Studying the Positioning Accuracy

Causes of Error in the Positioning Accuracy

The causes of error in the positioning accuracy include the lead angle accuracy, the axial clearance and the axial rigidity of the feed screw system. Other important factors include the thermal displacement from heat and the orientation change of the guide system during traveling.

Studying the Lead Angle Accuracy

It is necessary to select the correct accuracy grade of the Ball Screw that satisfies the required positioning accuracy from the Ball Screw accuracies (Table1 on A-678). Table20 on A-712 shows examples of selecting the accuracy grades by the application.

Studying the Axial Clearance

The axial clearance is not a factor of positioning accuracy in single-directional feed. However, it will cause a backlash when the feed direction is inversed or the axial load is inversed. Select an axial clearance that meets the required backlash from Table10 and Table12 on A-685.

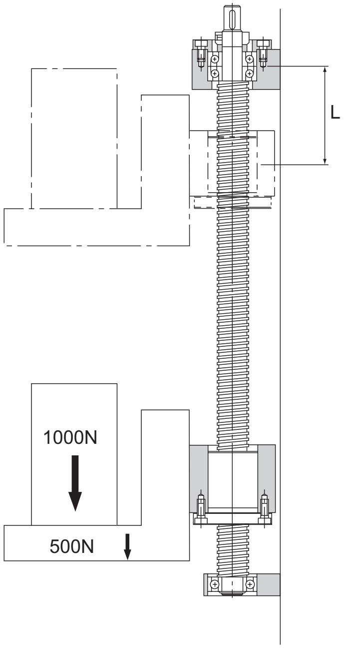
Table20 Examples of Selecting Accuracy Grades by Application

Applications		Shaft	C0	C1	C2	C3	C5	C7	C8	C10
			Accuracy grades							
NC machine tools	Lathe	X		●	●	●	●			
		Z				●	●			
	Machining center	XY			●	●	●			
		Z			●	●	●			
	Drilling machine	XY				●	●			
		Z					●	●		
	Jig borer	XY	●	●						
		Z	●	●						
	Surface grinder	X				●	●			
		Y		●	●	●	●			
		Z		●	●	●	●			
	Cylindrical grinder	X	●	●	●					
		Z		●	●	●				
	Electric discharge machine	XY	●	●	●					
		Z		●	●	●	●			
	Electric discharge machine Wire cutting machine	XY	●	●	●					
		Z	●	●	●	●				
		UV		●	●	●				
	Punching press	XY				●	●	●		
	Laser beam machine	X				●	●	●		
		Z				●	●	●		
	Woodworking machine						●	●	●	●
General-purpose machine; dedicated machine						●	●	●	●	●
Industrial robot	Cartesian coordinate	Assembly				●	●	●	●	
		Other					●	●	●	●
	Vertical articulated type	Assembly					●	●	●	
		Other						●	●	
	Cylindrical coordinate					●	●	●		
Semiconductor manufacturing machine	Photolithography machine		●	●						
	Chemical treatment machine				●	●	●	●	●	●
	Wire bonding machine			●	●					
	Prober		●	●	●	●				
	Printed circuit board drilling machine			●	●	●	●	●		
	Electronic component inserter				●	●	●	●		
3D measuring instrument			●	●	●					
Image processing machine			●	●	●					
Injection molding machine								●	●	●
Office equipment							●	●	●	●

Studying the Axial Clearance of the Feed Screw System

Of the axial rigidities of the feed screw system, the axial rigidity of the screw shaft fluctuates according to the stroke position. When the axial rigidity is large, such change in the axial rigidity of the screw shaft will affect the positioning accuracy. Therefore, it is necessary to take into account the rigidity of the feed screw system (A-707 to A-710).

Example: Positioning error due to the axial rigidity of the feed screw system during a vertical transfer



[Conditions]
Transferred weight: 1,000 N; table weight: 500 N
Ball Screw used: model BNF2512–2.5 (screw-shaft thread minor diameter d_1 = 21.9 mm)
Stroke length: 600 mm (L=100 mm to 700 mm)
Screw shaft mounting type: fixed-supported

[Consideration]
The difference in axial rigidity between L = 100 mm and L = 700 mm applied only to the axial rigidity of the screw shaft.
Therefore, positioning error due to the axial rigidity of the feed screw system equals to the difference in the axial displacement of the screw shaft between L = 100 mm and L = 700 mm.

[Axial Rigidity of the Screw Shaft (see A-707 and A-708)]

$$K_S = \frac{A \cdot E}{1000L} = \frac{376.5 \times 2.06 \times 10^5}{1000 \times L} = \frac{77.6 \times 10^3}{L}$$

$$A = \frac{\pi}{4} d_1^2 = \frac{\pi}{4} \times 21.9^2 = 376.5\text{mm}^2$$

$$E = 2.06 \times 10^5 \text{ N/mm}^2$$

(1) When L = 100 mm

$$K_{S1} = \frac{77.6 \times 10^3}{100} = 776 \text{ N/}\mu\text{m}$$

(2) When L = 700mm

$$K_{S2} = \frac{77.6 \times 10^3}{700} = 111 \text{ N/}\mu\text{m}$$

[Axial Displacement due to Axial Rigidity of the Screw Shaft]

(1) When L = 100 mm

$$\delta_1 = \frac{Fa}{K_{S1}} = \frac{1000+500}{776} = 1.9\mu\text{m}$$

(2) When L = 700mm

$$\delta_2 = \frac{Fa}{K_{S2}} = \frac{1000+500}{111} = 13.5\mu\text{m}$$

[Positioning Error due to Axial Rigidity of the Feed Screw System]

Positioning accuracy=$\delta_1 - \delta_2$=1.9–13.5

=–11.6µm

Therefore, the positioning error due to the axial rigidity of the feed screw system is 11.6 µm.

Studying the Thermal Displacement through Heat Generation

If the temperature of the screw shaft increases during operation, the screw shaft is elongated due to heat thereby to lowering the positioning accuracy. The expansion and contraction of the screw shaft is calculated using the equation (38) below.

$$\Delta \ell = \rho \times \Delta t \times \ell \quad \cdots\cdots\cdots (38)$$

$\Delta \ell$: Axial expansion/contraction of the screw shaft (mm)
ρ : Thermal expansion coefficient (12×10^{-6}/℃)
Δt : Temperature change in the screw shaft (℃)
ℓ : Effective thread length (mm)

Thus, if the temperature of the screw shaft increases by 1℃, the screw shaft is elongated by 12 μm per meter. Therefore, as the Ball Screw travels faster, the more heat is generated. So, as the temperature increases, the positioning accuracy lowers. Accordingly, if high accuracy is required, it is necessary to take measures to cope with the temperature increase.

[Measures to Cope with the Temperature Rise]

● Minimize the Heat Generation

- Minimize the preloads on the Ball Screw and the support bearing.
- Increase the Ball Screw lead and reduce the rotational speed.
- Select a correct lubricant. (See Accessories for Lubrication on A-954.)
- Cool the circumference of the screw shaft with a lubricant or air.

● Avoid Effect of Temperature Rise through Heat Generation

- Set a negative target value for the reference travel distance of the Ball Screw.
  Generally, set a negative target value for the reference travel distance assuming a temperature increase of 2℃ to 5℃ by heat.
  (−0.02mm to −0.06 mm/m)
- Preload the shaft screw with tension. (See Fig.3 of the structure on A-825.)

Studying the Orientation Change during Traveling

The lead angle accuracy of the Ball Screw equals the positioning accuracy of the shaft center of the Ball Screw. Normally, the point where the highest positioning accuracy is required changes according to the ball screw center and the vertical or horizontal direction. Therefore, the orientation change during traveling affects the positioning accuracy.

The largest factor of orientation change affecting the positioning accuracy is pitching if the change occurs in the ball screw center and the vertical direction, and yawing if the change occurs in the horizontal direction.

Accordingly, it is necessary to study the orientation change (accuracy in pitching, yawing, etc.) during the traveling on the basis of the distance from the ball screw center to the location where positioning accuracy is required.

Positioning error due to pitching and yawing is obtained using the equation (39) below.

$$A = \ell \times \sin\theta \quad \cdots\cdots\cdots(39)$$

A: Positioning accuracy due to pitching (or yawing) (mm)

ℓ : Vertical (or horizontal) distance from the ball screw center (mm) (see Fig.12)

θ : Pitching (or yawing) (°)

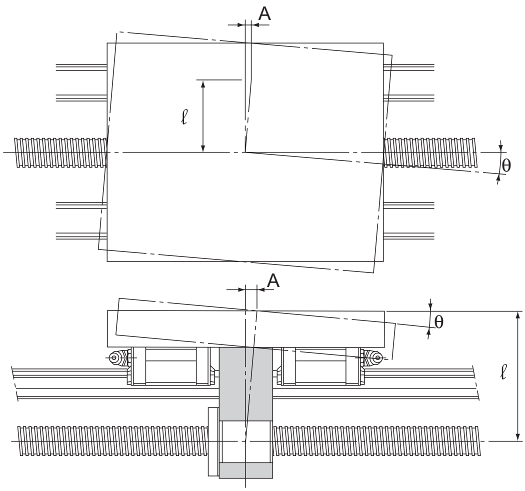


Fig.12

Studying the Rotational Torque

The rotational torque required to convert rotational motion of the Ball Screw into straight motion is obtained using the equation (40) below.

[During Uniform Motion]

$$T_t = T_1 + T_2 + T_4 \quad \cdots\cdots\cdots(40)$$

T_t : Rotational torque required during uniform motion (N-mm)
T_1 : Frictional torque due to an external load (N-mm)
T_2 : Preload torque of the Ball Screw (N-mm)
T_4 : Other torque (N-mm)
(frictional torque of the support bearing and oil seal)

[During Acceleration]

$$T_K = T_t + T_3 \quad \cdots\cdots\cdots(41)$$

T_K : Rotational torque required during acceleration (N-mm)
T_3 : Torque required for acceleration (N-mm)

[During Deceleration]

$$T_g = T_t - T_3 \quad \cdots\cdots\cdots(42)$$

T_g : Rotational torque required for deceleration (N-mm)

Frictional Torque Due to an External Load

Of the turning forces required for the Ball Screw, the rotational torque needed for an external load (guide surface resistance or external force) is obtained using the equation (43) below

$$T_1 = \frac{Fa \cdot Ph}{2\pi \cdot \eta} \cdot A \quad \cdots\cdots\cdots(43)$$

T_1 : Frictional torque due to an external load (N-mm)
Fa : Applied axial load (N)
Ph : Ball Screw lead (mm)
η : Ball Screw efficiency (0.9 to 0.95)
A : Reduction ratio

Torque Due to a Preload on the Ball Screw

For a preload on the Ball Screw, see "Preload Torque" on A-688.

$$T_2 = T_d \cdot A \quad \cdots\cdots\cdots (44)$$

T_2 : Preload torque of the Ball Screw (N-mm)
T_d : Preload torque of the Ball Screw (N-mm)
A : Reduction ratio

Torque Required for Acceleration

$$T_3 = J \times \omega' \times 10^3 \quad \cdots\cdots\cdots (45)$$

T_3 : Torque required for acceleration (N-mm)
J : Inertial moment (kg • m²)
ω´ : Angular acceleration (rad/s²)

$$J = m\left(\frac{Ph}{2\pi}\right)^2 \cdot A^2 \cdot 10^{-6} + J_S \cdot A^2 + J_A \cdot A^2 + J_B$$

m : Transferred mass (kg)
Ph : Ball Screw lead (mm)
J_S : Inertial moment of the screw shaft (kg • m²)
(indicated in the specification tables of the respective model number)
A : Reduction ratio
J_A : Inertial moment of gears, etc. attached to the screw shaft side (kg • m²)
J_B : Inertial moment of gears, etc. attached to the motor side d (kg • m²)

$$\omega' = \frac{2\pi \cdot Nm}{60t}$$

Nm : Motor revolutions per minute (min^{-1})
t : Acceleration time (s)

[Ref.] Inertial moment of a round object

$$J = \frac{m \cdot D^2}{8 \cdot 10^6}$$

J : Inertial moment (kg • m²)
m : Mass of a round object (kg)
D : Screw shaft outer diameter (mm)

Studying the Driving Motor

When selecting a driving motor required to rotate the Ball Screw, normally take into account the rotational speed, rotational torque and minimum feed amount.

When Using a Servomotor

[Rotational Speed]

The rotational speed required for the motor is obtained using the equation (46) based on the feed speed, Ball Screw lead and reduction ratio.

$$N_M = \frac{V \times 1000 \times 60}{Ph} \times \frac{1}{A} \quad \cdots\cdots\cdots (46)$$

N_M : Required rotational speed of the motor (min^{-1})
V : Feeding speed (m/s)
Ph : Ball Screw lead (mm)
A : Reduction ratio

The rated rotational speed of the motor must be equal to or above the calculated value (N_M) above.

$N_M \leqq N_R$

N_R : The rated rotational speed of the motor (min^{-1})

[Required Resolution]

Resolutions required for the encoder and the driver are obtained using the equation (47) based on the minimum feed amount, Ball Screw lead and reduction ratio.

$$B = \frac{Ph \cdot A}{S} \quad \cdots\cdots\cdots (47)$$

B : Resolution required for the encoder and the driver (p/rev)
Ph : Ball Screw lead (mm)
A : Reduction ratio
S : Minimum feed amount (mm)

[Motor Torque]
The torque required for the motor differs between uniform motion, acceleration and deceleration. To calculate the rotational torque, see "Studying the Rotational Torque" on A-717.

a. Maximum torque
The maximum torque required for the motor must be equal to or below the maximum peak torque of the motor.

$T_{max} \leqq Tp_{max}$

T_{max} : Maximum torque acting on the motor
Tp_{max} : Maximum peak torque of the motor

b. Effective torque value
The effective value of the torque required for the motor must be calculated. The effective value of the torque is obtained using the equation (48) below.

$$T_{rms} = \sqrt{\frac{T_1^2 \times t_1 + T_2^2 \times t_2 + T_3^2 \times t_3}{t}} \quad \cdots\cdots\cdots (48)$$

T_{rms} : Effective torque value (N-mm)
T_n : Fluctuating torque (N-mm)
t_n : Time during which the torque T_n is applied (s)
t : Cycle time (s)
($t=t_1+t_2+t_3$)

The calculated effective value of the torque must be equal to or below the rated torque of the motor.

$T_{rms} \leqq T_R$

T_R : Rated torque of the motor (N-mm)

[Inertial Moment]
The inertial moment required for the motor is obtained using the equation (49) below.

$$J_M = \frac{J}{C} \quad \cdots\cdots\cdots (49)$$

J_M : Inertial moment required for the motor (kg・m^2)
C : Factor determined by the motor and the driver
(It is normally between 3 to 10. However, it varies depending on the motor and the driver. Check the specific value in the catalog by the motor manufacturer.)
The inertial moment of the motor must be equal to or above the calculated J_M value.

When Using a Stepping Motor (Pulse Motor)

[Minimal Feed Amount(per Step)]

The step angle required for the motor and the driver is obtained using the equation (50) below based on the minimum feed amount, the Ball Screw lead and the reduction ratio.

$$E = \frac{360S}{Ph \cdot A} \quad \cdots\cdots\cdots(50)$$

E : Step angle required for the motor and the driver (°)
S : Minimum feed amount (per step) (mm)
Ph : Ball Screw lead (mm)
A : Reduction ratio

[Pulse Speed and Motor Torque]

a. Pulse speed

The pulse speed is obtained using the equation (51) below based on the feed speed and the minimum feed amount.

$$f = \frac{V \times 1000}{S} \quad \cdots\cdots\cdots(51)$$

f : Pulse speed (Hz)
V : Feeding speed (m/s)
S : Minimum feed amount (mm)

b. Torque required for the motor

The torque required for the motor differs between the uniform motion, the acceleration and the deceleration. To calculate the rotational torque, see "Studying the Rotational Torque" on A-717.

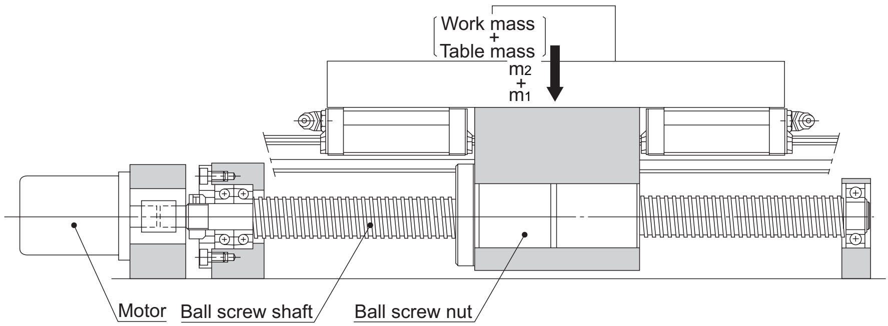
Thus, the pulse speed required for the motor and the required torque can be calculated in the manner described above.
Although the torque varies depending on the motors, normally the calculated torque should be doubled to ensure safety. Check if the torque can be used in the motor's speed-torque curve.

Examples of Selecting a Ball Screw

High-speed Transfer Equipment (Horizontal Use)

[Selection Conditions]

Table Mass	m_1 =60kg
Work 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
Number of 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 amount	s = 0.02mm/pulse
Desired service life time	30000h
Driving motor	AC servo motor Rated rotational speed: 3,000 min^{-1}
Inertial moment of the motor	J_m =1×10^{-3} kg•m^2
Reduction gear	None (direct coupling) A=1
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:

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

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 A-678).
C7 (travel distance error: ±0.05mm/300mm)
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 Table12 on A-685) 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 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:

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

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 A-723: 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 A-723: a lead of 20, 30, 40, 60 or 80 mm (see Table17 on A-693) 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 A-723, 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 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 = 0.15s

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 η_2=10 (see A-694)

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

Distance between two mounting surfaces ℓ_a=1100 mm (estimate)

Screw-shaft thread minor diameter d_1=17.5 mm

$$P_1 = \eta_2 \cdot \frac{d_1^4}{\ell_a^2} \times 10^4 = 10 \times \frac{17.5^4}{1100^2} \times 10^4 = 7750 \text{ N}$$

■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 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 λ_2=15.1 (see A-696)

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 ℓ_b=1100 mm (estimate)

● Screw shaft diameter: 20 mm; lead: 20 mm 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: 30mm; lead: 60mm

Screw-shaft thread minor diameter d_1=26.4mm

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

■Permissible Rotational Speed Determined by the DN Value

● Screw shaft diameter: 20 mm; lead: 20 mm and 40mm (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_{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 high-speed transfer equipment and an impact load is applied during deceleration, set the static safety factor (f_S) at 2.5 (see Table18 on A-703).

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

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 = 0.15s

Deceleration time t_3 = 0.15s

● 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 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 (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 $Fa_{3,4,5}$ = 0N.

$$F_{m1} = \sqrt[3]{\frac{Fa_1^3 \times \ell_1 + Fa_2^3 \times \ell_2 + Fa_6^3 \times \ell_6}{\ell_1 + \ell_2 + \ell_3 + \ell_4 + \ell_5 + \ell_6}} = 225\ \text{N}$$

● Average axial load in the negative direction

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

$$F_{m2} = \sqrt[3]{\frac{|Fa_3|^3 \times \ell_3 + |Fa_4|^3 \times \ell_4 + |Fa_5|^3 \times \ell_5}{\ell_1 + \ell_2 + \ell_3 + \ell_4 + \ell_5 + \ell_6}} = 225\ \text{N}$$

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

■Nominal Life

Load factor	f_W= 1.5 (see Table19 on A-704)
Average load	F_m= 225 N
Nominal life	L (rev)

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

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 $\ell_s = 1000$ mm

● Lead: Ph = 40 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 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 $L = 4.1 \times 10^9$ rev

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

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

● WTF2040-3

Nominal life $L = 7.47 \times 10^9$ rev

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

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

● WTF3060-2

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

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

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

● WTF3060-3

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

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

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

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

- WTF2040-2

  Nominal life $L=4.1\times10^{9}$ rev

  Lead $Ph= 40$ mm

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

- WTF2040-3

  Nominal life $L=7.47\times10^{9}$ rev

  Lead $Ph= 40$ mm

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

- WTF3060-2

  Nominal life $L=4.27\times10^{10}$ rev

  Lead $Ph= 60$ mm

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

- WTF3060-3

  Nominal life $L=7.93\times10^{10}$ rev

  Lead $Ph= 60$ mm

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

[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 A-723.

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 through Heat Generation
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:

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

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 A-723 to Section [Studying the Positioning Accuracy] on A-732, the most compact model WTF2040-2 is selected.

[Studying the Rotational Torque]

● Friction Torque Due to an External Load

The friction toruque is obtained as follows:

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

● Torque Due to a Preload on the Ball Screw

The Ball Screw is not provided with a preload.

● Torque Required for Acceleration

Inertial Moment

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

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

$= 1.48 \times 10^{-4}\ kg \cdot m^2$

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

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

Angular acceleration:

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

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

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

$= 4.61 \times 10^3\ N \cdot mm$

Therefore, the required torque is specified as follows.

During acceleration

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

During uniform motion

$T_t = T_1 = 120\ N \cdot mm$

During deceleration

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

[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 A-733 is the required maximum torque.

T_{max} = 4730 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 Section [Studying the Rotational Torque] on A-733 can be expressed as follows.

During acceleration:
T_k = 4730 N・mm
t_1 = 0.15 s

During uniform motion:
T_t = 120 N・mm
t_2 = 0.85 s

During deceleration:
T_g = 4490 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 1305 N•mm or greater.

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

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

● **Inertial Moment**

The inertial moment applied to the motor equals to the inertial moment calculated in Section [Studying the Rotational Torque] on A-733.

$J = 3.39 \times 10^{-3}$ kg・m^2

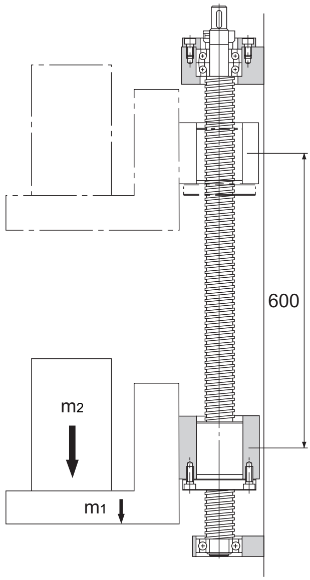
Normally, the motor needs to have an inertial moment at least one tenth of the inertial moment applied to the motor, although the specific value varies depending on the motor manufacturer. Therefore, the inertial moment of the AC servomotor must be 3.39×10^{-4}kg-m^2 or greater.

The selection has been completed.

Vertical Conveyance System

[Selection Conditions]

Table Mass	m_1 =40kg
Work Mass	m_2 =10kg
Stroke length	ℓ_s= 600mm
Maximum speed	V_{max}=0.3m/s
Acceleration time	t_1 = 0.2s
Deceleration time	t_3 = 0.2s
Number of reciprocations per minute	
	n =5min^{-1}
Backlash	0.1mm
Positioning accuracy	±0.7mm/600mm
Positioning Repeatability	±0.05mm
Minimum feed amount	s = 0.01mm/pulse
Service life time	20000h
Driving motor	AC servo motor
	Rated rotational speed:
	3,000 min^{-1}
Inertial moment of the motor	
	J_m =5×10^{-5} kg•m^2
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 ±0.7mm/600mm:

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

The lead angle accuracy must be ±0.35mm/300 mm or higher.
Therefore, the accuracy grade of the Ball Screw (see Table1 on A-678) needs to be C10 (travel distance error: ±0.21 mm/300 mm).
Accuracy grade C10 is available for low priced, Rolled Ball Screws. Assume that a Rolled Ball Screw is selected.

● Selecting 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 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:

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

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(quadrupled)
6000 p/rev(quadrupled)

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 A-737 and Section [Selecting a Screw Shaft] on A-737 (see Table17 on A-693) 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 = 0.2s

Accordingly, the required values are obtained as follows.

Acceleration

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

During upward acceleration:

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

During upward uniform motion:

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

During upward deceleration:

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

During downward acceleration:

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

During downward uniform motion:

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

During downward deceleration:

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

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 η_2=20 (see A-694)

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	ℓ_a=700 mm (estimate)
Screw-shaft thread minor diameter	d_1=12.5 mm

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

■Permissible Compressive and Tensile Load of the Screw Shaft

$$P_2 = 116 d_1^{\,2} = 116 \times 12.5^2 = 18100\ \text{N}$$

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 m/s

Lead Ph= 10 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 λ_2=15.1 (see A-696)

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 ℓ_b=700 mm (estimate)

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

Screw-shaft thread minor diameter d_1=12.5 mm

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

■**Permissible 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 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 Table18 on A-703).

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

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.

● Studying the Service Life

■Calculating the Travel Distance

Maximum speed	V_{max}=0.3 m/s
Acceleration time	t_1 = 0.2s
Deceleration time	t_3 = 0.2s

● 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 Fa_N(N)	Travel distance ℓ_N(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.

[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 A-743 is the required maximum torque.

$T_{max} = T_{k1} = 1100$ N•mm

Therefore, the maximum peak torque of the AC servomotor needs to be at least 1100 N-mm.

● **Effective Torque Value**

The selection requirements and the torque calculated in Section [Studying the Rotational Torque] on A-743 can be expressed as follows.

During upward acceleration:

$T_{k1} = 1100$ N•mm

$t_1 = 0.2$ s

During upward uniform motion:

$T_{t1} = 900$ N•mm

$t_2 = 1.8$ s

During upward deceleration:

$T_{g1} = 700$ N•mm

$t_3 = 0.2$ s

During downward acceleration:

$T_{k2} = 630$ N•mm

$t_1 = 0.2$ s

During downward uniform motion:

$T_{t2} = 830$ N•mm

$t_2 = 1.8$ s

During downward deceleration:

$T_{g2} = 1030$ N-mm

$t_3 = 0.2$ s

When stationary(m_2=0):

$T_S = 658$ N•mm

$t_4 = 7.6$ s

■Average Axial Load

$$F_m = \sqrt[3]{\frac{1}{2\times \ell_s}(Fa_1{}^3\bullet \ell_1 + Fa_2{}^3\bullet \ell_2 + Fa_3{}^3\bullet \ell_3 + Fa_4{}^3\bullet \ell_4 + Fa_5{}^3\bullet \ell_5 + Fa_6{}^3\bullet \ell_6)} = 225\ N$$

■Nominal Life

Dynamic load rating	Ca= 9800 N
Load factor	f_W= 1.5 (see Table19 on A-704)
Average load	F_m= 492 N
Nominal life	L (rev)

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

■Average Revolutions per Minute

Number of reciprocations per minute	n = 5 min^{-1}
Stroke	ℓ_s=600 mm
Lead	Ph= 10 mm

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

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

Nominal life	L=2.34×10^9 rev
Average revolutions per minute	N_m = 600 min^{-1}

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

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

Nominal life	L=2.34×10^9 rev
Lead	Ph= 10 mm

$L_s = L \times Ph \times 10^{-6}$ = 23400 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 A-737.
C10 (travel distance error: ±0.21mm/300mm)

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

● **Studying the Axial Rigidity**
Since the lead 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:

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

During downward uniform motion:

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

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

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

$= 0.31 \times 10^{-4}\ kg \cdot m^2$

$$J = (m_1+m_2)\left(\frac{Ph}{2\times\pi}\right)^2 \cdot A^2 \times 10^{-6} + J_S \cdot A^2 = (40+10)\left(\frac{10}{2\times\pi}\right)^2 \times 1^2 \times 10^{-6} + 0.31\times10^{-4}\times1^2$$

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

Angular acceleration:

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

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

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

Therefore, the required torque is specified as follows.

During upward acceleration:

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

During upward uniform motion:

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

During upward deceleration:

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

During downward acceleration:

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

During downward uniform motion:

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

During downward deceleration:

$T_{g2} = 1030$ N-mm

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

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

$$= \sqrt{\frac{1100^2 \times 0.2 + 900^2 \times 1.8 + 700^2 \times 0.2 + 630^2 \times 0.2 + 830^2 \times 1.8 + 1030^2 \times 0.2 + 658^2 \times 7.6}{0.2 + 1.8 + 0.2 + 0.2 + 1.8 + 0.2 + 7.6}}$$

$$= 743 \text{ N} \cdot \text{mm}$$

● **Inertial Moment**

The inertial moment applied to the motor equals to the inertial moment calculated in Section [Studying the Rotational Torque] on A-743.

$J = 1.58 \times 10^{-4}$ kg・m^2

Normally, the motor needs to have an inertial moment at least one tenth of the inertial moment applied to the motor, although the specific value varies depending on the motor manufacturer.

Therefore, the inertial moment of the AC servomotor must be 1.58×10^{-5}kg-m^2 or greater.

The selection has been completed.