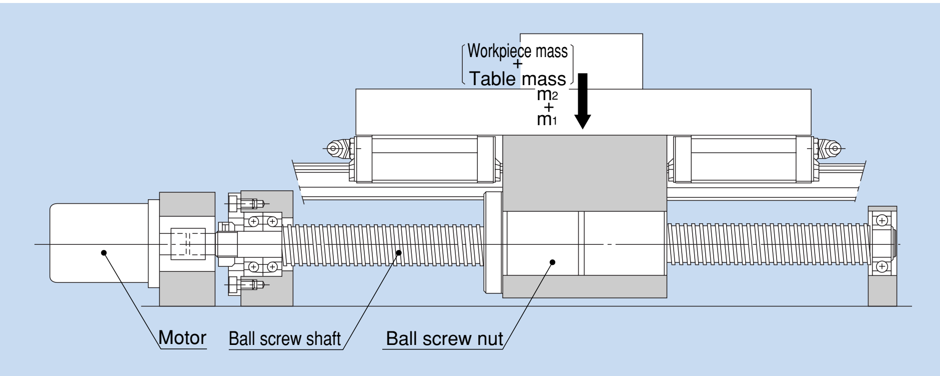
12. Examples of Selecting a Ball Screw

12.1. High Speed Conveyance System (Horizontal Use)

12.1.1. Selection Conditions

Table mass	m_1	=60kg
Workpiece mass	m_2	=20kg
Stroke length	ℓ_s	=1000mm
Maximum speed	V_{max}	=1m/s
Acceleration time	t_1	=0.15s
Deceleration time	t_3	=0.15s
Reciprocations per minute	n	=8min^{-1}
Backlash	0.15mm	
Positioning accuracy	±0.3 mm/1000 mm (Perform positioning from the negative direction)	

Positioning repeatability	±0.1 mm
Minimum feed distance	s =0.02mm/pulse
Desired service life time	30000h
Driving motor	AC servomotor Rated rotation speed: 3,000 min^{-1}
Motor inertial moment	J_m =1×10^{-3} kg•m^2
Deceleration mechanism	None (direct coupling) A=1
Friction coefficient of the guide surface	μ =0.003 (rolling)
Resistance of the guide surface	f =15 N (without load)



12.1.2. Selection Items

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

12.1.3. Selecting Lead Accuracy and Axial Clearance

●Selecting lead accuracy

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

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

The lead accuracy must be ±0.09 mm/300 mm or higher.
Therefore, the accuracy grade of the Ball Screw (see table 1 on page K-24) needs to be:

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 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 table 11 on page K-31) meets the requirements.
Thus, a Rolled Ball Screw model with a screw shaft diameter of 32 mm or less and accuracy grade of C7 is selected.

12.1.4. 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 1,000 mm.

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

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

●Selecting lead

With the driving motor's rated rotation speed being 3,000 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 distance of 0.02 mm/pulse, which is the selection requirement, the following should apply.

Lead20mm —— 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 12.1.3.: screw shaft diameter of 32 mm or less and being a rolled Ball Screw; and the requirement defined in Section 12.1.4.: lead being 20, 30, 40, 60 or 80 mm (see table 4 on page K-40) 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 12.1.4., 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 and is costly.

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 N(without load)
Table mass	m_1	=60 kg
Workpiece mass	m_2	=20 kg
Friction coefficient of the guide surface	μ	=0.003
Maximum speed	V_{max}	=1 m/s
Gravitational acceleration	g	=9.807 m/s²
Acceleration time	t_1	=0.15 s

Hence,

Acceleration:

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

During forward acceleration:

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

During forward uniform motion:

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

During forward deceleration:

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

During backward acceleration:

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

During uniform backward motion:

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

During backward deceleration:

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

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

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

The smaller the screw shaft diameter, the smaller the permissible axial load on the shaft becomes. 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 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 considered, is "fixed-fixed:"

Center distance: ℓ_a=1100 mm(estimate)

Thread minor diameter: d_1=17.5 mm

$$P_1 = \eta_2 \cdot \frac{d_1^4}{\ell_a^2} \times 10^4 = 20 \times \frac{17.5^4}{1100^2} \times 10^4 = 15500\ N$$

Permissible compressive and tensile load of the screw shaft

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

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: 20 mm; lead: 20 mm

Maximum speed: V_{max}=1 m/s

Lead: ℓ=20 mm

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

Screw shaft diameter: 20 mm; lead: 40 mm

Maximum speed: V_{max}=1 m/s

Lead: ℓ=40 mm

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

Screw shaft diameter: 30 mm; lead: 60 mm

Maximum speed: V_{max}=1 m/s

Lead: ℓ=60 mm

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

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=1100 mm (estimate)

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

Screw shaft thread minor diameter: d_1=17.5mm

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

Screw shaft diameter: 30 mm; lead: 60 mm

Screw shaft thread minor diameter: d_1=26.4 mm

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

Permissible rotation speed determined by the DN value

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

Ball 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 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 rotation 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, meet the critical 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.

12.1.5. Selecting a Nut

●Selecting a Nut Model Number

Roller 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. The following variations are selected.

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)

●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 a high-speed conveyance system and an impact load is applied during deceleration, set the static safety factor (f_S) at 2.5 (see table 1 on page K-54).

$$\frac{C_{0a}}{f_S} = \frac{13.6}{2.5} = 5.44\ \text{kN} = 5440\ \text{N}$$

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

$$\ell_{2,5} = \ell_3 - \frac{V_{max} \cdot t_1 + V_{max} \cdot t_3}{2} \times 10^3 = 1000 - \frac{1 \times 0.15 + 1 \times 0.15}{2} \times 10^3 = 850\ \text{mm}$$

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 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 backward uniform 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 Fa_3, Fa_4 and Fa_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 $Fa_{3,4,5}$ = ON.

$$Fm_1 = \sqrt[3]{\frac{Fa_1^3 \times \ell_1 + Fa_2^3 \times \ell_2 + Fa_6^3 \times \ell_6}{\ell_1 + \ell_2 + \ell_3 + \ell_4 + \ell_5 + \ell_6}} = 225\ \text{N}$$

Average axial load in the negative direction

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

$$Fm_2 = \sqrt[3]{\frac{|Fa_3|^3 \times \ell_3 + |Fa_4|^3 \times \ell_4 + |Fa_5|^3 \times \ell_5}{\ell_1 + \ell_2 + \ell_3 + \ell_4 + \ell_5 + \ell_6}} = 225\ \text{N}$$

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

Rated life

Load factor: $f_W = 1.5$ (see table 2 on page K-55)
Average load: $F_m = 225$ N
Rated life L (rev.)

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

Model No. under consideration	Dynamic load rating Ca(N)	Rated 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}

Reciprocations per minute

Reciprocations per minute: $n=8\ \text{min}^{-1}$

Stroke: $\ell_s=1000$ mm

Lead : ℓ =40 mm

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

Lead : ℓ =60 mm

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

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

WTF2040−2

Rated life: $L=4.1\times10^9$ rev.

Average rotation speed 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

Rated life: $L=7.47\times10^9$ rev.

Average rotation speed 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

Rated life: $L=4.27\times10^{10}$ rev.

Average rotation speed 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

Rated life: $L=7.93\times10^{10}$ rev.

Average rotation speed 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 rated life

WTF2040−2

Rated life: $L=4.1\times10^{9}$ rev.

Lead: $\ell=40$ mm

$L_S = L \times \ell \times 10^{-6} = 164000$ km

WTF2040−3

Rated life: $L=7.47\times10^{9}$ rev.

Lead: $\ell=40$ mm

$L_S = L \times \ell \times 10^{-6} = 298800$ km

WTF3060−2

Rated life: $L=4.27\times10^{10}$ rev.

Lead: $\ell=60$ mm

$L_S = L \times \ell \times 10^{-6} = 2562000$ km

WTF3060−3

Rated life: $L=7.93\times10^{10}$ rev.

Lead: $\ell=60$ mm

$L_S = L \times \ell \times 10^{-6} = 4758000$ 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

12.1.6. Studying the Rigidity

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

12.1.7. Studying the Positioning Accuracy

●Studying the lead accuracy

Accuracy grade C7 was selected in Section 12.1.3.
C7 (travel distance error:±0.05mm/300mm)

●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 due to heat

Assume the temperature rise during operation to be 5℃.
The positioning accuracy based on the temperature rise is obtained as follows:

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

●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:

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

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

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

Accordingly, the selection requirements are met.
Since models WTF2040-2, WTF2040-3, WTF3060-2 and WTF3060-3 meet the selection requirements throughout the studying process in Section 12.1.3. to Section 12.1.7., the most compact model WTF2040-2 is selected.

12.1.8. Studying the Rotation Torque

●Friction torque due to an external torque

The friction torque is obtained as follows:

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

●Torque due to a preload on the Ball Screw

The Ball Screw is not provided with a preload.

●Torque required for acceleration

Inertial moment:

The inertial moment per unit length of the screw shaft can be specified as follows.

Since 1.23×10^{-3} 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 1,200 mm is obtained as follows.

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

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

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

Angular acceleration:

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

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:

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

During deceleration:

$$T_g = T_1 - T_2 = 120 - 4.61 \times 10^3 = -4490 \text{ N} \cdot \text{mm}$$

12.1.9. 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: 1500 min^{-1}

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

Doubled: 2000 p/rev

●Motor torque:

The torque during acceleration calculated in Section 12.1.8. is the required maximum torque.

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

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 12.1.8. can be expressed as follows.

During acceleration:

$T_k = 4730\ N \cdot mm$

$t_1 = 0.15\ s$

During uniform motion:

$T_t = 120\ N \cdot mm$

$t_2 = 0.85\ s$

During deceleration:

$T_g = 4490\ N \cdot mm$

$t_3 = 0.15\ s$

When stationary:

$T_S = 0$

$t_4 = 2.6\ sec$

Therefore, the effective torque is obtained as follows.

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

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

Accordingly, the rated torque of the motor must be 1,305 N-mm or greater.

●Inertial moment

The inertial moment applied to the motor equals to the inertial moment calculated in Section 12.1.8.

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

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 3.39×10^{-4}kg-m^2 or greater.

The selection has been completed.