B-2-16 Ball Screw Selection Exercise

[Drill 1] High-speed transporting system

1. Design conditions

Table mass :	$m_1 = 40$ kg
Mass of the transporting item :	$m_2 = 20$ kg
Maximum stroke :	$S_{max} = 700$ mm
Rapid traverse speed :	$V_{max} = 1000$ mm/sec (60 m/min)
Positioning accuracy :	±0.05/700 mm (0.005 mm/pulse)
Repeatability :	±0.005 mm
Required life :	$L_t = 25000$ h (5 years)
Guide way (rolling) :	μ = 0.01 (friction coefficient)
Drive motor :	AC servo motor ($N_{max} = 3000$ min^{-1})

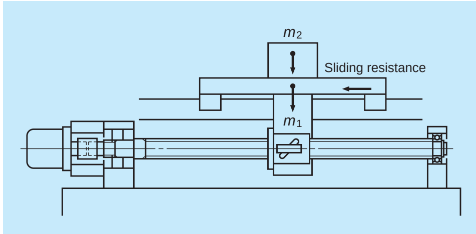

Fig. 16.1 System appearance

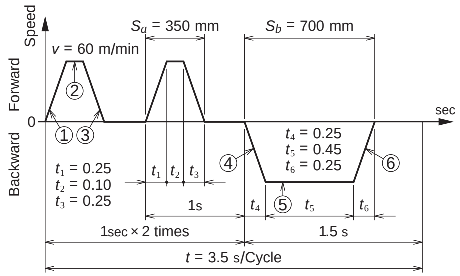

Fig. 16.2 Operating condition

2. Selection of basic factors

(1) Selection of accuracy grade and axial play

According to Table 4.1 Accuracy grades of ball screw and their application (B19), accuracy grade of industrial robots cartesian type and other purposes are C5 to Ct10.

From the following conditions in design, the axial play should be 0.005 mm or less.

Repeatability : ±0.005 (mm)

Resolution : 0.005 mm/pulse

According to Table 4.2 Combinations of accuracy grades and axial play (B20), you will require accuracy grade C5 if the axial play is below 0.005 mm. Therefore select accuracy grade C5, and axial play 0 mm (Z preload)

(2) Selection of lead

Calculate lead l based on AC servo motor maximum speed and rapid traverse speed V_{max}.

$$l \geq \frac{V_{max}}{N_{max}} = \frac{1000 \times 60}{3000} = 20 \text{ (mm)}$$

Select a lead l of 20 mm or larger.

(3) Selection of screw shaft diameter

According to "Table 4.6 Shaft diameter, lead and stroke of standard ball screw" on Page B23, the screw shaft diameter d which has a lead l larger than 20 mm should be in the range of 15 mm to 32 mm. Select the smallest 15 mm.

(4) Selection of stroke

From "Table 4.6 Screw shaft diameter, lead, and stroke of standard ball screw" on page B23, ball screw with shaft diameter d = 15 mm and lead l = 20 mm meets maximum stroke 700 mm, therefore it is possible to select from standard ball screw. Primary selection is as follows:

Primary selection:

Shaft diameter :	15 (mm)
Lead :	20 (mm)
Stroke :	700 (mm)
Accuracy grade :	C5
Axial play :	Z

3. Confirmation of standard ball screw

In consideration of delivery time and price, select from the standard ball screw finished shaft end.

Primary candidate: W1507FA-3PG-C5Z20

4. Checking basic safety

Calculate for the primary candidate.

(1) Allowable axial load

① Calculation of allowable axial load

From Fig. 16.2: Acceleration α_1 at accelerating / decelerating is:

$$\alpha_1 = \frac{V_{max}}{t_1} = \frac{1000}{0.25} = 4000 \text{ (mm/s}^2\text{)} = 4 \text{ (m/s}^2\text{)}$$

Axial load F_i is:

(At time of acceleration ①④)

$$F_1 = \mu (m_1 + m_2) \times g + (m_1 + m_2) \times \alpha_1$$
$$= 0.01 \times (40 + 20) \times 9.80665 + (40 + 20) \times 4$$
$$= 246 \text{ (N)}$$

(At time of constant speed ②⑤)

$$F_2 = \mu (m_1 + m_2) \times g = 0.01 \times (40 + 20) \times 9.80665$$
$$= 6 \text{ (N)}$$

(At time of deceleration ③⑥)

$$F_3 = -\mu (m_1 + m_2) \times g + (m_1 + m_2) \times \alpha_1$$
$$= -0.01 \times (40 + 20) \times 9.80665 + (40 + 20) \times 4$$
$$= 234 \text{ (N)}$$

Thus, the maximum axial load P is 246 N.

② Buckling load

W1507FA-3PG-C5Z20 has distance La = 804 mm (per specifications on Page B277), table maximum axial load P = 246 (N). Supporting condition of screw shaft is Fixed - Simple support, and supporting condition of ball nut is Fixed. Due to the direction of the load, supporting condition is Fixed – Fixed support (Factor m = 19.9).

From Fomula (Ⅱ-2) on Page B48:

$$d_r \geq \left(\frac{P \cdot L_a^2}{m} \times 10^{-4}\right)^{1/4} = \left(\frac{246 \times 804^2}{19.9} \times 10^{-4}\right)^{1/4}$$
$$= 5.3 \text{ (mm)}$$

W1507FA-3PG-C5Z20 has dimension dr = 12.2 mm per dimension chart (Page B277) and therefore meets the condition.

Result: Acceptable

(2) Checking allowable value of rotational speed

The permissible rotational speed listed in the dimension table is 3000 min^{-1}. Since the motor maximum rotational speed is 3000 min^{-1}, the operation is in the range of permissible rotational speed.

Result: Acceptable

(3) Checking life expectation

① Mean load F_m, mean rotational speed N_m

From calculation of axial load. Rotational speed N_i and operating time t_i is:

(At time of acceleration ①④)

$$F_1 = 246 \text{ (N)}$$
$$N_1 = \frac{n}{2} = \frac{3000}{2} = 1500 \text{ (min}^{-1}\text{)}$$
$$t_a = 2 \times t_1 + t_4 = 0.75 \text{ (s)}$$

(At time of constant speed ②⑤)

$$F_2 = 6 \text{ (N)}$$
$$N_2 = 3000 \text{ (min}^{-1}\text{)}$$
$$t_b = 2 \times t_2 + t_5 = 0.65 \text{ (s)}$$

(At time of deceleration ③⑥)

$$F_3 = 234 \text{ (N)}$$
$$N_3 = 1500 \text{ (min}^{-1}\text{)}$$
$$t_c = 2 \times t_3 + t_6 = 0.75 \text{ (s)}$$

Calculation result is shown in Table 16.1

Table 16.1 Axial load and rotational speed

Operating condition	Axial load (N)	Rotational speed (mean) (min^{-1})	Operating time (s)
① ④	$F_1 = 246$	$N_1 = 1500$	$t_a = 0.75$
② ⑤	$F_2 = 6$	$N_2 = 3000$	$t_b = 0.65$
③ ⑥	$F_3 = 234$	$N_3 = 1500$	$t_c = 0.75$

From Formulas (Ⅱ-11) and (Ⅱ-12) on Page B57:

$$F_m = \left(\frac{F_1^3 \cdot N_1 \cdot t_a + F_2^3 \cdot N_2 \cdot t_b + F_3^3 \cdot N_3 \cdot t_c}{N_1 \cdot t_a + N_2 \cdot t_b + N_3 \cdot t_c}\right)^{1/3}$$
$$= 195 \text{ (N)}$$

$$N_m = \frac{N_1 \cdot t_a + N_2 \cdot t_b + N_3 \cdot t_c}{t}$$
$$= 1200 \text{ (min}^{-1}\text{)}$$

② Calculation of life expectation

W1507FA-3PG-C5Z20 (Clearance Z) is C_a=3870N (From dimension table on Page B277), from Formulas (Ⅱ-8) and (Ⅱ-9) on Page B57:

$$L_t = \left(\frac{C_a}{F_m \bullet f_w}\right)^3 \times \frac{1}{60N_m} \times 10^6$$

$$= \left(\frac{3870}{195 \times 1.2}\right)^3 \times \frac{1}{60 \times 1200} \times 10^6$$

$$\fallingdotseq 62800$$

This grade satisfies the required life.

Result: Acceptable

5. Check whether the following figures meet requirements

(1) Accuracy and axial play

From the dimension table and the permissible value of lead accuracy on Page B42:

According to Table 1.2:

Accuracy grade: C5

$e_p = \pm 0.035/800$ (mm)

$\upsilon_u = 0.025$ (mm)

This grade satisfies the required positioning accuracy ±0.05/700 mm.

Checking axial play is omitted here since it is explained in "2. Selection of basic factors."

(2) Drive torque

Required specifications are as follows.

Motor rotational speed : 3000 min^{-1}

Time to reach maximum speed : Under 0.25 sec

① Load (converted to motor axis)

Using Formula (Ⅱ-32) and (Ⅱ-33) on Page B68, calculate the moment of inertia whereas γ is density.

(Screw shaft)

$$J_B = \frac{\pi \bullet \gamma}{32} D^4 \bullet L = \frac{\pi \times 7.8 \times 10^{-3}}{32} \times 1.5^4 \times 80$$

$$= 0.31 \text{ (kg} \cdot \text{cm}^2)$$

(Moving part)

$$J_w = m \times \left(\frac{l}{2\pi}\right)^2 = 60 \times \left(\frac{2}{2\pi}\right)^2$$

$$= 6.1 \text{ (kg} \cdot \text{cm}^2)$$

(Coupling)

$J_c = 0.25$ (kg · cm^2)···Temporary

(As a whole)

Moment of inertia of the ball screw J_L is:

$$J_L = J_B + J_W + J_C$$

$$= 0.31 + 6.1 + 0.25$$

$$= 6.7 \times 10^{-4} \text{ (kg} \cdot \text{m}^2)$$

② Driving torque

Assuming that WBK12-01 compact light load type will be used, as recommended for W1507FA-3PG-C5Z20, and moment of inertia of motor $J_M = 3.1$ (kg · cm^2) = 3.1×10^{-4} (kg · m^2).

(At time of constant speed)

Torque which is necessary to drive a ball screw at constant speed resisting to external loads is per Formula (Ⅱ-30) on Page B68

$$T_1 = T_a + T_{pmax} + T_u$$

in this Formula, T_a is drive torque at constant speed, T_{pmax} is upper limit of the dynamic friction torque of ball screw, T_u is friction torque of the support bearing.

From dimension chart on Page B227 T_{pmax} = 7.8 (N · cm) and from Page B444 T_u = 2.1 (N · cm)

$$T_a = \frac{F_a \bullet l}{2\pi\eta_1}$$

Using Formula (Ⅱ-28) on Page B67, Drive torque at constant speed T_1 is:

$$T_1 = \frac{F_a \bullet l}{2\pi \bullet \eta_1} + T_{pmax} + T_u$$

$$= \frac{6 \times 2}{2\pi \times 0.9} + 7.8 + 2.1$$

$$= 12 \text{ (N} \cdot \text{cm)} = 0.12 \text{ (N} \cdot \text{m)}$$

(At time of acceleration)

Drive torque necessary for accelerating the ball screw resisting axial load can be calculated by Formula (Ⅱ-31) on Page 68

$$T_2 = T_1 + J \bullet \frac{2\pi \bullet n}{60t_1}$$

$$= T_1 + (J_L + J_M) \bullet \frac{2\pi \bullet n}{60t_1}$$

$$= 0.12 + (6.7 \times 10^{-4} + 3.1 \times 10^{-4}) \frac{2\pi \times 3000}{60 \times 0.25}$$

$$= 1.35 \text{ (N} \cdot \text{m)}$$

(At time of deceleration)

Similarly at time of acceleration.

$$T_3 = T_1 - J \bullet \frac{2\pi \bullet n}{60t_3}$$

$$= T_1 - (J_L + J_M) \bullet \frac{2\pi \bullet n}{60t_3}$$

$$= 0.12 - (6.7 \times 10^{-4} + 3.1 \times 10^{-4}) \frac{2\pi \times 3000}{60 \times 0.25}$$

$$= -1.11 \text{ (N} \cdot \text{m)}$$

③ Selection of motor

Selection conditions are as follows.

Maximum rotational speed: $N_M \geq 3000$ (min^{-1})

Motor rating torque: $T_M \geq T_{rms}$ (N · m)

(T_{rms}: Effective torque)

Motor's rotor inertia -- $J_M > J_L/3$ or more

Form above: select an AC servo motor with the following specifications.

Motor specifications:	
Rating power output:	$W_M = 300$ (W)
Maximum rotational speed:	
	$N_M = 3000$ (min^{-1})
Rating torque:	$T_M = 1$ (N · m) = 1×10^2 (N · cm)
Rotor inertia:	$J_M = 3.1 \times 10^{-4}$ (kg · m^2)
	= 3.1 (kg · cm^2)

④ Checking effective torque

Effective torque T_{rms} can be calculated as follows:

$$T_{rms} = \sqrt{\frac{T_2^2 \times t_a + T_1^2 \times t_b + T_3^2 \times t_c}{t}}$$

$$= \sqrt{\frac{1.35^2 \times 0.75 + 0.12^2 \times 0.55 + 1.11^2 \times 0.75}{3.5}}$$

$$= 0.81$$

and meets $T_M \geq _{rms}$.

⑤ Checking time to reach maximum speed

Time required to reach rapid traverse speed can be calculated as follows whereas $T_M' = 2 \times T_M$

$$t_a = \frac{(J_L + J_M) \times 2\pi \times n}{(T_M' - T_1)} \times 1.4$$

$$= \frac{(6.7 \times 10^{-4} + 3.1 \times 10^{-4}) \times 2\pi \times 3000}{(2 \times 1 - 0.12) \times 60} \times 1.4$$

$$= 0.23$$

and meets requirement 0.25 sec or less.

From above: Use W1507FA-3PG-C5Z20

B 90

[Drill 2] Processing table for special machines

1. Design conditions

Table mass:	m_1 = 1000 kg
Mass of the moving item:	m_2 = 600 kg
Maximum stroke:	S_{max} = 1000 mm
Maximum speed:	V_{max} = 15000 mm/min
Positioning accuracy:	±0.035/1000 mm (no load)

∗ Attitude accuracy of the table and thermal displacement are not included in the accuracy requirement of the ball screw.

Repeatability:	±0.005 mm (no load)
Lost motion:	0.020 mm (no load)
Required life expectancy:	L_t = 20000 h (16 h × 250 days × 10 years × 0.5 rate of operation)
Guide way (sliding):	μ = 0.15 (friction coefficient)
Processing:	Milling and drilling
Drive motor:	AC servo motor (N_{max} = 2000 min^{-1})

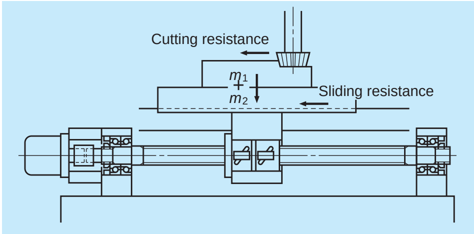

Fig. 16.3 System appearance

Table 16.2 Operating conditions

Operation	Axial load (N)		Feed speed (mm/min)	Use time ratio (%)
	Cutting resistance	Sliding resistance		
Rapid traverse	0	2354	15000	30
Light/medium cutting	4000	2354	500	50
Heavy cutting	8000	2354	100	20

∗ Sliding resistance: $F_r = \mu\,(m_1 + m_2)\,g = 0.15 \times (1000 + 600) \times 9.80665 = 2354$ (N)

∗ Ignore inertia at time of acceleration/deceleration because their time ratios are small.

2. Selection of basic factors

(1) Selection of accuracy grade and axial play

Accuracy grade should be in the range from C1 to C5 according to "Table 4.1 Precision grades of ball screw and their applications" on Page B19.

Assuming nut length 200 mm and extra stroke 100 mm, shaft length L_0 is assumed as follows:

L_0 = Maximum stroke + nut length + margin

= 1000 = (200) + (100) = 1300

From "Table 1.2 Tolerance on specified travel and travel variation of the positioning ball screws" on Page B42, the accuracy that satisfies required function is possibly:

Accuracy C3 grade

$e_p = \pm 0.029/1600$ (mm)

$\upsilon_u = 0.018$ (mm)

Considering importance on the volume of lost motion, select Z code (axial play 0 mm and less) for axial play.

(2) Selection of lead

From the maximum rotational speed of AC servo motor N_{max} and rapid traverse speed of table V_{max} , lead l is :

$$l \geq \frac{V_{max}}{N_{max}} = \frac{15000}{2000} = 7.5 \text{ (mm)}$$

Larger lead l would be beneficial for feed speed. But from the view of the control system (resolution), limit the lead l to 8 mm or 10 mm.

(3) Selection of screw shaft diameter

According to "Table 4.6 shaft diameter, lead and stroke of standard ball screw" on Page B23, shafts whose lead l is 8 mm or 10 mm are in the range of 10 mm to 50 mm. Placing more importance on rigidity than to the volume of lost motion, select a relatively large size in the range of 32 mm to 50 mm.

(4) Selection of stroke

Select 1000 mm, the maximum stroke in request.

Primary selection:

Standard ball screw	
Shaft diameter:	32, 36, 40, 45, 50 mm
Lead:	8, 10 mm
Stroke:	1000 mm
grade:	C3
Axial play code:	Z

3. Confirmation of standard ball screw

Giving consideration to delivery time and price, select from the standard series.

C3 grade chosen in the Primary selection was not found in the standard ball screw. Let us check whether there is a C3 grade among ball screw.

4. Confirmation of made-to-order ball screw

Because standard ball screw does not meet accuracy grade requirement, we will consider made-to-order ball screw which is based on standard ball screw but with accuracy grade C3.

Second selection:

Made-to-order ball screw	
Shaft diameter :	32, 36, 40, 45, 50 mm
Lead :	8, 10 mm
Stroke :	1000 mm
Accuracy grade :	C3
Axial play :	Z

5. Selection of screw shaft diameter, lead, and nut

(1) Dynamic load rating

Obtain required load carrying capacity of each lead through load conditions. From table 16.2 operating conditions on Page B91, calculate the rotation speed N_i as shown in Table 16.3.

$$N_i \geq \frac{V_i}{l}$$

Table 16.3 Load conditions

Operating condition	Axial load (N)	Rotations per minute (min^{-1})		Use time ratio (%)
		l = 8	l = 10	
Rapid traverse	F_1 = 2354	N_1 = 1875	N_1 = 1500	t_1 = 30
Light/medium cutting	F_2 = 6354	N_2 = 62.5	N_2 = 50	t_2 = 50
Heavy cutting	F_3 = 10354	N_3 = 12.5	N_3 = 10	t_3 = 20

By using Formula (Ⅱ-11) and (Ⅱ-12) on Page B57, calculate mean load F_m and mean rotational speed N_m as shown below.

$$F_m = \left(\frac{F_1^3 \bullet N_1 \bullet t_1 + F_2^3 \bullet N_2 \bullet t_2 + F_3^3 \bullet N_3 \bullet t_3}{N_1 \bullet t_1 + N_2 \bullet t_2 + N_3 \bullet t_3} \right)^{1/3}$$

$$N_m = \frac{N_1 \bullet t_a + N_2 \bullet t_b + N_3 \bullet t_c}{t}$$

Table 16.4 Mean load and mean rotational speed

Lead (mm)	8	10
Mean load F_m (N)	3122	3122
Mean rotational speed N_m (min^{-1})	596	477

Required dynamic load rating C_a is:

From Formulas (Ⅱ-8) and (Ⅱ-9) on Page B57:

$$C_a \geq (60 N_m \bullet L_t)^{1/3} \bullet F_m \bullet f_w \times 10^{-2} \ (N)$$

Whereas required life expectancy L_t = 20000 (h), load coefficient f_w = 1.2 (refer to Page B57),

l = 8 (mm)············$C_a \geq$ 33500 (N)

l = 10 (mm)··········$C_a \geq$ 31100 (N)

(2) Selection of the nut

Due to lost motion requirements rigidity will be important, so the nut will be selected as follows. Table 16.5 shows the dynamic load rating of each specification.

- Standard nut ball screw, tube type
- Model: ZFT, DFT (Pages B475 to B504)
- Number of turns of balls : Select from 2.5 turns 2 circuits or 2.5 turns 3 circuits

From Table 16.5 select item that meets required dynamic load rating C_a as follows:

Third selection: In the range surrounded by the dotted lines ☐ in Table 16.5

Table 16.5 Dynamic load rating of each specification

Screw shaft diameter (mm)	Dynamic load rating Ca: (N)			
	Lead 8 mm		Lead 10 mm	
	2.5 turns 2 circuits	2.5 turns 3 circuits	2.5 turns 2 circuits	2.5 turns 3 circuits
32	31700	–	46300	–
36	–	–	49300	–
40	34900	–	52000	–
45	–	–	54200	76800
50	38700	54900	57700	81800

(3) Permissible rotational speed

① Critical speed

Calculate based on rapid traverse speed V_{max} = 15000 mm/min. Ball screw rotational speed at each lead N is:

l = 8 (mm)·······N = 1875 (min^{-1})

l = 10 (mm)·····N = 1500 (min^{-1})

Based on Formula (Ⅱ-7) on Page B51, screw shaft root diameter to meet critical speed requirement is:

$$d_r \geq \frac{n \bullet L_2}{f} \times 10^{-7} \ (\text{mm})$$

In this formula, unsupported length L_a is:

L_a = Maximum stroke + nut length/2 + shaft end extra length

= 1000 + 100 + 200 = 1300 (mm)

Supporting condition of screw shaft is Fixed - Fixed support, and supporting condition of ball nut is Fixed. Therefore, supporting condition is Fixed - Fixed support (Factor f = 21.9)

l = 8 (mm)······$d_r \geq$ 14.5 (mm)

l = 10 (mm)····$d_r \geq$ 11.6 (mm)

② $d \bullet n$ value

From Table 3.2 on Page B54, as the d·n is 70000 or less, screw shaft diameter to meet the d·n value is:

$$d \leq \frac{70000}{N} \ (\text{mm})$$

l = 8 (mm)·············$d \leq$ 37.3 (mm)

l = 10 (mm)···········$d \leq$ 46.7 (mm)

Based on nut specifications (Page B475-504) select item that meets screw shaft root diameter and screw shaft diameter.

∗ Please consult NSK if it is necessary to use at d • n > 70000.

Fourth selection: In the range surrounded by the solid-lines in Table 16.5

(4) Rigidity of the ball screw system

Set the lost motion of the ball screw system (screw shaft, nut and support bearing) at 80% of the specified value. Then calculate the system rigidity. The lost motion is:

20 (µm) × 0.8 = 16 (µm)

At this time, the single-direction elastic deformation ΔL of the major factors of ball screw system becomes half.

$\Delta L \leq$ 8 (µm)

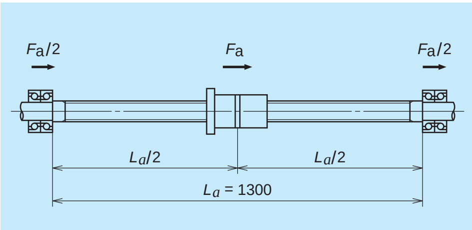

Fig. 16.3 Unsupported length

① Rigidity of the screw shaft K_S

Calculate at the screw shaft center where axial deformation becomes the largest. Because supporting condition of screw shaft is Fixed - Fixed support, from Formula (Ⅱ-21) on Page B62:

$$K_s = \frac{\pi \bullet d_r^2 \bullet E}{L_a} \times 10^{-3} \ (\text{N/mm})$$

Whereas E is Elastic Modules. From Formula (Ⅱ-17) on page B61, elastic deformation of the screw shaft ΔL_S is

$$\Delta L_s = \frac{F_a}{K_s} = \frac{F_a \bullet L_a}{\pi \bullet d_r^2 \bullet E} \times 10^3 \ (\mu\text{m})$$

F_a: Sliding resistance

$F_a = \mu \ (m_1 + m_2)$ = 0.15 × (1000 + 600)

= 2354 (N)

Table 16.7 shows the rigidity of screw shaft K_S and the elastic deformation ΔL_S.

② Rigidity of the nut K_N

Set about 1/3 of the maximum axial load as the preload value.

$$F_{a0} = \frac{F_{max}}{3} = \frac{10354}{3} = 3452 \rightarrow 3500 \ (\text{N})$$

From Formula (Ⅱ-23) on Page B64:

Rigidity:

$$K_N = 0.8 \times K \left(\frac{F_{a0}}{\varepsilon \bullet C_a}\right)^{1/3} = 0.8 \times K \left(\frac{3500}{0.1 \bullet C_a}\right)^{1/3} \ (\text{N}/\mu\text{m})$$

K : Theoretical rigidity

From Formula (Ⅱ-17) on page B62, elastic deformation of the ball nut ΔL_N is

$$\Delta L_N = \frac{F_a}{K_N} = \frac{2354}{K_N}$$

Table 16.7 shows the rigidity of nut K_N and the elastic deformation ΔL_N.

③ Rigidity of the support bearing K_B

The bearing is thrust angular contact ball bearing for ball screw support (TAC Series). Assume each shaft diameter is as shown in Table 16.6 (Refer to Page B457).

Table 16.6 Bearing code

Screw shaft diameter (mm)	Bearing code
32	25TAC62BDF
36	25TAC62BDF
40	30TAC62BDF
45	35TAC72BDF

Refer to Page B461 for rigidity K_B of each bearing (axial spring modulus). Elastic deformation of bearing ΔL_B is:

$$\Delta L_B = \frac{F_a}{2K_B}$$

Table 16.7 shows the rigidity of support bearing K_B and the elastic deformation ΔL_B.

Table 16.7 Rigidity and elestic deformation

Nut model number	Screw shaft		Nut		Support bearing		Total
	K_S	ΔL_S	K_N	ΔL_N	K_B	ΔL_B	ΔL
DFT3210-5	347	6.8	839	2.8	1000	1.2	10.8
DFT3610-5	460	5.1	907	2.6			8.9
DFT4010-5	589	4.0	973	2.4	1030	1.1	7.5
DFT4510-5	772	3.0	1050	2.2	1180	1.0	6.2
DFT4510-7.5			1375	1.7			5.7

Choose the most economical ball screw which meets single direction deformation requirement ΔL is 8 µm or less.

The selected ball screw:

Nut model code :	DFT4010-5
Shaft diameter :	40 (mm)
Lead :	10 (mm)
Dynamic load rating :	52000 (N)

6. Decision of screw shaft length

Nut reference number DFT4010 has nut length 193 mm and unsupported length L_a is:

L_a = Maximum stroke + nut length + margin

= 1000 + 193 + 100 = 1293 → 1300 mm

7. Checking basic safety

(1) Permissible axial load

Calculate buckling load for conditions shown in Fig. 16.4 with P = 10354 (N) and L_1 = 1210 (mm)

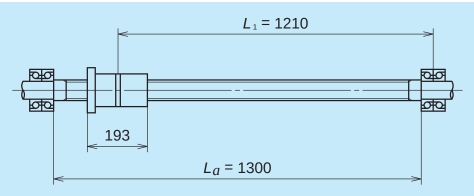

Fig. 16.4 Examination of bucking load

Supporting condition is Fixed - Fixed support, from buckling load calculation Formula (Ⅱ-2) on Page B48, screw shaft diameter d_r to prevent buckling

$$d_r \geq \left(\frac{P \bullet L_1^2}{m} \times 10^{-4}\right)^{1/4}$$

$$= \left(\frac{10354 \times 1210^2}{19.9} \times 10^{-4}\right)^{1/4} = 16.6\ (\text{mm})$$

From DFT4010-5 specifications (page B493) shaft root diameter is d_r = 34.4 and meets requirement.

Result: Acceptable

(2) Permissible rotational speed

① Critical speed n

From critical speed calculation Formula (Ⅱ-7) on Page B51,

$$n = f \bullet \frac{d_r}{L_1^2} \times 10^7 = 21.9 \times \frac{34.4}{1210^2} \times 10^7$$

$$\fallingdotseq 5140$$

Maximum rotational speed N_{max} = 1500 min^{-1} is smaller than critical speed and meets requirement.

Result: Acceptable

② $d \bullet n$ value

$d \bullet n$ value is:

$$d \bullet n = 40 \times 1500 = 60000$$

From Table 3.2 on Page B54, d·n of tube type is 70000 or less and meets requirement.

Result: Acceptable

(3) Life L_t

Dynamic load rating C_a = 52000 N (See dimension table on page B491), and from Formulas (Ⅱ-8) and (Ⅱ-9) on Page B57,

$$L_t = \left(\frac{C_a}{f_w \bullet F_m}\right)^3 \times 10^6 \times \frac{1}{60 \bullet N_m}$$

$$\fallingdotseq 95000$$

and meets required life 20000 (h).

Result: Acceptable

8. Check whether the following factors satisfy requirements

(1) Checking accuracy

① Positioning accuracy

Positioning accuracy ±0.035/1000 mm, and therefore from "Table 1.2 Tolerance of specified travel and travel variation" on Page B42:

Accuracy grade : C3
e_p = ±0.029/1600 (mm)
υ_u = 0.018 (mm)

and meets required positioning accuracy.

② Measures against thermal expansion

Provide pre-tension force equivalent to the elongation of 3°C temperature rise, taking in consideration of the load carrying capacity of bearing. Also, adjust the travel compensation for the specified travel by a volume equivalent to 3°C temperature rise. (Refer to Page B44)

(a) Thermal elongation : ΔL_θ

From Formula (Ⅱ-1) on Page B44:

$$\Delta L_\theta = \rho \bullet \theta \bullet L_a = 12.0 \times 10^{-6} \times 3 \times 1300$$

$$= 0.047\ (\text{mm})$$

(b) Pre-tension force : F_θ

$$F_\theta = \Delta L_\theta \bullet Ks = \frac{\Delta L_\theta \bullet E \bullet \pi \bullet d_r^2}{4L_a}$$

$$= \frac{0.047 \times 2.06 \times 10^5 \times \pi \times 34.4^2}{4L \times 1300}$$

$$\fallingdotseq 6922 \to 6900\ (\text{N})$$

Travel compensation :	–0.047/1300 (mm)
Pre-tension force :	6900 (N)
Tension (elongation) volume :	0.047 (mm)

③ Selection of support bearing

Assuming that the ratio of basic dynamic load rating of support bearing (C_a) and pre-tension force (F_θ) is ε, select a bearing which generally satisfies:

$$\varepsilon = F_\theta / C_B < 0.20$$

Design the bearing supporting configuration to which pre-tension force is applied in such way that the axial load is received by the duplex combination or more. Please consult to NSK when one bearing must sustain the pre-tension load.

Table 16.8 Comparison of dynamic load rating and pre-tension force

Bearing reference number	C_B (N)	ε
30TAC62BDF	29200	0.23
30TAC62BDFD	47500	0.14

Selected support bearing: 30TAC62BDFD

(2) Checking drive torque of motor

Selection of driving motor

❬Required specifications❭

Motor rotational speed : 1500 min^{-1}

Time to reach maximum speed : Under 0.16 sec

(At time of rapid traverse)

① Load (converted to the motor load)

Calculate the moment of inertia of ball screw.

From Formulas (Ⅱ-32) and (Ⅱ-33) of Page B68, moment of inertia of ball screw parts J are calculated as follows, whereas γ is material density and ball screw shaft length L_o = 1550 mm

(Screw shaft)

$$J_B = \frac{\pi \bullet \gamma}{32} D^4 \bullet L_o = \frac{\pi \times 7.8 \times 10^{-3}}{32} \times 4^4 \times 155$$

$$= 30\ (\text{kg} \cdot \text{cm}^2)$$

(Moving part)

$$J_w = m \times \left(\frac{l}{2\pi}\right)^2 = 1600 \times \left(\frac{1}{2\pi}\right)^2$$

$$= 40\ (\text{kg} \cdot \text{cm}^2)$$

(Coupling)

$$J_c = 10\ (\text{kg} \cdot \text{cm}^2) \cdots \text{assumed}$$

(Total)

$$J_L = J_B + J_w + J_c = 30 + 40 + 10$$

$$= 80\ (\text{kg} \cdot \text{cm}^2) \to 80 \times 10^{-4}\ (\text{kg} \cdot \text{m}^2)$$

② Driving torque

Necessary torque to drive a ball screw resisting to external loads T_1 can be obtained by Formula (Ⅱ-29) on Page 66:

$$T_1 = T_A + T_P + T_U$$

In this formula, T_A is drive torque at constant speed, T_P is dynamic friction torque, and, T_U is friction torque of the support bearing. From Formula (Ⅱ-26) on page B66 and Formula (Ⅱ-27) on B67, T_A and T_P are:

$$T_A = \frac{Fa \bullet l}{2\pi \eta_1}$$

$$T_P = 0.014 F_{a0} \sqrt{d_m \bullet l}$$

$$\eta_1 = 0.9$$

Refer to the starting torque value in Table 2.7 on Page B461:

T_U is:

$$T_U = 33 + 33 = 66\ (\text{N} \cdot \text{cm})$$

So, the required drive torque during rapid traverse and heavy cutting T_{11} and T_{13} are:

(At time of rapid traverse)

$$T_{11} = T_{A1} + T_{P1} + T_{U1}$$

$$= \frac{2354 \times 1}{2\pi \times 0.9} + 0.014 \times 3500 \sqrt{4.1 \times 1} + 66$$

$$= 580\ (\text{N} \cdot \text{cm}) \to 580 \times 10^{-2}\ (\text{N} \cdot \text{m})$$

(At time of heavy cutting)

$$T_{12} = T_{A2} + T_{P2} + T_{U2}$$

$$= \frac{10354 \times 1}{2\pi \times 0.9} + 0.014 \times 3500 \sqrt{4.1 \times 1} + 66$$

$$= 1995\ (\text{N} \cdot \text{cm}) \to 1995 \times 10^{-2}\ (\text{N} \cdot \text{m})$$

③ Selection of the motor

❬Selection conditions❭

Maximum rotational speed : $N_M \geq 1500$ (min^{-1})

Motor rating torque : $T_M > T_1$ (N · m)

Motor's rotor inertia : $J_M > J_L / 3$ (kg · m^2)

Based on this, select AC servo motor as below.

Motor specifications

Rating power output: W_M = 1.8 (kW)

Maximum rotational speed:

N_M = 1500 (min^{-1})

Rating torque: T_M = 22.5 (N · m)

= 22.5×10^2 (N · cm)

Rotor inertia: J_M = 190×10^{-4} (kg · m^2)

= 190 (kg · cm^2)

④ Checking time to reach maximum speed:

Required time to reach rapid traverse speed can be calculated as follows, whereas $T_M' = 2 \times T_M$

$$t_a = \frac{(J_L + J_M) \times 2\pi \times N}{(T_M' - T_1) \times 60} \times 1.4$$

$$= \frac{(80 \times 10^{-4} + 190 \times 10^{-4}) \times 2\pi \times 1500}{(2 \times 22.5 - 580 \times 10^{-2}) \times 60} \times 1.4$$

$$= 0.15 \text{ (sec)}$$

and meets requirement 0.16 sec or less.

[Drill 3] Cartesian type robot Z axis (vertical axis)

1. Design conditions

Mass of the traveling item : m = 300 kg

Maximum travel : S_{max} = 1500 mm

Rapid traverse speed : V_{max} = 10000 mm/min

Repeatability : 0.3 mm

Required life : L_t = 24000 h

(16 hours × 300 days × 5 years)

Screw shaft supporting condition :

Fixed -- Simple support

Nut: Flanged single nut

Guide way (rolling) : μ = 0.01 (friction coefficient)

Drive motor : AC servo motor (N_{max} = 1000 min^{-1})

Environment : Slightly dusty

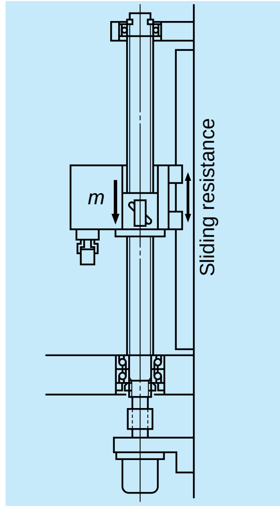

Fig. 16.5 System appearance

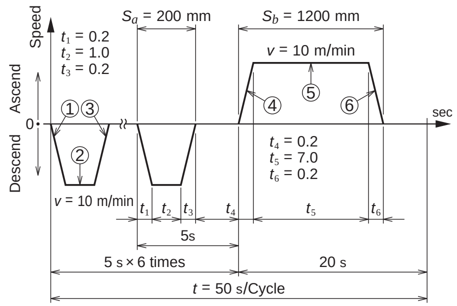

Fig. 16.6 Operating condition

2. Selection of basic factors

(1) Selection of accuracy grade

Although this application is not listed in Table 4.1 Accuracy grades of ball screw and their application on page B19, possibility is to use ball screw for transfer equipment R series, because the required repeatability is 0.3 mm that is not very high.

(2) Selection of lead

From the maximum rotational speed of AC motor:

$$l \geq \frac{V_{max}}{N_{max}} = \frac{10000}{1000} = 10 \text{ (mm)}$$

Select a lead 10 mm or over.

(3) Selection of screw shaft diameter

According to "Table 4.5 Shaft diameter, lead and standard screw length of R Series" on Page B22, the shaft diameters whose lead is 10 mm or over are in the range of 12 mm to 50 mm.

(4) Selection of stroke

From Table 4.5 Screw shaft diameter, lead and standard screw shaft length of R series on page B22, it is possible to select from R series because diameter d = 15 to 50 mm and lead l = 10 mm will meet the required maximum stroke 1500 mm.

Primary selection : R Series ball screw for transfer equipment

Screw shaft diameter :	15 – 50(mm)
Lead :	10(mm)
Stroke :	1500(mm)

3. Confirmation of standard ball screw

Select from Flanged single nuts of R Series ball screw for transfer equipment.

Second selection : R Series ball screw for transfer equipment

Screw shaft diameter :	16, 20, 25, 32, 36 40, 45, 50 (mm)
Lead :	10 (mm)
Stroke :	1500 (mm)

4. Decision of screw length

Screw length L_o is:

L_o = Stroke + nut length + margin + shaft end length

= 1500 + 100 + 100 + 200 = 1900 (mm)

Normally, $L_o/d \leq 70$ is recommended.

Therefore, screw shaft diameter d is:

$$d \geq \frac{L_s}{70} = \frac{1900}{70} = 27.1 \text{ (mm)}$$

Third selection : R Series ball screw for transfer equipment

Shaft diameter:	32, 36, 40, 45, 50 (mm)
Lead:	10 (mm)
Stroke:	1500 (mm)

5. Checking basic safety

(1) Allowable axial load

①Calculation of allowable axial load

Accelerating/decelerating time is:

$$\alpha = \frac{V}{60\,t} = \frac{10 \times 10^3}{60 \times 0.2} = 833 \text{ (mm/s}^2\text{)}$$

$$= 0.833 \text{ (m/s}^2\text{)}$$

$$t = t_1 = t_3 = t_4 = t_6$$

①, ⑥ ……$F_1 = mg - m\alpha$

$= 300 \times 9.80665 - 300 \times 0.833$

$= 2690$ (N)

②, ⑤ ……$F_2 = mg = 2940$ (N)

③, ④ ……$F_3 = mg + m\alpha = 3190$ (N)

②Buckling load

For condition in Fig. 16.7, use values below.

$P = 3190$ N, $L_1 = 1600$ mm

Bearing supporting condition is common Fixed -- Simple support.

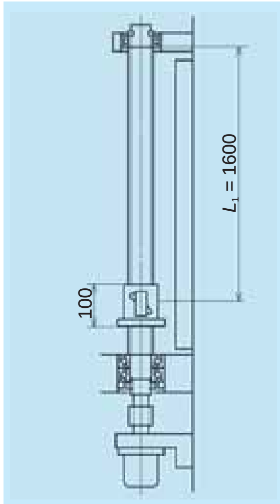

Fig. 16.7 Checking the buckling load

From Formula (Ⅱ-2) on Page B48:

$$d_r \geq \left(\frac{P \cdot L_1^2}{m} \times 10^{-4}\right)^{1/4}$$

$$= \left(\frac{3190 \times 1600^2}{10.0} \times 10^{-4}\right)^{1/4} = 16.8 \text{ (mm)}$$

(2) Checking permissible rotational speed

① Critical speed

Use values below.

$n = 1000$ (min^{-1}), $L_1 = 1600$ (mm)

From Formula (Ⅱ-7) on Page B51:

$$d_r \geq \frac{n \cdot L_1^2}{f} \times 10^{-7} = \frac{1000 \times 1600^2}{15.1} \times 10^{-7}$$

$$= 17 \text{ (mm)}$$

②$d \cdot n$ value

From Table 3.2 on Page B54:

$$d \leq \frac{50000}{n} = \frac{50000}{1000}$$

$$= 50 \text{ (mm)}$$

＊Please consult NSK if d • n > 50000 is required.

(4) Checking life (dynamic load rating)

Determine required load carrying capacity from load conditions of Table 16.9.

Table 16.9 Load conditions

Operating condition	Axial load (N)	Rotational speed (mean) (min^{-1})	Use time (s)
①, ⑥	$F_1 = 2690$	$N_1 = 500$	$t_a = 1.4$
②, ⑤	$F_2 = 2940$	$N_2 = 1000$	$t_b = 13.0$
③, ④	$F_3 = 3190$	$N_3 = 500$	$t_c = 1.4$

Calculate mean load F_m and mean rotational speed N_m from Formulas (Ⅱ-11) and (Ⅱ-12) on Page B57:

Required load carrying capacity is:

$$F_m = \left(\frac{F_1^3 \cdot N_1 \cdot t_a + F_2^3 \cdot N_2 \cdot t_b + F_3^3 \cdot N_3 \cdot t_c}{N_1 \cdot t_a + N_2 \cdot t_b + N_3 \cdot t_c}\right)^{1/3}$$

$$= 2940 \text{ (N)}$$

$$N_m = \frac{N_1 \cdot t_a + N_2 \cdot t_b + N_3 \cdot t_c}{t}$$

$$= 288 \text{ (min}^{-1}\text{)}$$

From Formulas (Ⅱ-8) and (Ⅱ-9) on Page B57:

$$C_a \geq (60N_m \cdot L_t)^{1/3} \cdot F_m \cdot f_w \times 10^{-2} \text{ (N)}$$

$$= (60 \times 288 \times 24000)^{1/3} \times 2940 \times 1.2 \times 10^{-2}$$

$$= 26300 \text{ (N)}$$

(5) Checking static load rating

$$C_{0a} = F_{max} \times f_s = 3190 \times 2$$

$$= 6380 \text{ (N)}$$

In consideration of expense:

Fourth selection : R Series ball screw for transfer equipment

Shaft diameter :	32 (mm)
Lead :	10 (mm)
Stroke :	
Turns of balls and circuit number :	2.5 × 2
Screw length :	2000 (mm)
Basic dynamic load rating :	35700 (N)

6. Selection of nut

Select a "standard nut with a flange and a seal (Brush-seals contained inside)" based on the necessity as well as on the environmental conditions.

Selected ball screw:

Nut assembly	RNFTL3210A5S
Screw shaft	RS3210A20