screw shaft are at least equal to the maximum axial load. Therefore, a Ball Screw that meets these requirements can be used without a problem.

●Studying the permissible rotation speed

Maximum rotation speed

Screw shaft diameter: 15 mm; lead: 10 mm

Maximum speed: V_{max}=0.3 m/s

Lead: ℓ=10 mm

$$N_{max} = \frac{V_{max} \times 60 \times 10^3}{\ell} = 1800 \text{ min}^{-1}$$

Permissible rotation speed determined by the critical speed of the screw shaft

Coefficient determined by the mounting method: λ_2=15.1 (see page K-45)

Since the mounting method for the section between the nut and the bearing, where critical speed is to be considered, is "fixed-supported:"

Center distance: ℓ_b=700 mm (estimate)

Screw shaft diameter: 15 mm; lead: 10 mm

Screw shaft thread minor diameter d_1=12.5 mm

$$N_1 = \lambda_2 \times \frac{d_1}{\ell_b^2} 10^7 = 15.1 \times \frac{12.5}{700^2} \times 10^7 = 3852 \text{ min}^{-1}$$

Permissible rotation speed determined by the DN value

Screw shaft diameter: 15 mm; lead: 10 mm (large-lead Ball Screw)

Ball center diameter: D=15.75 mm

$$N_2 = \frac{70000}{D} = \frac{70000}{15.75} = 4444 \text{ min}^{-1}$$

Thus, the critical speed and the DN value of the screw shaft are met.

12.2.5. Selecting a Nut

●Selecting a Nut Model Number

The Roller Ball Screw model with a screw shaft diameter of 15 mm and a lead of 10 mm is large-lead Rolled Ball Screw model BLK1510-5.6.

(C_a=9.8 kN、C_{0a}=25.2 kN)

●Studying the Permissible Axial Load

Assuming that an impact load is applied during acceleration and deceleration, set the static safety factor (f_S) at 2 (see table 1 on page K-54).

$$Fa_{max} = \frac{C_{0}a}{f_S} = \frac{25.2}{2} = 12.6\ \text{kN} = 12600\ \text{N}$$

The obtained permissible axial load is greater than the maximum axial load of 585 N, and therefore, there will be no problem with this model.

●Studying the Service Life

■Calculating the travel distance

Maximum speed: V_{max} =0.3 m/s

Acceleration time: t_1 =0.2 s

Deceleration time: t_3 =0.2 s

Travel distance during acceleration

$$\ell_{1,4} = \frac{V_{max} \cdot t_1}{2} \times 10^3 = \frac{0.3 \times 0.2}{2} \times 10^3 = 30\ \text{mm}$$

Travel distance during uniform motion

$$\ell_{2,5} = \ell_S - \frac{V_{max} \cdot t_1 + V_{max} \cdot t_3}{2} \times 10^3 = 600 - \frac{0.3 \times 0.2 + 0.3 \times 0.2}{2} \times 10^3 = 540\ \text{mm}$$

Travel distance during deceleration

$$\ell_{3,6} = \frac{V_{max} \cdot t_3}{2} \times 10^3 = \frac{0.3 \times 0.2}{2} \times 10^3 = 30\ \text{mm}$$

Based on the conditions above, the relationship between the applied axial load and the travel distance is shown in the table below.

Motion	Applied axial load Fa_N(N)	Travel distance ℓ_N(mm)
No.1: During upward acceleration	585	30
No.2: During upward uniform motion	510	540
No.3: During upward deceleration	435	30
No.4: During downward acceleration	395	30
No.5: During downward uniform motion	470	540
No.6: During downward deceleration	545	30

* The subscript (N) indicates a motion number.

Average axial load

$$F_m = \sqrt[3]{\frac{1}{2 \times \ell_s} (Fa_1^3 \cdot \ell_1 + Fa_2^3 \cdot \ell_2 + Fa_3^3 \cdot \ell_3 + Fa_4^3 \cdot \ell_4 + Fa_5^3 \cdot \ell_5 + Fa_6^3 \cdot \ell_6)} = 492N$$

Rated life

Dynamic load rating:	Ca=9800 N
Load factor:	f_w=1.5(see table 2 on page K-55)
Average load:	F_m=492 N
Rated life	L(rev.)

$$L = \left(\frac{Ca}{f_w \cdot F_m}\right)^3 \times 10^6 = \left(\frac{9800}{1.5 \times 492}\right)^3 \times 10^6 = 2.34 \times 10^9 \text{ rev.}$$

Reciprocations per minute

Reciprocations per minute:	n=5 min^{-1}
Stroke:	ℓ_s=600 mm
Lead:	ℓ=10 mm

$$N_m = \frac{2 \times n \times \ell_s}{\ell} = \frac{2 \times 5 \times 600}{10} = 600min^{-1}$$

Calculating the service life time on the basis of the rated life

Rated life:	L=2.34×10^9 rev.
Average rotation speed per minute:	N_m=600 min^{-1}

$$L_h = \frac{L}{60 \cdot N_m} = \frac{2.34 \times 10^9}{60 \times 600} = 65000h$$

Calculating the service life in travel distance on the basis of the rated life

Rated life:	L=2.34×10^9 rev.
Lead:	ℓ=10 mm

$$L_s = L \times \ell \times 10^{-6} = 23400 \text{ km}$$

With all the conditions stated above, model BLK1510-5.6 satisfies the desired service life time of 20,000 hours.

12.2.6. Studying the Rigidity

Since the conditions for selection do not include rigidity and this element is not particularly necessary, it is no described here.

12.2.7. Studying the Positioning Accuracy

●Studying the lead accuracy

Accuracy grade C10 was selected in Section 12.2.3.

C10 (travel distance error:±0.21mm/300mm)

●Studying the axial clearance

Since the axial load is constantly present in a given direction only because of vertical mount, there is no need to study the axial clearance.

●Studying the axial rigidity

Since the lead accuracy is achieved at a much higher degree than the required positioning accuracy, there is no need to study the positioning accuracy determined by axial rigidity.

●Studying the thermal displacement due to heat

Since the lead accuracy is achieved at a much higher degree than the required positioning accuracy, there is no need to study the positioning accuracy determined by heat generation.

●Studying the orientation change during traveling

Since the lead accuracy is achieved at a much higher degree than the required positioning accuracy, there is no need to study the positioning accuracy.

12.2.8. Studying the Rotation Torque

●Friction torque due to an external torque

During upward acceleration:

$$T_1 = \frac{Fa_1 \cdot \ell}{2 \times \pi \times \eta} = \frac{585 \times 10}{2 \times \pi \times 0.9} = 1030\ \text{N} \cdot \text{mm}$$

During upward uniform motion:

$$T_2 = \frac{Fa_2 \cdot \ell}{2 \times \pi \times \eta} = \frac{510 \times 10}{2 \times \pi \times 0.9} = 900\ \text{N} \cdot \text{mm}$$

Similarly,
During upward deceleration:

$T_3 = 770\ N \cdot mm$

During downward acceleration:

$T_4 = 700\ N \cdot mm$

During downward uniform motion:

$T_5 = 830\ N \cdot mm$

During downward deceleration:

$T_6 = 960\ N \cdot mm$

●Torque due to a preload on the Ball Screw

The Ball Screw is not provided with a preload.

●Torque required for acceleration

Inertial moment:

The inertial moment per unit length of the screw shaft can be specified as follows.
Since 3.9×10^{-4}kg-cm²/mm (see the dimensional table in the "THK General Catalog - Product Specifications," provided separately), the inertial moment of the screw shaft with an overall length of 800 mm is obtained as follows.

$$J_S = 3.9 \times 10^{-4} \times 800 = 0.31\ kg \cdot cm^2$$
$$= 0.31 \times 10^{-4}\ kg \cdot m^2$$

$$J = (m_1 + m_2)\left(\frac{\ell}{2 \times \pi}\right)^2 \cdot A^2\ 10^{-6} + J_S \cdot A^2 = (40 + 10)\left(\frac{10}{2 \times \pi}\right)^2 \times 1^2 \times 10^{-6} + 0.31 \times 10^{-4} \times 1^2$$

$$= 1.58 \times 10^{-4}\ kg \cdot m^2$$

Angular acceleration:

$$\omega' = \frac{2\pi \cdot Nm}{60 \cdot t} = \frac{2\pi \times 1800}{60 \times 0.2} = 942\ rad/s^2$$

Based on the above, the torque required for acceleration is obtained as follows.

$T_7 = (J + J_m) \cdot \omega' = (1.58 + 10^{-4} + 5 \times 10^{-5}) \times 942 = 0.2\ N \cdot m = 200\ N \cdot mm$

Therefore, the required torque is specified as follows.

During upward acceleration:

$T_{k1} = T_1 + T_7 = 1030 + 200 = 1230\ N \cdot mm$

During upward uniform motion:

$T_{t1} = T_2 = 900\ N \cdot mm$

During upward deceleration:

$T_{g1} = T_3 - T_7 = 770 - 200 = 570\ N \cdot mm$

Similarly,

During downward acceleration:

T_{k2} = 500 N · mm

During downward uniform motion:

T_{t2} = 830 N · mm

During downward deceleration:

T_{g2} = 1160 N · mm

12.2.9. Studying the Driving Motor

●Rotation speed

Since the Ball Screw lead is selected based on the rated rotation speed of the motor, it is unnecessary to study the rotation speed of the motor.

Maximum working rotation speed :1800min^{-1}

Rated rotation speed of the motor :3000min^{-1}

●Minimum feed distance:

As with the rotation speed, the Ball Screw lead is selected based on the encoder normally used for an AC servomotor. Therefore, it is unnecessary to study this factor.

Encoder resolution :1000 p/rev.

●Motor torque:

The torque during acceleration calculated in Section 12.2.8. is the required maximum torque.

T_{max} = T_{g2} = 1160 N · mm

Therefore, the instantaneous maximum torque of the AC servomotor needs to be at least 1,160 N-mm.

●Effective torque value

The selection requirements and the torque calculated in Section 12.2.8. can be expressed as follows.

During upward acceleration:

T_{k1} = 1100 N · mm

t_1 = 0.2 s

During upward uniform motion:

T_{t1} = 900 N · mm

t_2 = 1.8 s

During upward deceleration:

T_{g1} = 700 N · mm

t_3 = 0.2 s

During downward acceleration:

T_{k2} = 500 N · mm

t_1 = 0.2 s

During downward uniform motion:

T_{t2} = 830 N · mm

t_2 = 1.8 s

During downward deceleration:

T_{g2} = 1160 N · mm

t_3 = 0.2 s

When stationary (m_2=0):

T_S = 830 N · mm

t_4 = 7.6s

Therefore, the effective torque is obtained as follows.

$$T_{rms} = \sqrt{\frac{T_{k1}^2 \cdot t_1 + T_{t1}^2 \cdot t_2 + T_{g1}^2 \cdot t_3 + T_{k2}^2 \cdot t_1 + T_{t2}^2 \cdot t_2 + T_{g2}^2 \cdot t_3 + T_S^2 \cdot t_1}{t_1 + t_2 + t_3 + t_1 + t_2 + t_3 + t_7}}$$

$$= \sqrt{\frac{1100^2 \times 0.2 + 900^2 \times 1.8 + 700^2 \times 0.2 + 500^2 \times 0.2 + 830^2 \times 1.8 + 1160^2 \times 0.2 + 830^2 \times 7.6}{0.2 + 1.8 + 0.2 + 0.2 + 1.8 + 0.2 + 7.6}}$$

= 846 N · mm

Accordingly, the rated torque of the motor must be 846 N-mm or greater.

●Inertial moment

The inertial moment applied to the motor equals to the inertial moment calculated in Section 12.2.8.

$J = 1.58 \times 10^{-4}$ kg · m^2

Normally, the motor needs to have an inertial moment at least one tenth of the inertial moment applied to the motor, although the specific value varies depending on the motor manufacturer. Therefore, the inertial moment of the AC servomotor must be 1.58×10^{-5}kg-m^2 or greater.

The selection has been completed.