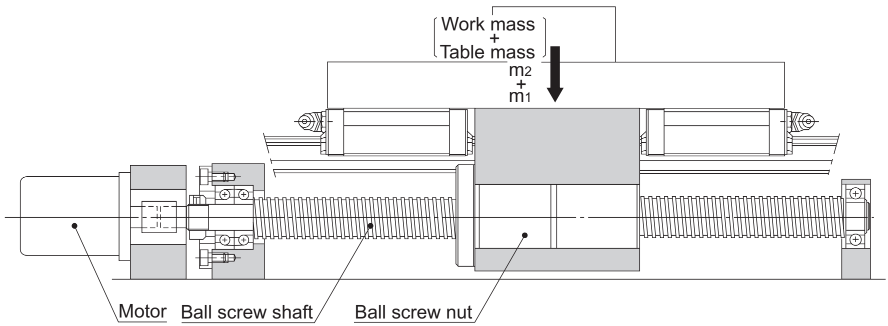
Example Ball Screw Selections

High-Speed Transfer Equipment (Horizontal Use)

Selection Conditions

Table mass	m_1 = 60 kg	Positioning accuracy repeatability	±0.1 mm
Work mass	m_2 = 20 kg	Minimum feed amount	s = 0.02 mm/pulse
Stroke length	ℓ_S = 1,000 mm	Desired service life time	30,000 h
Maximum speed	V_{max} = 1 m/s	Driving motor	AC servo motor Rated rotational speed: 3,000 min^{-1}
Acceleration time	t_1 = 0.15 s		
Deceleration time	t_3 = 0.15 s		
Number of reciprocations per minute	n = 8 min^{-1}	Inertial moment of the motor	J_m = 1×10^{-3} kg•m^2
Backlash	0.15 mm	Reduction gear	None (direct coupling) A = 1
Positioning accuracy	±0.3 mm/1,000 mm (Perform positioning from the negative direction)	Frictional coefficient of the guide surface	μ = 0.003 (rolling)
		Guide surface resistance	f = 15 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:

$$\frac{\pm 0.3}{1{,}000} = \frac{\pm 0.09}{300}$$

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 Table 1 on **B15-20**).

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

Accuracy grade C7 is available for both rolled and precision ball screws. Assume that a rolled ball screw is selected here because it is less costly.

● Selecting Axial Clearance

To satisfy the backlash requirement of 0.15 mm, it is necessary to select a ball screw with an axial clearance of 0.15 mm or less.
For this reason, 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 will meet the requirement (see Table 13 on **B15-27**).
Therefore, 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.

1,000 + 200 = 1,200 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 min^{-1} and the maximum speed 1 m/s, the ball screw lead is obtained as follows:

$$\frac{1 \times 1{,}000 \times 60}{3{,}000} = 20 \text{ mm}$$

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.

1,000 p/rev (without multiplication)
1,500 p/rev (without multiplication)
2,000 p/rev (doubled)
3,000 p/rev (doubled)
4,000 p/rev (quadrupled)
6,000 p/rev (quadrupled)

To meet the minimum feed amount of 0.02 mm/pulse, which is the selection requirement, the following should apply.

Lead	20 mm	——	1,000 p/rev
	30 mm	——	1,500 p/rev
	40 mm	——	2,000 p/rev
	60 mm	——	3,000 p/rev
	80 mm	——	4,000 p/rev

● Selecting a Screw Shaft Diameter

Ball screw models that meet the requirements defined in the 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 the section "Selecting a Screw Shaft" on **B15-70**: a lead of 20, 30, 40, 60, or 80 mm (see Table 20 on **B15-35**) are as follows.

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

Since the screw shaft length has to be 1,200 mm as indicated in the 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 a 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 and highly-accurate installation.

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

● Considering the Permissible Axial Load

■Calculating the Maximum Axial Load

Guide surface resistance	F = 15 N (without load)
Table mass	m_1 = 60 kg
Work mass	m_2 = 20 kg
Frictional coefficient of the guide surface	μ = 0.003
Maximum speed	V_{max} = 1 m/s
Gravitational acceleration	g = 9.807 m/s^2
Acceleration time	t_1 = 0.15 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 (minimum 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 η_2 = 20 (see B15-38)

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 ℓ_a = 1,100 mm (estimate)

Screw-shaft thread minor diameter d_1 = 17.5 mm

$$P_1 = \eta_2 \cdot \frac{d_1^4}{\ell_a^2} \times 10^4 = 20 \times \frac{17.5^4}{1{,}100^2} \times 10^4 = 15{,}500 \text{ N}$$

■Permissible Compressive and Tensile Load of the Screw Shaft

$P_2 = 116 \times d_1^2 = 116 \times 17.5^2 = 35{,}500$ 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.

● Considering 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

$$N_{max} = \frac{V_{max} \times 60 \times 10^3}{Ph} = 3{,}000 \text{ min}^{-1}$$

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

Maximum speed V_{max} = 1 m/s

Lead Ph = 40 mm

$$N_{max} = \frac{V_{max} \times 60 \times 10^3}{Ph} = 1{,}500 \text{ min}^{-1}$$

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

Maximum speed V_{max} = 1 m/s

Lead Ph = 60 mm

$$N_{max} = \frac{V_{max} \times 60 \times 10^3}{Ph} = 1{,}000 \text{ min}^{-1}$$

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

Factor according to the mounting method $\lambda_2 = 15.1$ (see B15-40)

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

Distance between two mounting surfaces $\ell_b = 1{,}100$ mm (estimate)

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

  Screw-shaft thread minor diameter $d_1 = 17.5$ mm

$$N_1 = \lambda_2 \times \frac{d_1}{\ell_b^2} 10^7 = 15.1 \times \frac{17.5}{1{,}100^2} \times 10^7 = 2{,}180 \text{ min}^{-1}$$

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

  Screw-shaft thread minor diameter $d_1 = 26.4$ mm

$$N_1 = \lambda_2 \times \frac{d_1}{\ell_b^2} 10^7 = 15.1 \times \frac{26.4}{1{,}100^2} \times 10^7 = 3{,}294 \text{ min}^{-1}$$

■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

$$N_2 = \frac{70{,}000}{D} = \frac{70{,}000}{20.75} = 3{,}370 \text{ min}^{-1}$$

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

  Ball center-to-center diameter $D = 31.25$ mm

$$N_2 = \frac{70{,}000}{D} = \frac{70{,}000}{31.25} = 2{,}240 \text{ min}^{-1}$$

Thus, in a ball screw with a screw shaft diameter of 20 mm and a lead of 20 mm, the maximum rotational speed exceeds the critical 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, satisfy the critical speed and the DN value requirements.

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 screws 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, $C_{0a} = 13.6$ kN)
WTF2040-3
($C_a = 6.6$ kN, $C_{0a} = 17.2$ kN)
WTF3060-2
($C_a = 11.8$ kN, $C_{0a} = 30.6$ kN)
WTF3060-3
($C_a = 14.5$ kN, $C_{0a} = 38.9$ kN)

● Considering the Permissible Axial Load

Consider 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 Table 1 on B15-47).

$$\frac{C_0a}{f_S} = \frac{13.6}{2.5} = 5.44\text{ kN} = 5{,}440\text{ N}$$

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

$$\ell_{2,5} = \ell_S - \frac{V_{max} \cdot t_1 + V_{max} \cdot t_3}{2} \times 10^3 = 1{,}000 - \frac{1 \times 0.15 + 1 \times 0.15}{2} \times 10^3 = 850\text{ mm}$$

● 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 Fa_N (N)	Travel distance ℓ_N (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 is reversed with Fa_3, Fa_4, and Fa_5, (as expressed by the negative sign), calculate the average axial load in each of 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 $Fa_{3,4,5} = 0$ N.

$$F_{am1} = \sqrt[3]{\frac{Fa_1^3 \times \ell_1 + Fa_2^3 \times \ell_2 + Fa_6^3 \times \ell_6}{\ell_1 + \ell_2 + \ell_3 + \ell_4 + \ell_5 + \ell_6}} = 225 \text{ N}$$

- Average axial load in the negative direction

  Since the load direction varies, calculate the average axial load while assuming $Fa_{1,2,6} = 0$ N.

$$F_{am2} = \sqrt[3]{\frac{|Fa_3|^3 \times \ell_3 + |Fa_4|^3 \times \ell_4 + |Fa_5|^3 \times \ell_5}{\ell_1 + \ell_2 + \ell_3 + \ell_4 + \ell_5 + \ell_6}} = 225 \text{ N}$$

Since $F_{am1} = F_{am2}$, assume the average axial load to be $F_{am} = F_{am1} = F_{am2} = 225$ N.

■Nominal Life

Load factor	$f_W = 1.5$ (see Table 2 on **B15-48**)
Average load	$F_m = 225$ N
Nominal life	L_{10m} (rev)

$$L_{10m} = \left(\alpha \times \frac{C_a}{F_{am}}\right)^3 \times 10^6$$

$$\alpha = \frac{1}{f_W}$$

Assumed model number	Dynamic load rating Ca (N)	Nominal life L_{10m} (rev)
WTF 2040-2	5,400	4.1×10^9
WTF 2040-3	6,600	7.47×10^9
WTF 3060-2	11,800	4.27×10^{10}
WTF 3060-3	14,500	7.93×10^{10}

■Average Revolutions per Minute

Number of reciprocations per minute $n = 8\ \text{min}^{-1}$

Stroke $\ell_s = 1{,}000\ \text{mm}$

- Lead: Ph = 40 mm

$$N_m = \frac{2 \times n \times \ell_s}{Ph} = \frac{2 \times 8 \times 1{,}000}{40} = 400\ \text{min}^{-1}$$

- Lead: Ph = 60 mm

$$N_m = \frac{2 \times n \times \ell_s}{Ph} = \frac{2 \times 8 \times 1{,}000}{60} = 267\ \text{min}^{-1}$$

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

- WTF2040-2

Nominal life $L_{10m} = 4.1 \times 10^9$ rev

Average revolutions per minute $Nm = 400\ \text{min}^{-1}$

$$L_h = \frac{L_{10m}}{60 \times N_m} = \frac{4.1 \times 10^9}{60 \times 400} = 171{,}000\ \text{h}$$

- WTF2040-3

Nominal life $L_{10m} = 7.47 \times 10^9$ rev

Average revolutions per minute $Nm = 400\ \text{min}^{-1}$

$$L_h = \frac{L_{10m}}{60 \times N_m} = \frac{7.47 \times 10^9}{60 \times 400} = 311{,}000\ \text{h}$$

- WTF3060-2

Nominal life $L_{10m} = 4.27 \times 10^{10}$ rev

Average revolutions per minute $Nm = 267\ \text{min}^{-1}$

$$L_h = \frac{L_{10m}}{60 \times N_m} = \frac{4.27 \times 10^{10}}{60 \times 267} = 2{,}670{,}000\ \text{h}$$

- WTF3060-3

Nominal life $L_{10m} = 7.93 \times 10^{10}$ rev

Average revolutions per minute $Nm = 267\ \text{min}^{-1}$

$$L_h = \frac{L_{10m}}{60 \times N_m} = \frac{7.93 \times 10^{10}}{60 \times 267} = 4{,}950{,}000\ \text{h}$$

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

- WTF2040-2
  - Nominal life $L_{10m} = 4.1 \times 10^{9}$ rev
  - Lead $Ph = 40$ mm
  - $L_S = L_{10m} \times Ph \times 10^{-6} = 164{,}000$ km
- WTF2040-3
  - Nominal life $L_{10m} = 7.47 \times 10^{9}$ rev
  - Lead $Ph = 40$ mm
  - $L_S = L_{10m} \times Ph \times 10^{-6} = 298{,}800$ km
- WTF3060-2
  - Nominal life $L_{10m} = 4.27 \times 10^{10}$ rev
  - Lead $Ph = 60$ mm
  - $L_S = L_{10m} \times Ph \times 10^{-6} = 2{,}562{,}000$ km
- WTF3060-3
  - Nominal life $L_{10m} = 7.93 \times 10^{10}$ rev
  - Lead $Ph = 60$ mm
  - $L_S = L_{10m} \times Ph \times 10^{-6} = 4{,}758{,}000$ 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

Considering the Rigidity

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

Considering the Positioning Accuracy

● Considering the Lead Angle Accuracy

Accuracy grade C7 was selected in the section "Selecting Lead Angle Accuracy and Axial Clearance" on B **15-70**.

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

● Considering 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 consider the axial clearance.

WTF2040: axial clearance: 0.1 mm

WTF3060: axial clearance: 0.14 mm

● Considering 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.

● Considering the Thermal Displacement through Heat Generation

Assume the temperature increase during operation to be 5℃.

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

$$\Delta\ell = \rho \times \Delta t \times \ell = 12 \times 10^{-6} \times 5 \times 1{,}000 = 0.06\text{ mm}$$

● Considering the Orientation Change during Travel

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

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

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

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

$$\Delta p = \frac{\pm 0.05 \times 1{,}000}{300} \pm 0.007 + 0.06 = 0.234\text{ mm}$$

Since models WTF2040-2, WTF2040-3, WTF3060-2 and WTF3060-3 meet the selection requirements throughout the consideration process in the section "Selecting Lead Angle Accuracy and Axial Clearance" on B **15-70** to the section "Considering the Positioning Accuracy" on B **15-79**, the most compact model WTF2040-2 is selected.

Considering the Rotational Torque

● Friction Torque Due to an External Load

The friction torque is obtained as follows:

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

● Torque Due to a Preload on the Ball Screw

The ball screw does not have a preload applied.

● Torque Required for Acceleration

Inertial Moment

Since the inertial moment per unit length of the screw shaft is 1.23 × 10^{-3} kg•cm²/mm (see the dimensional table), the inertial moment of the screw shaft with an overall length of 1,200 mm is obtained as follows.

$J_s = 1.23 \times 10^{-3} \times 1{,}200 = 1.48 \text{ kg·cm}^2$

$\quad = 1.48 \times 10^{-4} \text{ kg·m}^2$

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

$\quad = 3.39 \times 10^{-3} \text{ kg·m}^2$

Angular acceleration:

$$\omega' = \frac{2\pi \cdot Nm}{60 \cdot t_1} = \frac{2\pi \times 1{,}500}{60 \times 0.15} = 1{,}050 \text{ rad/s}^2$$

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

$T_2 = (J + J_m) \times \omega' = (3.39 \times 10^{-3} + 1 \times 10^{-3}) \times 1{,}050 = 4.61 \text{N·m}$

$\quad = 4.61 \times 10^3 \text{ N·mm}$

Therefore, the required torque is specified as follows.

During acceleration

$\quad T_k = T_1 + T_2 = 120 + 4.61 \times 10^3 = 4{,}730 \text{ N·mm}$

During uniform motion

$\quad T_t = T_1 = 120 \text{ N·mm}$

During deceleration

$\quad T_g = T_1 - T_2 = 120 - 4.61 \times 10^3 = -4{,}490 \text{ N·mm}$

Considering 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 consider the rotational speed of the motor.

Maximum working rotational speed : 1,500 min^{-1}

Rated rotational speed of the motor: 3,000 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 not necessary to consider this factor.

Encoder resolution: 1,000 p/rev.

Doubled: 2,000 p/rev

● Motor Torque

The torque during acceleration calculated in the section “Considering the Rotational Torque” on B15-80 is the required maximum torque.

T_{max} = 4,730 N·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 the section “Considering the Rotational Torque” on B15-80 can be expressed as follows.

During acceleration:

T_k = 4,730 N·mm

t_1 = 0.15 s

During uniform motion:

T_t = 120 N·mm

t_2 = 0.85 s

During deceleration:

T_g = 4,490 N·mm

t_3 = 0.15 s

When stationary:

T_S = 0

t_4 = 2.6 s

The effective torque is obtained as follows, and the rated torque of the motor must be 1,305 N·mm or greater.

$$T_{rms} = \sqrt{\frac{T_k^2 \cdot t_1 + T_t^2 \cdot t_2 + T_g^2 \cdot t_3 + T_s^2 \cdot t_4}{t_1 + t_2 + t_3 + t_4}} = \sqrt{\frac{4{,}730^2 \times 0.15 + 120^2 \times 0.85 + 4{,}490^2 \times 0.15 + 0}{0.15 + 0.85 + 0.15 + 2.6}}$$

$$= 1{,}305 \text{ N} \cdot \text{mm}$$

Ball Screw

● **Inertial Moment**

The inertial moment applied to the motor equals the inertial moment calculated in the section “Considering the Rotational Torque” on B15-80.

$J = 3.39 \times 10^{-3}$ kg·m^2

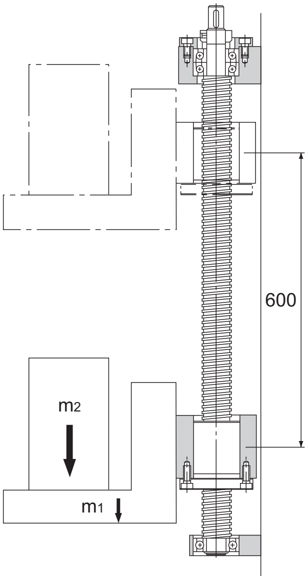
Normally, the motor needs to have an inertial moment at least one tenth of the inertial moment applied to the motor, although the specific value varies depending on the motor manufacturer.
Therefore, the inertial moment of the AC servomotor must be 3.39×10^{-4}kg-m^2 or greater.

The selection has been completed.

Vertical Conveyance System

Selection Conditions

Table mass	m_1 = 40 kg
Work 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
Number of reciprocations per minute	n = 5 min^{-1}
Backlash	0.1 mm
Positioning accuracy	±0.7 mm/600 mm
Positioning accuracy repeatability	±0.05 mm
Minimum feed amount	s = 0.01 mm/pulse
Service life time	20,000 h
Driving motor	AC servo motor Rated rotational speed: 3,000 min^{-1}
Inertial moment of the motor	$J_m = 5 \times 10^{-5}$ kg·m²
Reduction gear	None (direct coupling)
Frictional coefficient of the guide surface	μ = 0.003 (rolling)
Guide surface resistance	f = 20 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 ±0.7 mm/600 mm:

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

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

Therefore, the accuracy grade of the ball screw (see Table 1 on B15-20) needs to be C10 (travel distance error: ±0.21 mm/300 mm).

Accuracy grade C10 is available for low-cost rolled ball screws. Assume that a rolled ball screw is selected.

● Selecting the Axial Clearance

The backlash requirement is 0.1 mm or less. However, because a vertical orientation means that an axial load will constantly be applied in a single direction, the axial load will not cause backlash no matter how large it is.

Therefore, a low-cost rolled ball screw is selected since there will not be a problem with 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 600 mm.

600 + 200 = 800 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 min^{-1} and the maximum speed 0.3 m/s, the ball screw lead is obtained as follows:

$$\frac{0.3 \times 60 \times 1{,}000}{3{,}000} = 6 \text{ mm}$$

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.

1,000 p/rev (without multiplication)
1,500 p/rev (without multiplication)
2,000 p/rev (doubled)
3,000 p/rev (doubled)
4,000 p/rev (quadrupled)
6,000 p/rev (quadrupled)

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

Lead 6 mm —— 3,000 p/rev
8 mm —— 4,000 p/rev
10 mm —— 1,000 p/rev
20 mm —— 2,000 p/rev
40 mm —— 2,000 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, so 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

Ball screw models that meet the lead being 10 mm as described in the section "Selecting Lead Angle Accuracy and Axial Clearance" on B**15-84** and the section "Selecting a Screw Shaft" on B**15-84** (see Table 20 on B**15-35**) are as follows.

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

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

● Considering 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:

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

Factor according to the mounting method $\eta_2 = 20$ (see B15-38)

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 $d_1 = 12.5$ mm

$$P_1 = \eta_2 \cdot \frac{d_1^4}{\ell_a^2} \times 10^4 = 20 \times \frac{12.5^4}{700^2} \times 10^4 = 9{,}960\ \text{N}$$

■Permissible Compressive and Tensile Load of the Screw Shaft

$P_2 = 116 d_1^2 = 116 \times 12.5^2 = 18{,}100$ 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.

● Considering the Permissible Rotational Speed

■Maximum Rotational Speed

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

Maximum speed V_{max} = 0.3 m/s

Lead Ph = 10 mm

$$N_{max} = \frac{V_{max} \times 60 \times 10^3}{Ph} = 1{,}800\ min^{-1}$$

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

Factor according to the mounting method λ_2 = 15.1 (see B15-40)

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

Distance between two mounting surfaces ℓ_b = 700 mm (estimate)

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

Screw-shaft thread minor diameter d_1 = 12.5 mm

$$N_1 = \lambda_2 \times \frac{d_1}{\ell_b^{\,2}}\ 10^7 = 15.1 \times \frac{12.5}{700^2} \times 10^7 = 3{,}852\ min^{-1}$$

■Permissible Rotational Speed Determined by the DN Value

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

Ball center-to-center diameter D = 15.75 mm

$$N_2 = \frac{70{,}000}{D} = \frac{70{,}000}{15.75} = 4{,}444\ min^{-1}$$

Thus, the requirements for the critical speed and the DN value of the screw shaft are satisfied.

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)

● Considering 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 B15-47).

$$Fa_{max} = \frac{C_0a}{f_S} = \frac{25.2}{2} = 12.6\ \text{kN} = 12600\ \text{N}$$

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.

● Considering 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

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

■Nominal Life

Dynamic load rating	C_a = 9,800 N
Load factor	f_W = 1.5 (see Table 2 on B15-48)
Average load	F_{am} = 492 N
Nominal life	L_{10} (rev)

$$L_{10m} = \left(\alpha \times \frac{C_a}{F_{am}}\right)^3 \times 10^6 = \left(\frac{9{,}800}{1.5 \times 492}\right)^3 \times 10^6 = 2.34 \times 10^9\text{ rev}$$

$$\alpha = \frac{1}{f_W}$$

■Average Revolutions per Minute

Number of reciprocations per minute	$n = 5\text{ min}^{-1}$
Stroke	ℓ_S = 600 mm
Lead	Ph = 10 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	$L_{10m} = 2.34 \times 10^9$ rev
Average revolutions per minute	$N_m = 600\text{ min}^{-1}$

$$L_h = \frac{L_{10m}}{60 \cdot N_m} = \frac{2.34 \times 10^9}{60 \times 600} = 65{,}000\text{ h}$$

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

Nominal life	$L_{10m} = 2.34 \times 10^9$ rev
Lead	Ph = 10 mm

$L_S = L_{10m} \times Ph \times 10^{-6}$ = 23,400 km

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

Considering the Rigidity

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

Considering the Positioning Accuracy

● Considering the Lead Angle Accuracy

Accuracy grade C10 was selected in the section "Selecting Lead Angle Accuracy and Axial Clearance" on B15-84.

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

● Considering the Axial Clearance

Since mounting the product vertically causes the axial load to be constant in only one given direction, there is no need to consider the axial clearance.

● Considering the Axial Rigidity

Since the lead angle accuracy is achieved beyond the required positioning accuracy, there is no need to consider the positioning accuracy determined by axial rigidity.

● Considering the Thermal Displacement through Heat Generation

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

● Considering the Orientation Change during Travel

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

Considering the Rotational Torque

● Frictional Torque Due to an External Load

During upward uniform motion:

$$T_1 = \frac{Fa_2 \cdot Ph}{2 \times \pi \times \eta} = \frac{510 \times 10}{2 \times \pi \times 0.9} = 900\ N{\cdot}mm$$

During downward uniform motion:

$$T_2 = \frac{Fa_5 \cdot Ph}{2 \times \pi \times \eta} = \frac{470 \times 10}{2 \times \pi \times 0.9} = 830\ N{\cdot}mm$$

● Torque Due to a Preload on the Ball Screw

The ball screw does not have a preload applied.

● Torque Required for Acceleration

Inertial Moment:

Since the inertial moment per unit length of the screw shaft is 3.9×10^{-4} kg·cm²/mm (see the specification table), the inertial moment of a screw shaft with an overall length of 800 mm is obtained as follows.

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

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

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

Angular acceleration:

$$\omega' = \frac{2\pi \cdot Nmax}{60 \cdot t} = \frac{2\pi \times 1{,}800}{60 \times 0.2} = 942 \text{ rad/s}^2$$

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

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

Therefore, the required torque is specified as follows.

During upward acceleration:

$T_{k1} = T_1 + T_3 = 900 + 200 = 1{,}100$ N·mm

During upward uniform motion:

$T_{t1} = T_1 = 900$ N·mm

During upward deceleration:

$T_{g1} = T_1 - T_3 = 900 - 200 = 700$ N·mm

During downward acceleration:

$T_{k2} = 630$ N·mm

During downward uniform motion:

$T_{t2} = 830$ N·mm

During downward deceleration:

$T_{g2} = 1{,}030$ N·mm

Considering 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 consider the rotational speed of the motor.

Maximum working rotational speed : 1,800 min^{-1}

Rated rotational speed of the motor: 3,000 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 consider this factor.

Encoder resolution: 1,000 p/rev.

● Motor Torque

The torque during acceleration calculated in the section "Considering the Rotational Torque" on B15-90 is the required maximum torque.

$T_{max} = T_{k1} = 1{,}100$ N·mm

Therefore, the maximum peak torque of the AC servomotor needs to be at least 1,100 N·mm.

● Effective Torque Value

The selection requirements and the torque calculated in the section "Considering the Rotational Torque" on B15-90 can be expressed as follows.

During upward acceleration:

$T_{k1} = 1{,}100$ 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:

$T_{k2} = 630$ N·mm

$t_1 = 0.2$ s

During downward uniform motion:

$T_{t2} = 830$ N·mm

$t_2 = 1.8$ s

During downward deceleration:

$T_{g2} = 1{,}030$ N·mm

$t_3 = 0.2$ s

When stationary (m_2=0):

$T_S = 658$ N·mm

$t_4 = 7.6$ s

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

$$T_{rms} = \sqrt{\frac{T_{k1}^2 \cdot t_1 + T_{t1}^2 \cdot t_2 + T_{g1}^2 \cdot t_3 + T_{k2}^2 \cdot t_1 + T_{t2}^2 \cdot t_2 + T_{g2}^2 \cdot t_3 + T_s^2 \cdot t_4}{t_1 + t_2 + t_3 + t_1 + t_2 + t_3 + t_4}}$$

$$= \sqrt{\frac{1{,}100^2 \times 0.2 + 900^2 \times 1.8 + 700^2 \times 0.2 + 630^2 \times 0.2 + 830^2 \times 1.8 + 1{,}030^2 \times 0.2 + 658^2 \times 7.6}{0.2 + 1.8 + 0.2 + 0.2 + 1.8 + 0.2 + 7.6}}$$

$= 743$ N·mm

● **Inertial Moment**

The inertial moment applied to the motor equals the inertial moment calculated in the section “Considering the Rotational Torque” on B15-90.

$J = 1.58 \times 10^{-4}$ kg·m²

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-m² or greater.

The selection has been completed.