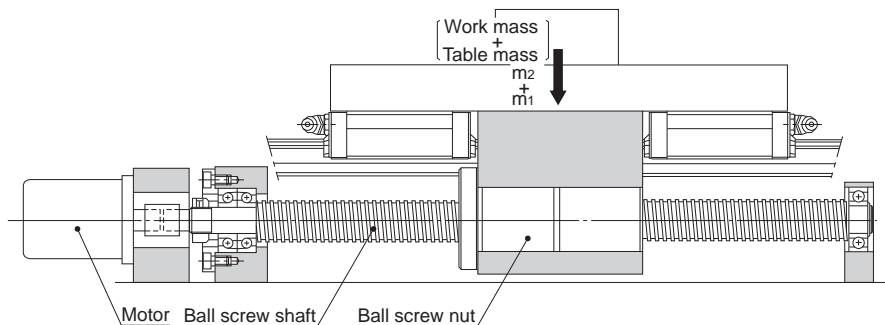


Examples of Selecting a Ball Screw

High-speed Transfer Equipment (Horizontal Use)

[Selection Conditions]

Table Mass	$m_1 = 60\text{kg}$	Positioning accuracy repeatability	$\pm 0.1\text{ mm}$
Work Mass	$m_2 = 20\text{kg}$	Minimum feed amount	$s = 0.02\text{mm/pulse}$
Stroke length	$\ell_s = 1000\text{mm}$	Desired service life time	30000h
Maximum speed	$V_{\max} = 1\text{m/s}$	Driving motor	AC servo motor
Acceleration time	$t_1 = 0.15\text{s}$		Rated rotational speed:
Deceleration time	$t_3 = 0.15\text{s}$		$3,000\text{ min}^{-1}$
Number of reciprocations per minute	$n = 8\text{min}^{-1}$	Inertial moment of the motor	$J_m = 1 \times 10^{-3}\text{ kg}\cdot\text{m}^2$
Backlash	0.15mm	Reduction gear	None (direct coupling) $A=1$
Positioning accuracy	$\pm 0.3\text{ mm}/1000\text{ mm}$ (Perform positioning from the negative direction)	Frictional coefficient of the guide surface	$\mu = 0.003$ (rolling)
		Guide surface resistance	$f = 15\text{ N}$ (without load)



[Selection Items]

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

[Selecting Lead Angle Accuracy and Axial Clearance]

● Selecting Lead Angle Accuracy

To achieve positioning accuracy of ± 0.3 mm/1,000 mm:

$$\frac{\pm 0.3}{1000} = \frac{\pm 0.09}{300}$$

The lead angle accuracy must be ± 0.09 mm/300 mm or higher.

Therefore, select the following as the accuracy grade of the Ball Screw (see Table1 on **B15-20**).

C7 (travel distance error: ± 0.05 mm/300 mm)

Accuracy grade C7 is available for both the Rolled and the Precision Ball Screws. Assume that a Rolled Ball Screw is selected here because it is less costly.

● Selecting Axial Clearance

To satisfy the backlash of 0.15 mm, it is necessary to select a Ball Screw with an axial clearance of 0.15 mm or less.

Therefore, a Rolled Ball Screw model with a screw shaft diameter of 32 mm or less that meets the axial clearance of 0.15 mm or less (see Table13 on **B15-27**) meets the requirements.

Thus, a Rolled Ball Screw model with a screw shaft diameter of 32 mm or less and an accuracy grade of C7 is selected.

[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 1,000 mm.

$$1000 + 200 = 1200 \text{ mm}$$

Thus, the screw shaft length is assumed to be 1,200 mm.

● Selecting a Lead

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

$$\frac{1 \times 1000 \times 60}{3000} = 20 \text{ mm}$$

Therefore, it is necessary to select a type with a lead of 20 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 amount of 0.02 mm/pulse, which is the selection requirement, the following should apply.

Lead	20mm — 1000 p/rev
	30mm — 1500 p/rev
	40mm — 2000 p/rev
	60mm — 3000 p/rev
	80mm — 4000 p/rev

● Selecting a Screw Shaft Diameter

Those Ball Screw models that meet the requirements defined in Section [Selecting Lead Angle Accuracy and Axial Clearance] on **B15-70**: a rolled Ball Screw with a screw shaft diameter of 32 mm or less; and the requirement defined in Section [Selecting a Screw Shaft] on **B15-70**: a lead of 20, 30, 40, 60 or 80 mm (see Table20 on **B15-35**) are as follows.

Shaft diameter	Lead
15mm	20mm
15mm	30mm
20mm	20mm
20mm	40mm
30mm	60mm

Since the screw shaft length has to be 1,200 mm as indicated in Section [Selecting a Screw Shaft] on **B15-70**, the shaft diameter of 15 mm is insufficient. Therefore, the Ball Screw should have a screw shaft diameter of 20 mm or greater.

Accordingly, there are three combinations of screw shaft diameters and leads that meet the requirements: screw shaft diameter of 20 mm/lead of 20 mm; 20 mm/40 mm; and 30 mm/60 mm.

● Selecting a Screw Shaft Support Method

Since the assumed type has a long stroke length of 1,000 mm and operates at high speed of 1 m/s, select either the fixed-supported or fixed-fixed configuration for the screw shaft support.

However, the fixed-fixed configuration requires a complicated structure, needs high accuracy in the installation.

Accordingly, the fixed-supported configuration is selected as the screw shaft support method.

● Studying the Permissible Axial Load

■ Calculating the Maximum Axial Load

Guide surface resistance	$f=15 \text{ N (without load)}$
Table Mass	$m_1=60 \text{ kg}$
Work Mass	$m_2=20 \text{ kg}$
Frictional coefficient of the guide surface	$\mu=0.003$
Maximum speed	$V_{\max}=1 \text{ m/s}$
Gravitational acceleration	$g=9.807 \text{ m/s}^2$
Acceleration time	$t_1=0.15 \text{ s}$

Accordingly, the required values are obtained as follows.

Acceleration:

$$\alpha = \frac{V_{\max}}{t_1} = 6.67 \text{ m/s}^2$$

During forward acceleration:

$$Fa_1 = \mu \cdot (m_1 + m_2) g + f + (m_1 + m_2) \cdot \alpha = 550 \text{ N}$$

During forward uniform motion:

$$Fa_2 = \mu \cdot (m_1 + m_2) g + f = 17 \text{ N}$$

During forward deceleration:

$$Fa_3 = \mu \cdot (m_1 + m_2) g + f - (m_1 + m_2) \cdot \alpha = -516 \text{ N}$$

During backward acceleration:

$$Fa_4 = -\mu \cdot (m_1 + m_2) g - f - (m_1 + m_2) \cdot \alpha = -550 \text{ N}$$

During uniform backward motion:

$$Fa_5 = -\mu \cdot (m_1 + m_2) g - f = -17 \text{ N}$$

During backward deceleration:

$$Fa_6 = -\mu \cdot (m_1 + m_2) g - f + (m_1 + m_2) \cdot \alpha = 516 \text{ N}$$

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

$$Fa_{\max} = Fa_1 = 550 \text{ N}$$

Therefore, if there is no problem with a shaft diameter of 20 mm and a lead of 20 mm (smallest thread minor diameter of 17.5 mm), then the screw shaft diameter of 30 mm should meet the requirements. Thus, the following calculations for the buckling load and the permissible compressive and tensile load of the screw shaft are performed while assuming a screw shaft diameter of 20 mm and a lead of 20 mm.

■Buckling Load on the Screw Shaft

Factor according to the mounting method

$\eta_2=20$ (see **B15-38**)

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

Distance between two mounting surfaces

$\ell_a=1100$ mm (estimate)

Screw-shaft thread minor diameter

$d_1=17.5$ mm

$$P_1 = \eta_2 \cdot \frac{d_1^4}{\ell_a^3} \times 10^4 = 20 \times \frac{17.5^4}{1100^3} \times 10^4 = 15500 \text{ N}$$

■Permissible Compressive and Tensile Load of the Screw Shaft

$$P_2 = 116 \times d_1^2 = 116 \times 17.5^2 = 35500 \text{ N}$$

Thus, the buckling load and the permissible compressive and the 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 Rotational Speed

■Maximum Rotational Speed

- Screw shaft diameter: 20 mm; lead: 20 mm

Maximum speed

$V_{\max}=1$ m/s

Lead

$Ph=20$ mm

$$N_{\max} = \frac{V_{\max} \times 60 \times 10^3}{Ph} = 3000 \text{ min}^{-1}$$

- Screw shaft diameter: 20 mm; lead: 40mm

Maximum speed

$V_{\max}=1$ m/s

Lead

$Ph=40$ mm

$$N_{\max} = \frac{V_{\max} \times 60 \times 10^3}{Ph} = 1500 \text{ min}^{-1}$$

- Screw shaft diameter: 30mm; lead: 60mm

Maximum speed

$V_{\max}=1$ m/s

Lead

$Ph=60$ mm

$$N_{\max} = \frac{V_{\max} \times 60 \times 10^3}{Ph} = 1000 \text{ min}^{-1}$$

■ Permissible Rotational Speed Determined by the Dangerous Speed of the Screw Shaft

Factor according to the mounting method

$\lambda_2=15.1$ (see **B15-40**)

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

Distance between two mounting surfaces

$\ell_b=1100$ mm (estimate)

- Screw shaft diameter: 20 mm; lead: 20 mm and 40 mm

Screw-shaft thread minor diameter

$d_1=17.5$ mm

$$N_1 = \lambda_2 \times \frac{d_1}{\ell_b^2} 10^7 = 15.1 \times \frac{17.5}{1100^2} \times 10^7 = 2180 \text{ min}^{-1}$$

- Screw shaft diameter: 30mm; lead: 60mm

Screw-shaft thread minor diameter

$d_1=26.4$ mm

$$N_1 = \lambda_2 \times \frac{d_1}{\ell_b^2} 10^7 = 15.1 \times \frac{26.4}{1100^2} \times 10^7 = 3294 \text{ min}^{-1}$$

■ Permissible Rotational Speed Determined by the DN Value

- Screw shaft diameter: 20 mm; lead: 20 mm and 40 mm (large lead Ball Screw)

Ball center-to-center diameter

$D=20.75$ mm

$$N_2 = \frac{70000}{D} = \frac{70000}{20.75} = 3370 \text{ min}^{-1}$$

- Screw shaft diameter: 30 mm; lead: 60 mm (large lead Ball Screw)

Ball center-to-center diameter

$D=31.25$ mm

$$N_2 = \frac{70000}{D} = \frac{70000}{31.25} = 2240 \text{ min}^{-1}$$

Thus, with a Ball Screw having a screw shaft diameter of 20 mm and a lead of 20 mm, the maximum rotational speed exceeds the dangerous speed.

In contrast, a combination of a screw shaft diameter of 20 mm and a lead of 40 mm, and another of a screw shaft diameter of 30 mm and a lead of 60 mm, meet the dangerous speed and the DN value.

Accordingly, a Ball Screw with a screw shaft diameter of 20 mm and a lead of 40 mm, or with a screw shaft diameter of 30 mm and a lead of 60 mm, is selected.

[Selecting a Nut]

● Selecting a Nut Model Number

Rolled Ball Screw models with a screw shaft diameter of 20 mm and a lead of 40 mm, or with a screw shaft diameter of 30 mm and a lead of 60 mm, are large lead Rolled Ball Screw model WTF variations.

WTF2040-2

($C_a=5.4$ kN, $C_o a=13.6$ kN)

WTF2040-3

($C_a=6.6$ kN, $C_o a=17.2$ kN)

WTF3060-2

($C_a=11.8$ kN, $C_o a=30.6$ kN)

WTF3060-3

($C_a=14.5$ kN, $C_o a=38.9$ kN)

● Studying the Permissible Axial Load

Study the permissible axial load of model WTF2040-2 ($C_0a = 13.6$ kN).

Assuming that this model is used in high-speed transfer equipment and an impact load is applied during deceleration, set the static safety factor (f_s) at 2.5 (see Table1 on **B15-47**).

$$\frac{C_0a}{f_s} = \frac{13.6}{2.5} = 5.44 \text{ kN} = 5440 \text{ N}$$

The obtained permissible axial load is greater than the maximum axial load of 550 N, and therefore, there will be no problem with this model.

■ Calculating the Travel Distance

Maximum speed $V_{\max} = 1$ m/s

Acceleration time $t_1 = 0.15$ s

Deceleration time $t_3 = 0.15$ s

● Travel distance during acceleration

$$\ell_{1,4} = \frac{V_{\max} \cdot t_1}{2} \times 10^3 = \frac{1 \times 0.15}{2} \times 10^3 = 75 \text{ mm}$$

● Travel distance during uniform motion

$$\ell_{2,5} = \ell_s - \frac{V_{\max} \cdot t_1 + V_{\max} \cdot t_3}{2} \times 10^3 = 1000 - \frac{1 \times 0.15 + 1 \times 0.15}{2} \times 10^3 = 850 \text{ mm}$$

● Travel distance during deceleration

$$\ell_{3,6} = \frac{V_{\max} \cdot t_3}{2} \times 10^3 = \frac{1 \times 0.15}{2} \times 10^3 = 75 \text{ mm}$$

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 F_{a_i} (N)	Travel distance ℓ_{a_i} (mm)
No.1: During forward acceleration	550	75
No.2: During forward uniform motion	17	850
No.3: During forward deceleration	-516	75
No.4: During backward acceleration	-550	75
No.5: During uniform backward motion	-17	850
No.6: During backward deceleration	516	75

* The subscript (N) indicates a motion number.

Since the load direction (as expressed in positive or negative sign) is reversed with F_{a_3} , F_{a_4} and F_{a_5} , calculate the average axial load in the two directions.

■Average Axial Load

- Average axial load in the positive direction

Since the load direction varies, calculate the average axial load while assuming $F_{a3, 4, 5} = 0\text{N}$.

$$F_{m1} = \sqrt[3]{\frac{F_{a1}^3 \times l_1 + F_{a2}^3 \times l_2 + F_{a6}^3 \times l_6}{l_1 + l_2 + l_3 + l_4 + l_5 + l_6}} = 225 \text{ N}$$

- Average axial load in the negative direction

Since the load direction varies, calculate the average axial load while assuming $F_{a1, 2, 6} = 0\text{N}$.

$$F_{m2} = \sqrt[3]{\frac{|F_{a3}|^3 \times l_3 + |F_{a4}|^3 \times l_4 + |F_{a5}|^3 \times l_5}{l_1 + l_2 + l_3 + l_4 + l_5 + l_6}} = 225 \text{ N}$$

Since $F_{m1} = F_{m2}$, assume the average axial load to be $F_m = F_{m1} = F_{m2} = 225 \text{ N}$.

■Nominal Life

Load factor $f_w = 1.5$ (see Table2 on **B15-48**)

Average load $F_m = 225 \text{ N}$

Nominal life L (rev)

$$L = \left(\frac{C_a}{f_w \cdot F_m} \right)^3 \times 10^6$$

Assumed model number	Dynamic load rating Ca(N)	Nominal life L(rev)
WTF 2040-2	5400	4.1×10^9
WTF 2040-3	6600	7.47×10^9
WTF 3060-2	11800	4.27×10^{10}
WTF 3060-3	14500	7.93×10^{10}

■Average Revolutions per Minute

Number of reciprocations per minute

$n = 8 \text{ min}^{-1}$

Stroke

$\ell_s = 1000 \text{ mm}$

- Lead: $Ph = 40 \text{ mm}$

$$N_m = \frac{2 \times n \times \ell_s}{Ph} = \frac{2 \times 8 \times 1000}{40} = 400 \text{ min}^{-1}$$

- Lead: $Ph = 60 \text{ mm}$

$$N_m = \frac{2 \times n \times \ell_s}{Ph} = \frac{2 \times 8 \times 1000}{60} = 267 \text{ min}^{-1}$$

■Calculating the Service Life Time on the Basis of the Nominal Life

- WTF2040-2

Nominal life

$L = 4.1 \times 10^9 \text{ rev}$

Average revolutions per minute

$N_m = 400 \text{ min}^{-1}$

$$L_h = \frac{L}{60 \times N_m} = \frac{4.1 \times 10^9}{60 \times 400} = 171000 \text{ h}$$

- WTF2040-3

Nominal life

$L = 7.47 \times 10^9 \text{ rev}$

Average revolutions per minute

$N_m = 400 \text{ min}^{-1}$

$$L_h = \frac{L}{60 \times N_m} = \frac{7.47 \times 10^9}{60 \times 400} = 311000 \text{ h}$$

- WTF3060-2

Nominal life

$L = 4.27 \times 10^{10} \text{ rev}$

Average revolutions per minute

$N_m = 267 \text{ min}^{-1}$

$$L_h = \frac{L}{60 \times N_m} = \frac{4.27 \times 10^{10}}{60 \times 267} = 2670000 \text{ h}$$

- WTF3060-3

Nominal life

$L = 7.93 \times 10^{10} \text{ rev}$

Average revolutions per minute

$N_m = 267 \text{ min}^{-1}$

$$L_h = \frac{L}{60 \times N_m} = \frac{7.93 \times 10^{10}}{60 \times 267} = 4950000 \text{ h}$$

■ Calculating the Service Life in Travel Distance on the Basis of the Nominal Life

- WTF2040-2

Nominal life	$L=4.1 \times 10^9 \text{ rev}$
Lead	$Ph=40 \text{ mm}$
$L_s = L \times Ph \times 10^{-6} = 164000 \text{ km}$	
- WTF2040-3

Nominal life	$L=7.47 \times 10^9 \text{ rev}$
Lead	$Ph=40 \text{ mm}$
$L_s = L \times Ph \times 10^{-6} = 298800 \text{ km}$	
- WTF3060-2

Nominal life	$L=4.27 \times 10^{10} \text{ rev}$
Lead	$Ph=60 \text{ mm}$
$L_s = L \times Ph \times 10^{-6} = 2562000 \text{ km}$	
- WTF3060-3

Nominal life	$L=7.93 \times 10^{10} \text{ rev}$
Lead	$Ph=60 \text{ mm}$
$L_s = L \times Ph \times 10^{-6} = 4758000 \text{ km}$	

With all the conditions stated above, the following models satisfying the desired service life time of 30,000 hours are selected.

WTF 2040-2
 WTF 2040-3
 WTF 3060-2
 WTF 3060-3

[Studying the Rigidity]

Since the conditions for selection do not include rigidity and this element is not particularly necessary, it is not described here.

[Studying the Positioning Accuracy]**● Studying the Lead Angle Accuracy**

Accuracy grade C7 was selected in Section [Selecting Lead Angle Accuracy and Axial Clearance] on **B15-70**.

C7 (travel distance error: $\pm 0.05\text{mm}/300\text{mm}$)

● Studying the Axial Clearance

Since positioning is performed in a given direction only, axial clearance is not included in the positioning accuracy. As a result, there is no need to study the axial clearance.

WTF2040: axial clearance: 0.1 mm

WTF3060: axial clearance: 0.14 mm

● Studying the Axial Rigidity

Since the load direction does not change, it is unnecessary to study the positioning accuracy on the basis of the axial rigidity.

● Studying the Thermal Displacement through Heat Generation

Assume the temperature rise during operation to be 5°C .

The positioning accuracy based on the temperature rise is obtained as follows:

$$\begin{aligned}\Delta\ell &= \rho \times \Delta t \times \ell \\ &= 12 \times 10^{-6} \times 5 \times 1000 \\ &= 0.06 \text{ mm}\end{aligned}$$

● Studying the Orientation Change during Traveling

Since the ball screw center is 150 mm away from the point where the highest accuracy is required, it is necessary to study the orientation change during traveling.

Assume that pitching can be done within ± 10 seconds because of the structure. The positioning error due to the pitching is obtained as follows:

$$\begin{aligned}\Delta a &= \ell \times \sin\theta \\ &= 150 \times \sin(\pm 10'') \\ &= \pm 0.007 \text{ mm}\end{aligned}$$

Thus, the positioning accuracy (Δp) is obtained as follows:

$$\Delta p = \frac{\pm 0.05 \times 1000}{300} \pm 0.007 + 0.06 = 0.234 \text{ mm}$$

Since models WTF2040-2, WTF2040-3, WTF3060-2 and WTF3060-3 meet the selection requirements throughout the studying process in Section [Selecting Lead Angle Accuracy and Axial Clearance] on **B15-70** to Section [Studying the Positioning Accuracy] on **B15-79**, the most compact model WTF2040-2 is selected.

[Studying the Rotational Torque]

● Friction Torque Due to an External Load

The friction torque is obtained as follows:

$$T_1 = \frac{F_a \cdot Ph}{2\pi \cdot \eta} \cdot A = \frac{17 \times 40}{2 \times \pi \times 0.9} \times 1 = 120 \text{ N} \cdot \text{mm}$$

● Torque Due to a Preload on the Ball Screw

The Ball Screw is not provided with a preload.

● Torque Required for Acceleration

Inertial Moment

Since the inertial moment per unit length of the screw shaft is $1.23 \times 10^{-3} \text{ kg} \cdot \text{cm}^2/\text{mm}$ (see the specification table), the inertial moment of the screw shaft with an overall length of 1200 mm is obtained as follows.

$$J_s = 1.23 \times 10^{-3} \times 1200 = 1.48 \text{ kg} \cdot \text{cm}^2 \\ = 1.48 \times 10^{-4} \text{ kg} \cdot \text{m}^2$$

$$J = (m_1 + m_2) \left(\frac{Ph}{2 \times \pi} \right)^2 \cdot A^2 \times 10^{-6} + J_s \cdot A^2 = (60 + 20) \left(\frac{40}{2 \times \pi} \right)^2 \times 1^2 \times 10^{-6} + 1.48 \times 10^{-4} \times 1^2 \\ = 3.39 \times 10^{-3} \text{ kg} \cdot \text{m}^2$$

Angular acceleration:

$$\omega' = \frac{2\pi \cdot \text{Nm}}{60 \cdot t_1} = \frac{2\pi \times 1500}{60 \times 0.15} = 1050 \text{ rad/s}^2$$

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

$$T_2 = (J + J_m) \times \omega' = (3.39 \times 10^{-3} + 1 \times 10^{-3}) \times 1050 = 4.61 \text{ N} \cdot \text{m} \\ = 4.61 \times 10^3 \text{ N} \cdot \text{mm}$$

Therefore, the required torque is specified as follows.

During acceleration

$$T_k = T_1 + T_2 = 120 + 4.61 \times 10^3 = 4730 \text{ N} \cdot \text{mm}$$

During uniform motion

$$T_i = T_1 = 120 \text{ N} \cdot \text{mm}$$

During deceleration

$$T_g = T_i - T_2 = 120 - 4.61 \times 10^3 = -4490 \text{ N} \cdot \text{mm}$$

[Studying the Driving Motor]● **Rotational Speed**

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

Maximum working rotational speed : 1500 min⁻¹

Rated rotational speed of the motor: 3000 min⁻¹

● **Minimum Feed Amount**

As with the rotational 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.

Doubled: 2000 p/rev

● **Motor Torque**

The torque during acceleration calculated in Section [Studying the Rotational Torque] on **B15-80** is the required maximum torque.

$$T_{\max} = 4730 \text{ N} \cdot \text{mm}$$

Therefore, the instantaneous maximum torque of the AC servomotor needs to be at least 4,730 N·mm.

● **Effective Torque Value**

The selection requirements and the torque calculated in Section [Studying the Rotational Torque] on **B15-80** can be expressed as follows.

During acceleration:

$$T_k = 4730 \text{ N} \cdot \text{mm}$$

$$t_1 = 0.15 \text{ s}$$

During uniform motion:

$$T_i = 120 \text{ N} \cdot \text{mm}$$

$$t_2 = 0.85 \text{ s}$$

During deceleration:

$$T_g = 4490 \text{ N} \cdot \text{mm}$$

$$t_3 = 0.15 \text{ s}$$

When stationary:

$$T_s = 0$$

$$t_4 = 2.6 \text{ s}$$

The effective torque is obtained as follows, and the rated torque of the motor must be 1305 N·mm or greater.

$$T_{\text{rms}} = \sqrt{\frac{T_k^2 \cdot t_1 + T_i^2 \cdot t_2 + T_g^2 \cdot t_3 + T_s^2 \cdot t_4}{t_1 + t_2 + t_3 + t_4}} = \sqrt{\frac{4730^2 \times 0.15 + 120^2 \times 0.85 + 4490^2 \times 0.15 + 0}{0.15 + 0.85 + 0.15 + 2.6}}$$

$$= 1305 \text{ N} \cdot \text{mm}$$

● Inertial Moment

The inertial moment applied to the motor equals to the inertial moment calculated in Section [Studying the Rotational Torque] on **B15-80**.

$$J = 3.39 \times 10^{-3} \text{ kg} \cdot \text{m}^2$$

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.

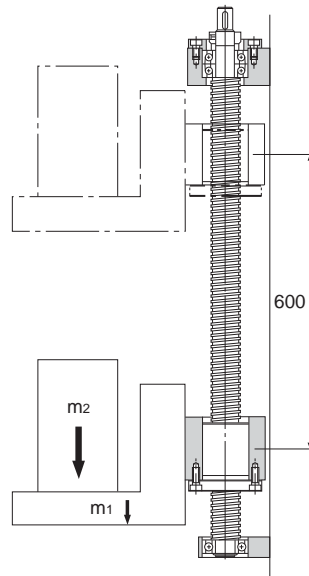
Therefore, the inertial moment of the AC servomotor must be $3.39 \times 10^{-4} \text{ kg} \cdot \text{m}^2$ or greater.

The selection has been completed.

Vertical Conveyance System

[Selection Conditions]

Table Mass	$m_1 = 40\text{kg}$
Work Mass	$m_2 = 10\text{kg}$
Stroke length	$\ell_s = 600\text{mm}$
Maximum speed	$V_{\max} = 0.3\text{m/s}$
Acceleration time	$t_1 = 0.2\text{s}$
Deceleration time	$t_3 = 0.2\text{s}$
Number of reciprocations per minute	$n = 5\text{min}^{-1}$
Backlash	0.1mm
Positioning accuracy	$\pm 0.7\text{mm}/600\text{mm}$
Positioning accuracy repeatability	$\pm 0.05\text{mm}$
Minimum feed amount	$s = 0.01\text{mm/pulse}$
Service life time	20000h
Driving motor	AC servo motor Rated rotational speed: $3,000\text{min}^{-1}$
Inertial moment of the motor	$J_m = 5 \times 10^{-6}\text{kg}\cdot\text{m}^2$
Reduction gear	None (direct coupling)
Frictional coefficient of the guide surface	$\mu = 0.003$ (rolling)
Guide surface resistance	$f = 20\text{N}$ (without load)



[Selection Items]

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

[Selecting Lead Angle Accuracy and Axial Clearance]

● Selecting the Lead Angle Accuracy

To achieve positioning accuracy of $\pm 0.7\text{mm}/600\text{mm}$:

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

The lead angle accuracy must be $\pm 0.35\text{mm}/300\text{ mm}$ or higher.

Therefore, the accuracy grade of the Ball Screw (see Table1 on **B15-20**) needs to be C10 (travel distance error: $\pm 0.21\text{ mm}/300\text{ mm}$).

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

● Selecting the 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.

[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 600mm.

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

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

● Selecting the Lead

With the driving motor's rated rotational speed being $3,000\text{ min}^{-1}$ 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 6mm 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(quadupled)
- 6000 p/rev(quadupled)

To meet the minimum feed amount of 0.010mm/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 the 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 the Screw Shaft Diameter

Those Ball Screw models that meet the lead being 10 mm as described in Section [Selecting Lead Angle Accuracy and Axial Clearance] on **B15-84** and Section [Selecting a Screw Shaft] on **B15-84** (see Table20 on **B15-35**) 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 the 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 rotational 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
Work Mass	$m_2=10$ kg
Maximum speed	$V_{\max}=0.3$ m/s
Acceleration time	$t_1=0.2$ s

Accordingly, the required values are obtained as follows.

Acceleration

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

During upward acceleration:

$$Fa_1 = (m_1 + m_2) \bullet g + f + (m_1 + m_2) \bullet \alpha = 585 \text{ N}$$

During upward uniform motion:

$$Fa_2 = (m_1 + m_2) \bullet g + f = 510 \text{ N}$$

During upward deceleration:

$$Fa_3 = (m_1 + m_2) \bullet g + f - (m_1 + m_2) \bullet \alpha = 435 \text{ N}$$

During downward acceleration:

$$Fa_4 = (m_1 + m_2) \bullet g - f - (m_1 + m_2) \bullet \alpha = 395 \text{ N}$$

During downward uniform motion:

$$Fa_5 = (m_1 + m_2) \bullet g - f = 470 \text{ N}$$

During downward deceleration:

$$Fa_6 = (m_1 + m_2) \bullet g - f + (m_1 + m_2) \bullet \alpha = 545 \text{ N}$$

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

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

■ Buckling Load of the Screw Shaft

Factor according to the mounting method

$\eta_2=20$ (see **B15-38**)

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

Distance between two mounting surfaces

$\ell_a=700$ mm (estimate)

Screw-shaft thread minor diameter

$d_i=12.5$ mm

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

■ Permissible Compressive and Tensile Load of the Screw Shaft

$$P_2 = 116d_i^2 = 116 \times 12.5^2 = 18100 \text{ N}$$

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 Rotational Speed

■ Maximum Rotational Speed

- Screw shaft diameter: 15mm; lead: 10mm

Maximum speed

$$V_{\max}=0.3 \text{ m/s}$$

Lead

$$Ph=10 \text{ mm}$$

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

■ Permissible Rotational Speed Determined by the Dangerous Speed of the Screw Shaft

Factor according to the mounting method

$$\lambda_z=15.1 \text{ (see B15-40)}$$

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

Distance between two mounting surfaces

$$\ell_b=700 \text{ mm (estimate)}$$

- Screw shaft diameter: 15mm; lead: 10mm

Screw-shaft thread minor diameter

$$d_1=12.5 \text{ mm}$$

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

■ Permissible Rotational Speed Determined by the DN Value

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

Ball center-to-center diameter

$$D=15.75 \text{ mm}$$

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

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

[Selecting a Nut]

● Selecting a Nut Model Number

The Rolled Ball Screw with a screw shaft diameter of 15 mm and a lead of 10 mm is the following 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 an acceleration and a deceleration, set the static safety factor (f_s) at 2 (see Table1 on **B15-47**).

$$F_{a_{\max}} = \frac{C_0a}{f_s} = \frac{25.2}{2} = 12.6 \text{ kN} = 12600 \text{ N}$$

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

$$\ell_{1,4} = \frac{V_{\max} \cdot t_1}{2} \times 10^3 = \frac{1.3 \times 0.2}{2} \times 10^3 = 30 \text{ mm}$$

- 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 $F_a(\text{N})$	Travel distance $\ell_N(\text{mm})$
No1: During upward acceleration	585	30
No2: During upward uniform motion	510	540
No3: During upward deceleration	435	30
No4: During downward acceleration	395	30
No5: During downward uniform motion	470	540
No6: During downward deceleration	545	30

* The subscript (N) indicates a motion number.

■Average Axial Load

$$F_m = \sqrt[3]{\frac{1}{2 \times \ell_s} (F_{a1}^3 \cdot \ell_1 + F_{a2}^3 \cdot \ell_2 + F_{a3}^3 \cdot \ell_3 + F_{a4}^3 \cdot \ell_4 + F_{a5}^3 \cdot \ell_5 + F_{a6}^3 \cdot \ell_6)} = 492 \text{ N}$$

■Nominal Life

Dynamic load rating
Load factor
Average load
Nominal life

$C_a = 9800 \text{ N}$
 $f_w = 1.5$ (see Table 2 on **B15-48**)
 $F_m = 492 \text{ N}$
 L (rev)

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

■Average Revolutions per Minute

Number of reciprocations per minute
Stroke
Lead

$n = 5 \text{ min}^{-1}$
 $\ell_s = 600 \text{ mm}$
 $Ph = 10 \text{ mm}$

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

■Calculating the Service Life Time on the Basis of the Nominal Life

Nominal life
Average revolutions per minute

$L = 2.34 \times 10^9 \text{ rev}$
 $N_m = 600 \text{ min}^{-1}$

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

■Calculating the Service Life in Travel Distance on the Basis of the Nominal Life

Nominal life
Lead

$L = 2.34 \times 10^9 \text{ rev}$
 $Ph = 10 \text{ mm}$

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

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

[Studying the Rigidity]

Since the conditions for selection do not include rigidity and this element is not particularly necessary, it is not described here.

[Studying the Positioning Accuracy]

● Studying the Lead Angle Accuracy

Accuracy grade C10 was selected in Section [Selecting Lead Angle Accuracy and Axial Clearance] on **B15-84**.

C10 (travel distance error: $\pm 0.21\text{mm}/300\text{mm}$)

● 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 angle accuracy is achieved beyond the required positioning accuracy, there is no need to study the positioning accuracy determined by axial rigidity.

● Studying the Thermal Displacement through Heat Generation

Since the lead angle accuracy is achieved beyond the required positioning accuracy, there is no need to study the positioning accuracy determined by the heat generation.

● Studying the Orientation Change during Traveling

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

[Studying the Rotational Torque]

● Frictional Torque Due to an External Load

During upward uniform motion:

$$T_1 = \frac{F_{a2} \cdot Ph}{2 \times \pi \times \eta} = \frac{510 \times 10}{2 \times \pi \times 0.9} = 900 \text{ N} \cdot \text{mm}$$

During downward uniform motion:

$$T_2 = \frac{F_{a5} \cdot Ph}{2 \times \pi \times \eta} = \frac{470 \times 10}{2 \times \pi \times 0.9} = 830 \text{ N} \cdot \text{mm}$$

● Torque Due to a Preload on the Ball Screw

The Ball Screw is not provided with a preload.

● Torque Required for Acceleration

Inertial Moment:

Since the inertial moment per unit length of the screw shaft is $3.9 \times 10^{-4} \text{ kg} \cdot \text{cm}^2/\text{mm}$ (see the specification table), the inertial moment of the screw shaft with an overall length of 800mm is obtained as follows.

$$\begin{aligned} J_s &= 3.9 \times 10^{-4} \times 800 = 0.31 \text{ kg} \cdot \text{cm}^2 \\ &= 0.31 \times 10^{-4} \text{ kg} \cdot \text{m}^2 \end{aligned}$$

$$\begin{aligned} J &= (m_1 + m_2) \left(\frac{Ph}{2 \times \pi} \right)^2 \cdot A^2 \times 10^{-6} + J_s \cdot A^2 = (40 + 10) \left(\frac{10}{2 \times \pi} \right)^2 \times 1^2 \times 10^{-6} + 0.31 \times 10^{-4} \times 1^2 \\ &= 1.58 \times 10^{-4} \text{ kg} \cdot \text{m}^2 \end{aligned}$$

Angular acceleration:

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

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

$$T_3 = (J + J_m) \cdot \omega' = (1.58 \times 10^{-4} + 5 \times 10^{-5}) \times 942 = 0.2 \text{ N} \cdot \text{m} = 200 \text{ N} \cdot \text{mm}$$

Therefore, the required torque is specified as follows.

During upward acceleration:

$$T_{k1} = T_1 + T_3 = 900 + 200 = 1100 \text{ N} \cdot \text{mm}$$

During upward uniform motion:

$$T_{t1} = T_1 = 900 \text{ N} \cdot \text{mm}$$

During upward deceleration:

$$T_{g1} = T_1 - T_3 = 900 - 200 = 700 \text{ N} \cdot \text{mm}$$

During downward acceleration:

$$T_{k2} = 630 \text{ N} \cdot \text{mm}$$

During downward uniform motion:

$$T_{t2} = 830 \text{ N} \cdot \text{mm}$$

During downward deceleration:

$$T_{g2} = 1030 \text{ N} \cdot \text{mm}$$

[Studying the Driving Motor]

● Rotational Speed

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

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

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

● Minimum Feed Amount

As with the rotational 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 [Studying the Rotational Torque] on **B15-90** is the required maximum torque.

$$T_{\max} = T_{k1} = 1100 \text{ N}\cdot\text{mm}$$

Therefore, the maximum peak torque of the AC servomotor needs to be at least $1100 \text{ N}\cdot\text{mm}$.

● Effective Torque Value

The selection requirements and the torque calculated in Section [Studying the Rotational Torque] on **B15-90** can be expressed as follows.

During upward acceleration:

$$T_{k1} = 1100 \text{ N}\cdot\text{mm}$$

$$t_1 = 0.2 \text{ s}$$

During upward uniform motion:

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

$$t_2 = 1.8 \text{ s}$$

During upward deceleration:

$$T_{g1} = 700 \text{ N}\cdot\text{mm}$$

$$t_3 = 0.2 \text{ s}$$

During downward acceleration:

$$T_{k2} = 630 \text{ N}\cdot\text{mm}$$

$$t_1 = 0.2 \text{ s}$$

During downward uniform motion:

$$T_{t2} = 830 \text{ N}\cdot\text{mm}$$

$$t_2 = 1.8 \text{ s}$$

During downward deceleration:

$$T_{g2} = 1030 \text{ N}\cdot\text{mm}$$

$$t_3 = 0.2 \text{ s}$$

When stationary($m_2=0$):

$$T_s = 658 \text{ N}\cdot\text{mm}$$

$$t_4 = 7.6 \text{ s}$$

Point of Selection

Examples of Selecting a Ball Screw

The effective torque is obtained as follows, and the rated torque of the motor must be 743 N•mm or greater.

$$\begin{aligned}
 T_{\text{rms}} &= \sqrt{\frac{T_{k1}^2 \cdot t_1 + T_{t1}^2 \cdot t_2 + T_{g1}^2 \cdot t_3 + T_{k2}^2 \cdot t_1 + T_{t2}^2 \cdot t_2 + T_{g2}^2 \cdot t_3 + T_s^2 \cdot t_4}{t_1 + t_2 + t_3 + t_1 + t_2 + t_3 + t_4}} \\
 &= \sqrt{\frac{1100^2 \times 0.2 + 900^2 \times 1.8 + 700^2 \times 0.2 + 630^2 \times 0.2 + 830^2 \times 1.8 + 1030^2 \times 0.2 + 658^2 \times 7.6}{0.2 + 1.8 + 0.2 + 0.2 + 1.8 + 0.2 + 7.6}} \\
 &= 743 \text{ N} \cdot \text{mm}
 \end{aligned}$$

● Inertial Moment

The inertial moment applied to the motor equals to the inertial moment calculated in Section [Studying the Rotational Torque] on **B15-90**.

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

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 $1.58 \times 10^{-5} \text{ kg} \cdot \text{m}^2$ or greater.

The selection has been completed.

