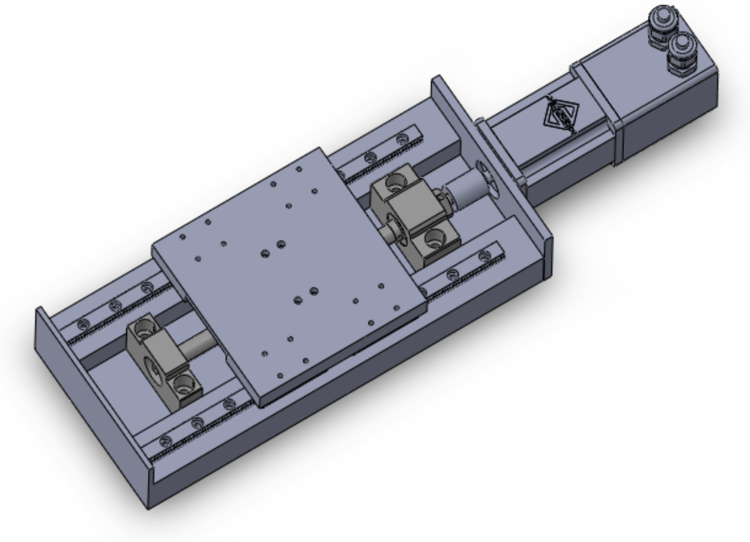
Design of Linear Micro Positioning Stage for High Speed Micro Machining Center



ME423 : Machine Design

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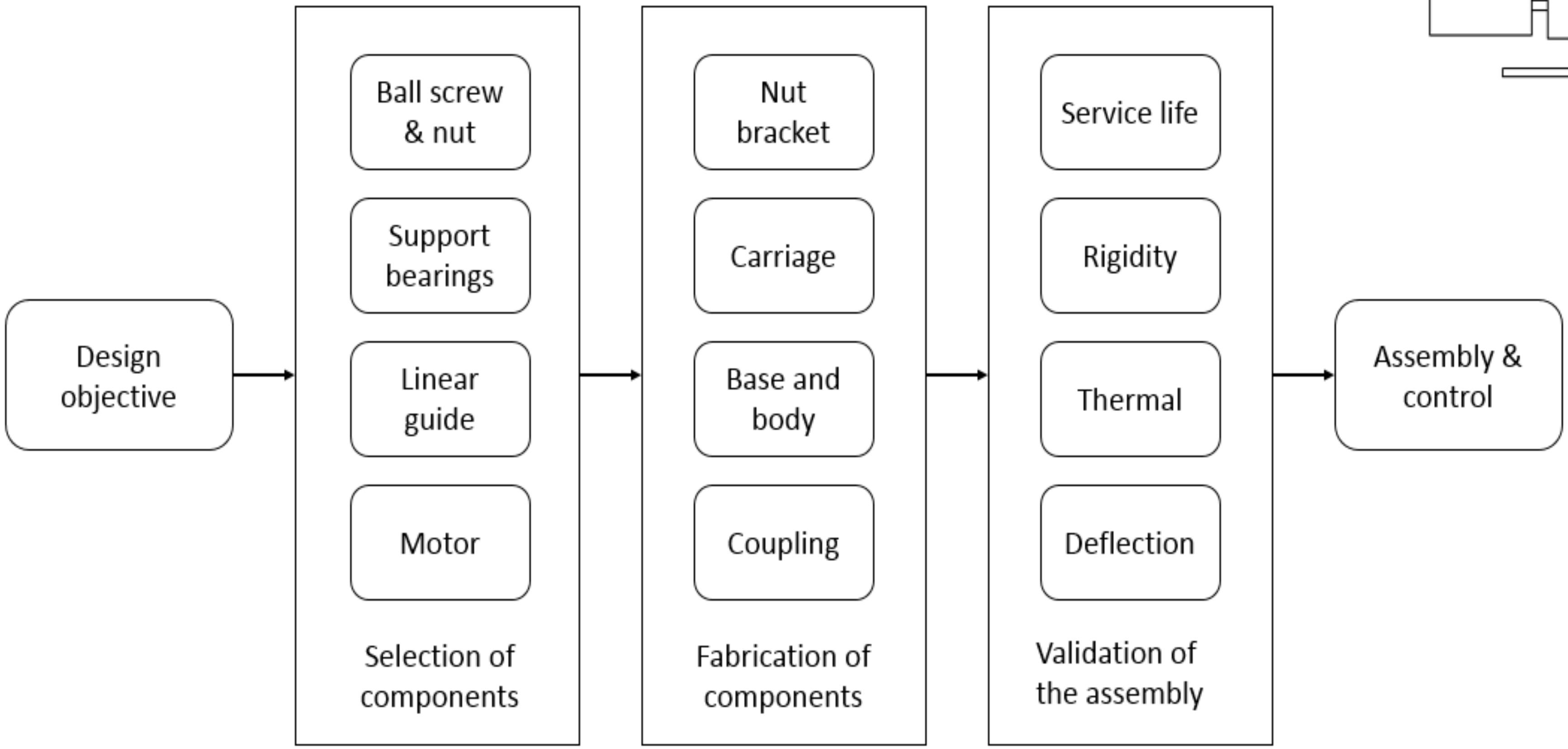
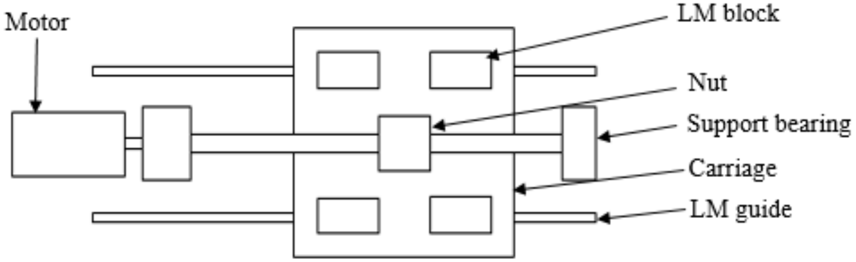
❑ Flowchart of linear stage design





❑ Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → Validation → Calculation of FOS & Service Life → Nominal life

- Accuracy: less than 2 µm
- Load capacity:

	For X stage
Horizontal	25 kg
Vertical	10 kg

↑ From Experimental machining data

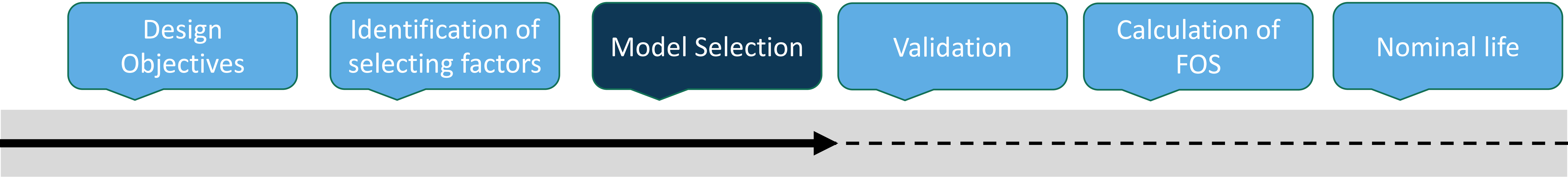
- Travel : 100mm
- Max. speed: 100 mm/s
- Resolution : 1 µm

Ball Screw Design

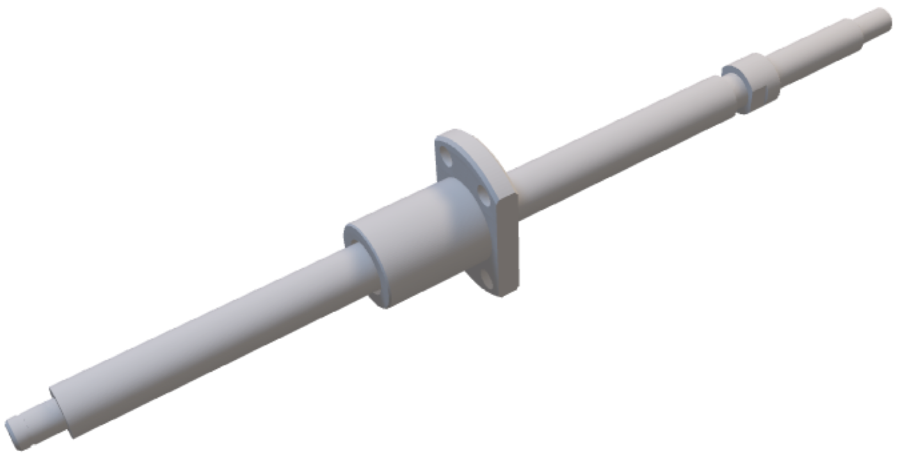
Design Objectives → **Identification of selecting factors** → Model Selection → Validation → Calculation of FOS → Nominal life

Accuracy grade of ball screw	C3 class (JIS B 1192 – 1997) (Travel distance error 8 µm and fluctuations 8 µm)
Material	1045 carbon steel
Screw shaft length	100 mm(stroke) + 35 mm (Nut length) + 70 mm (Unthreaded length)
Mounting Method	Fix-Supported mounting
Lead	$\frac{Speed \times 60}{RPM}$ Stepper motor (1500 rpm max.) Discreet and Jerky motion for 0.01 mm/s 200W AC servo motor with Max. 6000 rpm and rated rpm 3000-4000 rpm
Encoder Resolution	5000 lines/rev
Shaft diameter	10 mm

❑ Ball Screw Design



BNK 1002-3RRG0+193LC3Y



Specifications	True Value
Lead	2 mm
Stroke	100 mm
Shaft outer diameter	10 mm
Ball circle diameter	10.3 mm
Thread minor diameter	9 mm
Screw shaft length	135 mm
Total ball screw length	193 mm
Basic static load rating C_0	2.9 kN
Basic dynamic load rating C_{0a}	1.5 kN
Weight of the shaft (0.47kg/m)	0.09 kg
Weight of nut	0.045 kg
Preload torque	0.025 Nm
Rigidity value	100 N/µm

❑ Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → **Validation** → Calculation of FOS → Nominal life

1) Permissible speed criteria

- Critical speed of the screw shaft:

$$N_1 = \frac{60\times\lambda_1{}^2}{2\pi\times l_b{}^2}\times\sqrt{\frac{E\times10^3\times I}{\gamma\times A}}\times0.8\ rpm$$

$$N_1 = \lambda_1\times\frac{d_1}{l_b{}^2}\times10^7$$

74567 RPM

- DN value:

$$N_2 = \frac{70000}{D}$$

6863 RPM

l_b = Distance between two mounting surfaces (mm)

E = Young's modulus ($2.06\times105\ N/mm^2$)

$I = \frac{\pi}{64}\times d_1{}^4$

d_1 = screw – shaft thread minor diameter (mm)

λ_1 =Density (specific gravity) (7.85×10– 6kg/mm³)

A = Screw shaft cross – sectional area (mm^2)

Fixed – supported: $\lambda_1 = 3.927$, $\lambda_2 = 15.1$.

N_2= Permissible rotational speed determined by the DN value (rpm)

D = Ball center to center distance (10.3 mm)

❑ Ball Screw Design

Design Objectives | Identification of selecting factors | Model Selection | **Validation** | Calculation of FOS | CAD Model

2) Design axial loads

- Static load = 5 kg
- Machining load = F_{MH} = 50 N and F_{MV} = 100 N
- Direction change loading

$$\text{Force acting on the ball screw} = \frac{\text{change in the momentum}}{\text{time}}$$

$$= \frac{5 \times (0.100+0.100)}{0.1} = 10 \text{ N}$$

- Accelerating or decelerating loads = 10 N
- Friction force

$$F_F = \mu(mg + F_{MV}) = 0.005(50 + 100) = 0.75\ N$$

Maximum axial load = ***60.75 N***

Now, Compare maximum axial load with buckling load and maximum tensile load

❑ Ball Screw Design

Design Objectives | Identification of selecting factors | Model Selection | **Validation** | Calculation of FOS | Nominal life

2) Design axial loads

- Buckling load on the screw shaft:

$$P_1 = \frac{\eta_1 \times \pi^2 \times E \times I}{{l_a}^2} \times 0.5$$

$$P_1 = \eta_2 \times \frac{{d_1}^4}{{l_a}^2} \times 10^4 = \textbf{\textit{16200 N}}$$

Fixed – supported: $\eta_1 = 2, \eta_2 = 10$

- Permissible load on the screw shaft

$$P_2 = \sigma \times \frac{\pi}{4} \times {d_1}^2$$

$$P_2 = 116 \times {d_1}^2 = \textbf{\textit{16704 N}}$$

σ = Permissible stress (147 MPa)

❑ Ball Screw Design

Design Objectives | Identification of selecting factors | Model Selection | **Validation** | Calculation of FOS | Nominal life

3) Validation of ball screw as a rotating shaft

- Bending moment and torque criteria:

R_{1a} = 31 N, R_{2a} = 119 N and maximum BM at the center M_a = 8.1 Nm

R_{1b} = -22.1 N, R_{2b} = 22.1 N and maximum BM at the center M_b = 3 Nm

$$M = \sqrt{{M_a}^2 + {M_b}^2} = 8.5 \text{ Nm}$$

Torque varies from 0 Nm to 0.27 Nm

Plane a — Free body diagram — Plane b

Plane a — Moment diagram — Plane b

Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → **Validation** → Calculation of FOS → Nominal life

$$\text{ASME standard Modified Goodman Criteria} = d = \left\{\frac{32N_f}{\pi}\left[\frac{\sqrt{(K_f M_a)^2+\frac{3}{4}(K_{fs}T_a)^2}}{S_f}+\frac{\sqrt{(K_{fm} M_m)^2+\frac{3}{4}(K_{fsm}T_m)^2}}{S_{ut}}\right]\right\}^{\frac{1}{3}}$$

Factor of Safety = $\boldsymbol{N_f}$ **= 2**

Fatigue stress concentration factors = 1

M_a = Amplitude of moments = $\frac{8.5-(-8.5)}{2} = 8.5\ Nm$

M_m = Mean of the moments = $\frac{8.5+(-8.5)}{2} = 0\ Nm$

T_a = Amplitude of the torque = $\frac{0.27-(0)}{2} = 0.135\ Nm$

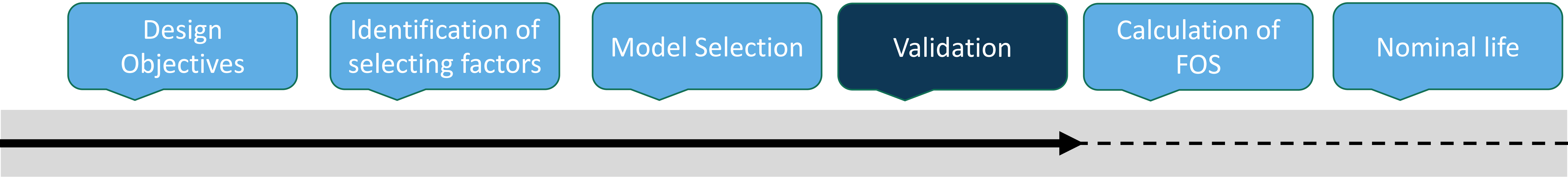
T_m = Mean of the torque = $\frac{0.27+(0)}{2} = 0.135\ Nm$

S_f = Fatigue strength = $250\times10^6\ N/m^2$

S_{ut} = Ultimate tensile strength = $565\times10^6\ N/m^2$

Minimum allowable diameter = 8.85 mm

❑ Ball Screw Design



3) Validation of ball screw as a rotating shaft

- Shear stress criteria:

Free body diagram

R_{1a} = -37.5 N, R_{1b} = 187.5 N and maximum at the position where nut is, which is V_a = 187.5 N

R_{2a} = -22.1 N, R_{2b} = 22.1 N and maximum at the position where nut is, which is V_b = 22.1 N

$$V = \sqrt{V_a{}^2 + V_b{}^2} = 188.8 \text{ N}$$

$$d = \left[\frac{4 \times N_f \times V}{\pi \times S_s}\right]^{\frac{1}{2}} = \underline{\mathbf{\textit{1.54 mm}}}$$

S_s = Ultimate shear strength = $200 \times 10^6 \; N/m^2$

❑ Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → Validation → **Calculation of FOS** → Nominal life

- Static safety factor:

$$f_a = \frac{C_{0a}}{F_a}$$

F_a = Permissible Axial Load (N) = 60.75 N

C_{0a} = Basic static load rating (N) = 2900 N

f_a = Static safety factor

Static safety factor, $f_a = \mathbf{47}$

❑ Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → Validation → Calculation of FOS → **Nominal life**

- Nominal life:

  Flaking phenomenon (raceways break from the fatigue)

  Service life v/s Nominal life

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

L = Nominal life (rev) (total number of revolutions)

C_a = Basic dynamic load rating (N)

F_{av} = Average axial load (N)

f_w = Load factor = 1.2 for considering medium vibration

❑ Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → Validation → Calculation of FOS → **Nominal life**

- Average dynamic stroke loading:

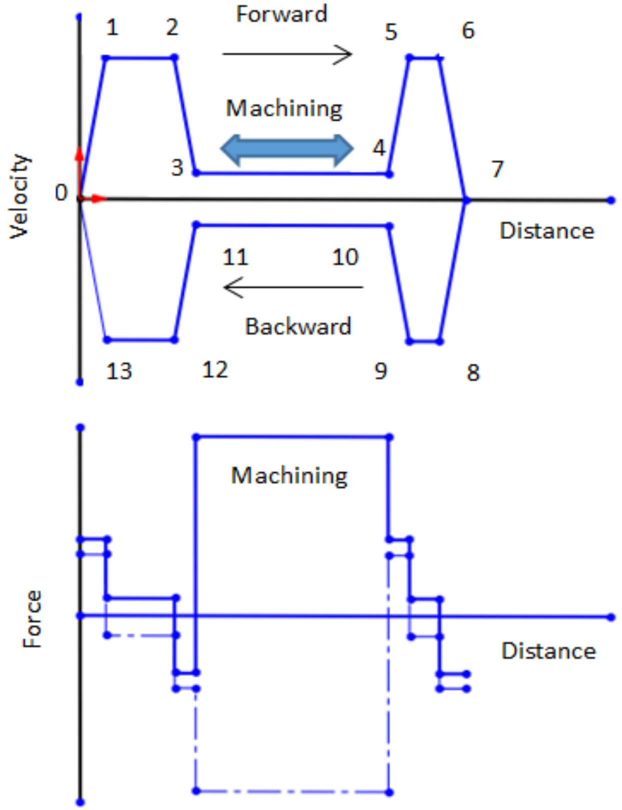
$$F_{av} = \sqrt[3]{\frac{1}{l}\left(F_{a1}{}^{3} l_1 + F_{a2}{}^{3} l_2 + \cdots + F_{an}{}^{3} l_n\right)}$$

F_{av} = Average axial load (N)

F_{an} = Varying load (N)

l_n = Distance travelled under load F_{an}

l = Total travelled distance



❑ Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → Validation → Calculation of FOS → **Nominal life**

- Average dynamic stroke loading:

$$F_{01} = F_I + F_F = 10 + 0.75 = 10.75\ N$$

$$F_{12} = F_F = 0.75\ N$$

$$F_{23} = -F_I + F_F = -10 + 0.75 = -9.25\ N$$

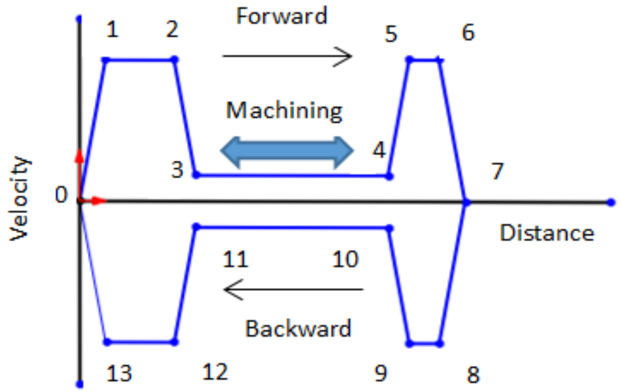
$$F_{34} = F_{MH} + F_F = 100 + 0.75 = 100.75\ N$$

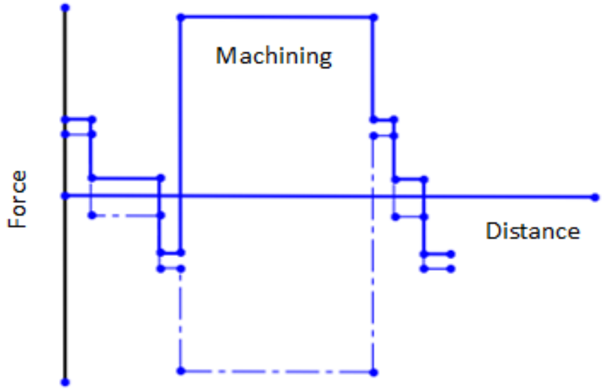
$$F_{45} = F_I + F_F = 10 + 0.75 = 10.75\ N$$

$$F_{56} = F_F = 0.75\ N$$

$$F_{67} = -F_I + F_F = -10 + 0.75 = -9.25\ N$$

Average axial force = 40.30 N





Ball Screw Design

Design Objectives → Identification of selecting factors → Model Selection → Validation → Calculation of FOS → **Nominal life**

- Nominal life:

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

$$L = 29841.1 \times 10^6 \; revolution$$

$$L_h = 16.57 \times 10^4 \; hours$$ (3000 rpm)

used for 8 hours per day, the Nominal life of the ball screw in years is 56.57 years.

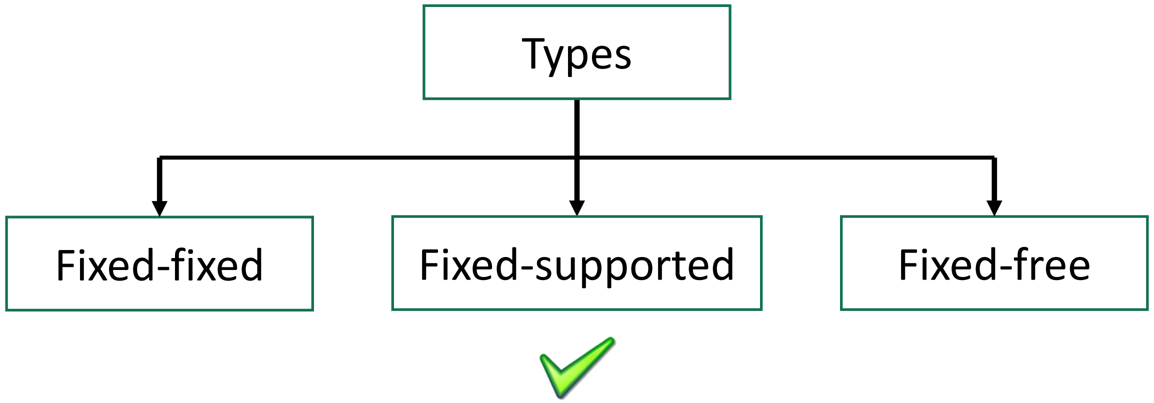
L = Nominal life (rev) (total number of revolutions)

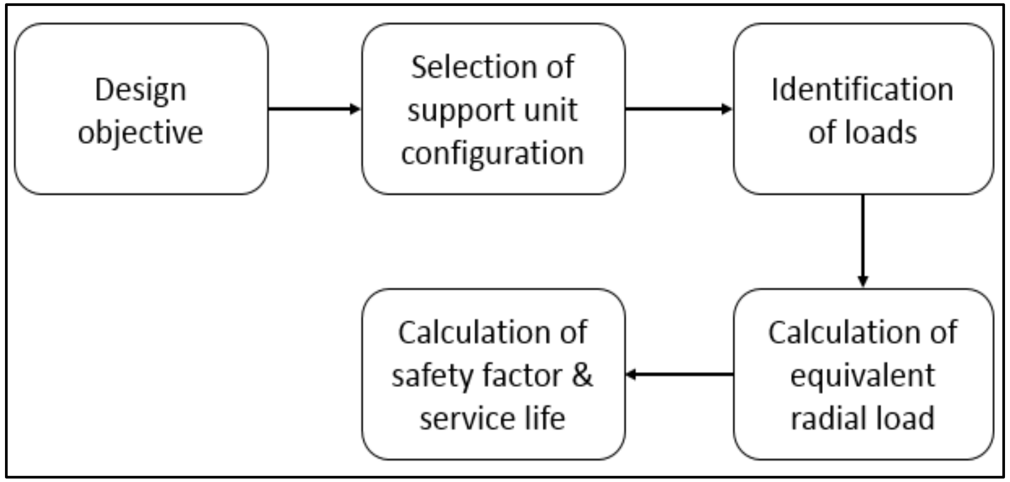
C_a = Basic dynamic load rating (N)

F_{av} = Average axial load (N)

f_w = Load factor = 1.2 for considering medium vibration

Support unit Design





❑ Support unit Design

Fixed side selected support unit :

Double row angular contact bearing

Model no: EK 8

Bearing Model: 7000 DF P5

Inner diameter: 8 mm

Basic dynamic load rating, C_a: 2.93 kN

Permissible load: 2.15 kN

Weight: 0.46 kg

Rigidity: 49 N/um

Supported side selected support unit :

Deep grove ball bearing

Model no: EF8

Bearing Model: 606ZZ

Inner diameter: 8 mm

Basic dynamic load rating, C: 2.19 kN

Basic static load rating, C0: 0.87 kN

Fatigue load limit, Pu: 0.057 kN

Reference speed: 75000 rpm

Limiting speed: 38000 rpm

Weight: 0.33 kg

Calculation factor, k_r: 0.025

Calculation factor, f_0 : 12

❑ Support unit Design

Loads and Reaction calculation

- **Loads on fixed side bearing:**

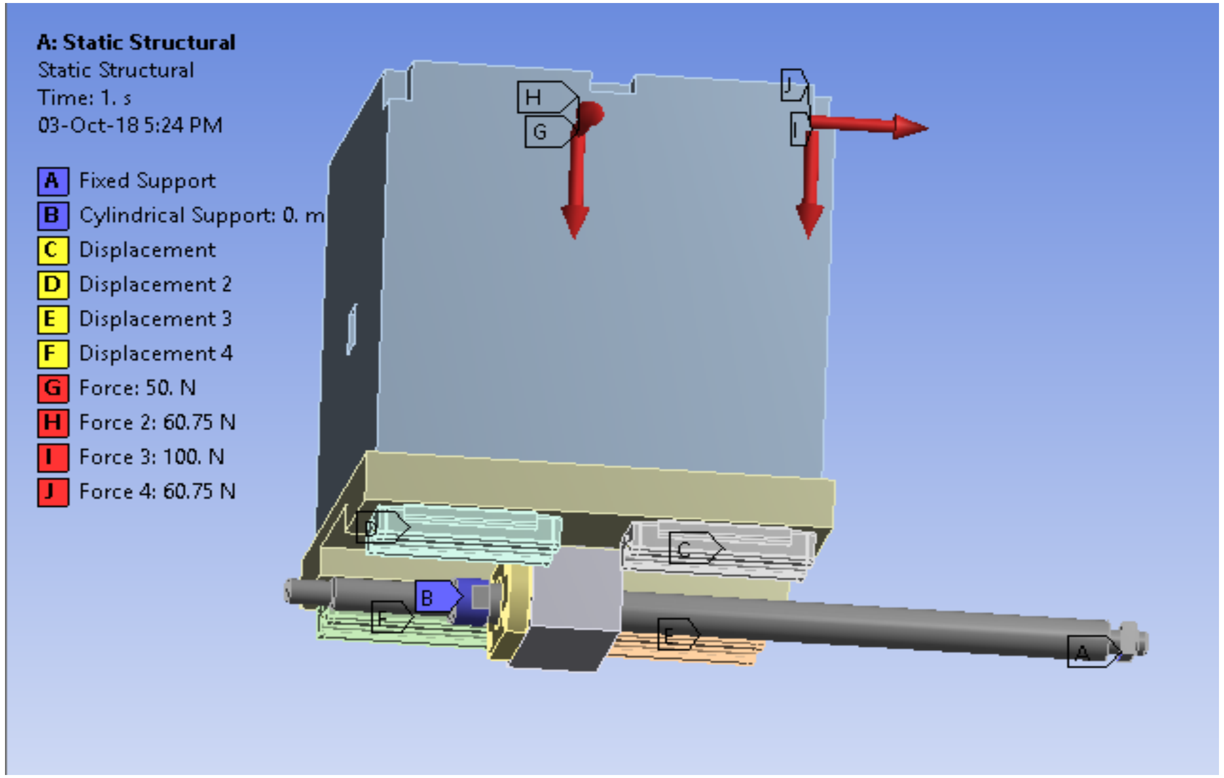
  F_x = 58.27 N

  F_y = -16.68 N

  F_z = 2.01 N

axial load, F_a = 60 N

Radial load, $F_r = \sqrt{{F_y}^2 + {F_z}^2} = 16.80$ N



❑ Support unit Design

Loads and Reaction calculation

- **Loads on supported side bearing:**

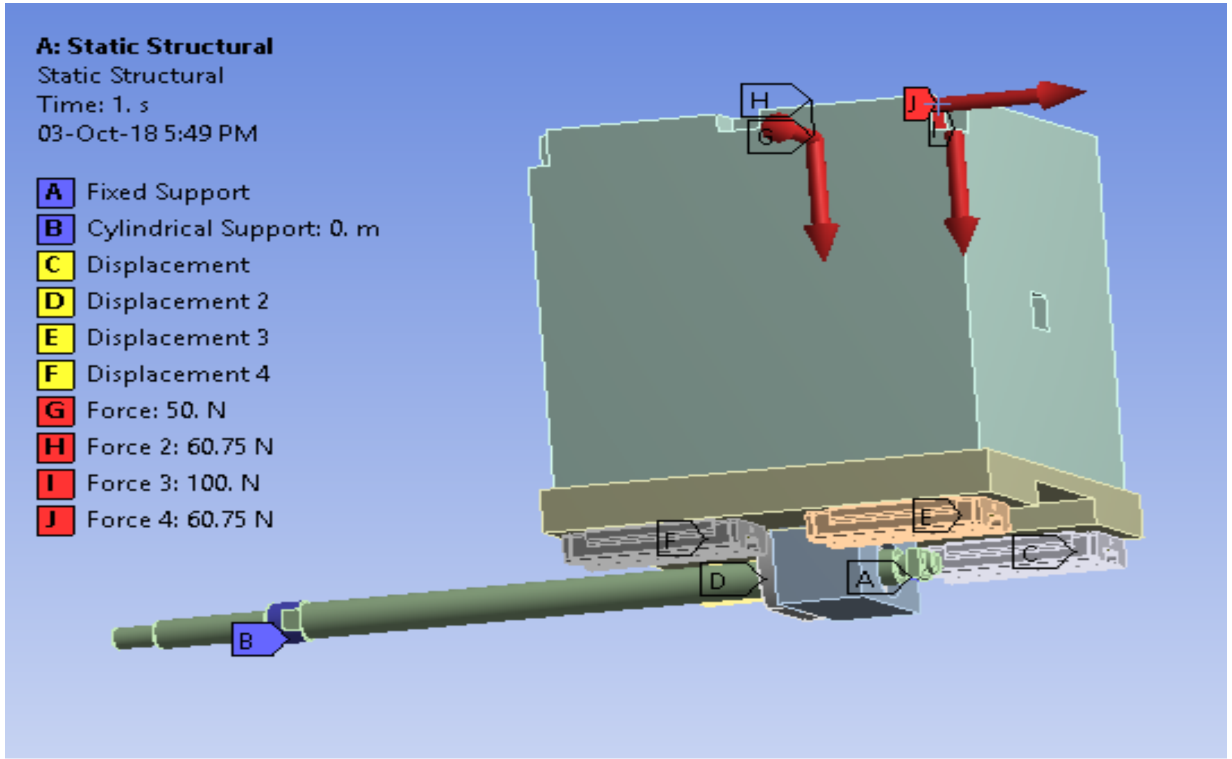
  F_x = 25.77 N

  F_y = 12.85 N

  F_z = -0.48 N

axial load, F_a = 26 N

Radial load, $F_r = \sqrt{F_y{}^2 + F_z{}^2} =$ 12.86 N



❑ Support unit Design

Fixed side bearing design

Dynamic Equivalent Load $P_e = XVP_r + YP_a$

$$\frac{F_a}{F_r} = \frac{60}{16.80} = 3.5 > 0.8$$

(From SKF catalog)

X = 1

Y = 0.78

V = 1

equivalent radial force, $P_e = 63.6\ N$

❑ Support unit Design

Fixed side bearing design

- Bearing safety factor (safety modulus)

$$f_s = \frac{C_{0r}}{P_e}$$

For the selected bearing, C_{0r} = 2150 N

Therefore, safety factor, $f_s = 33.8$

- Service life

$$L_{10} = \left(\frac{C}{P_e}\right)^3$$

L_{10} = Basic life rating

C =Basic dynamic load rating

For the selected bearing, C = 2.93 kN

$$L_{10} = 86310.23\ million\ revolution$$

$$L_{10h} = \frac{10^6}{60 \times n} \times L_{10}$$

$$L_{10h} = 47.95 \times 10^4\ hours$$

used for 8 hours per day, the Nominal life of the ball screw in years is 164 years.

❑ Support unit Design

Supporting side bearing design

From the SKF catalog,

Selection factor, f_0=12

Static load rating, C_0=1.4 kN

So, the factor, $\frac{f_0 F_a}{C_0} = 0.942$

$\frac{f_0 F_a}{C_0}$	Bearing selection factor (e)	Radial factor (X)	Axial factor (Y)
0.689	0.26	0.56	1.71
1.03	0.28	0.56	1.55

After interpolation,

e = 0.265 (bearing selection factor)

X = 0.56

Y = 1.67

Since $e < \frac{F_a}{F_r}$ ---→ $P_e = 0.56F_r + 1.67F_a$

equivalent radial load, $\mathbf{P_e = 50.62\ N}$.

❑ Support unit Design

Supporting side bearing design

- Bearing safety factor (safety modulus)

$$f_s = \frac{C_{0r}}{P_e}$$

For the selected bearing, C_{0r} = 870 N

Therefore safety factor, $f_s = 17.18$

- Service life

$$L_{10} = \left(\frac{C}{P_e}\right)^3$$

L_{10} = Basic life rating

C =Basic dynamic load rating

For the selected bearing, C = 3.35 kN

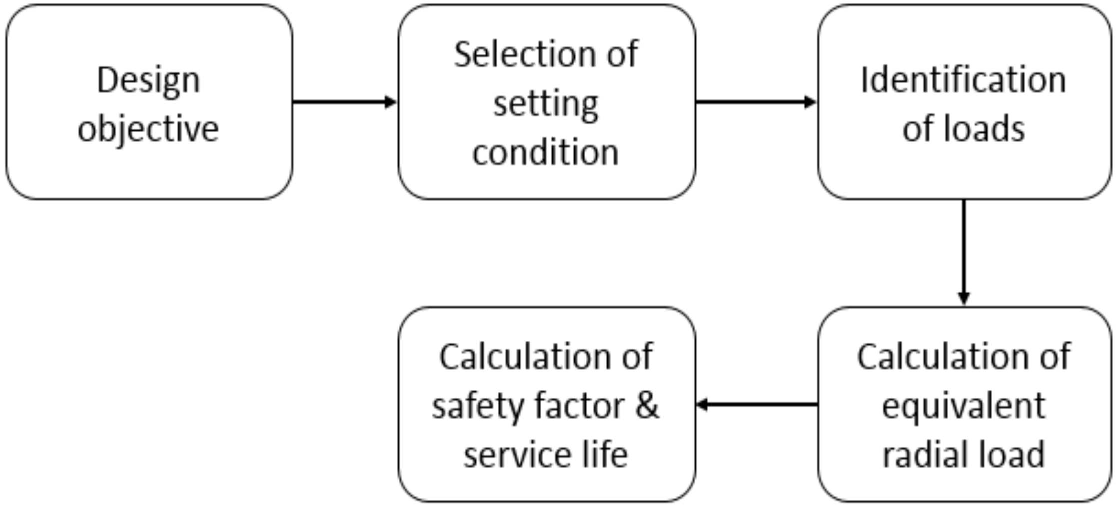
$$L_{10} = 80977.79\ million\ revolution$$

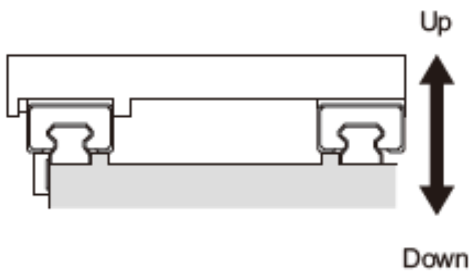
$$L_{10h} = \frac{10^6}{60 \times n} \times L_{10}$$

$$L_{10h} = 44.98 \times 10^4\ hours$$

used for 8 hours per day, the Nominal life of the ball screw in years is 154 years.

❑ Linear guide Design





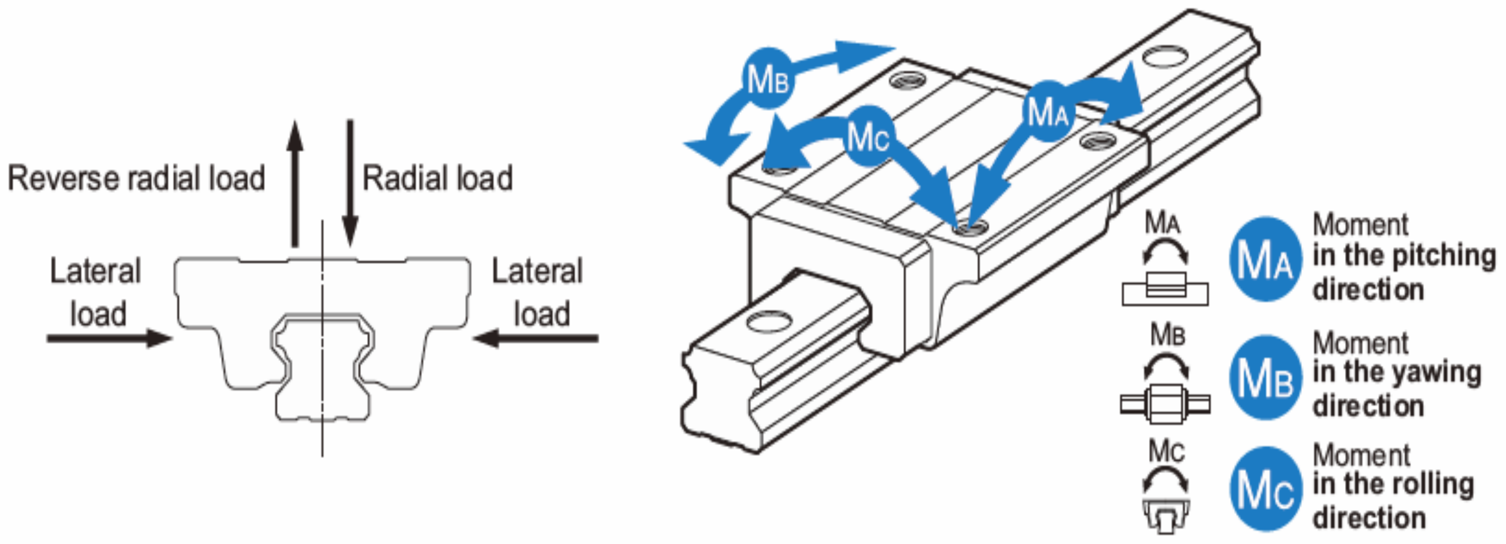
LM guide - caged ball type (miniature in size, light weight and compact)

Selected LM guide: **SRS 9XN**

Basic dynamic load rating, C_0 = 3.48 KN

Basic static load rating, C_{0a} = 3.98 KN

Linear guide Design



For designing:

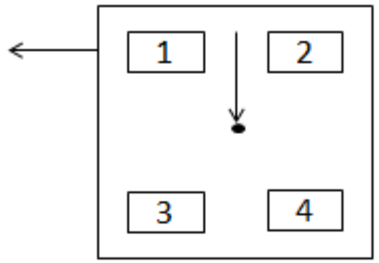
Identify maximum force acting on the LM block at any time of machining

Maximum when machining is done on the LM block

FEM analysis done for loads at different places and direction to find out highest load on LM blocks

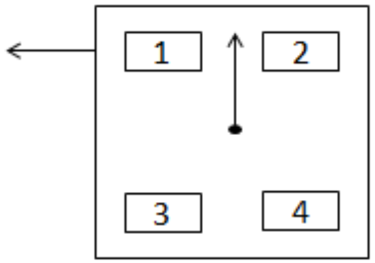
Linear guide Design

- **Maximum lateral load condition:**



	Block 1	Block 2	Block 3	Block 4
Radial load Fr (N)	110.93	-59.48	151.11	-36.07
Lateral load Ft (N)	-9.52	-3.97	-59.54	12.735

- **Maximum radial load condition:**



	Block 1	Block 2	Block 3	Block 4
Radial load Fr (N)	197.96	27.42	63.86	-122.77
Lateral load Ft (N)	20.58	25.69	-29.57	42.09

So taking maximum radial load Fr = 200 N and maximum lateral load Ft = 60 N.

❑ Linear guide Design

- **Equivalent load:**

$$P_e = XP_R + YP_T$$

P_R = Radial load (N) = 200 N

P_T = Lateral load (N) = 60 N

X, Y: Equivalent factor

For the selected guide, X=1 and Y = 0.839

Therefore, equivalent load, $P_e = \mathbf{250.16\ N}$

- **Safety factor calculation:**

When the radial load is large, static safety factor is defined by

$$\frac{F_T F_H F_C C_0}{P_R} \geq f_s$$

f_s = Static safety factor

F_C = Contact factor

F_H = Hardness factor

F_T = Temperature factor

For the selected guide, F_T=F_H=F_C=1 and static load rating,

C_0=3980 N

$$f_s \leq \frac{3980}{250.16} = \mathbf{15.9}$$

❑ Linear guide Design

- **Nominal life calculation:**

$$L = \left(\frac{f_h f_t f_c}{f_w} \times \frac{C}{P_m}\right)^3 \times 50$$

L = Nominal life (km)

C = Basic dynamic load rating (N)

P_m = Average dynamic load (N)

f_h = Hardness factor

f_t = Temperature factor

f_c = Contact factor

f_w = Load factor

Linear guide Design

- **Calculating average dynamic load:**

$$P_m = \sqrt[3]{\frac{1}{l}\left(P_{e1}{}^3 l_1 + P_{e2}{}^3 l_2 + \cdots + P_{en}{}^3 l_n\right)}$$

1. Accelerating and decelerating motion
2. Constant velocity motion
3. Machining motion

P_m = ***198.58 N***

Forces during the acceleration and deceleration:	$F_a = F_I + F_F$ = 10.75 N F_r = Weight W = 50 N P_{ra} =19 N (from Ansys) P_{ta} =3.5 N Equivalent radial load, $P_{ea} = P_{ra} + P_{ta} = 22.5\ N$
Loads during constant velocity:	$F_a = F_F$ = 0.75 N F_r = Weight = 50 N P_{rv} = 13.1 N P_{tv} = 3 N Equivalent radial load, $P_{ev} = P_{rv} + P_{tv} = 16.1\ N$
Load during machining:	P_e = 250.16 N (average machining load)

❑ Linear guide Design

- **Nominal life calculation:**

$$L = \left(\frac{f_h f_t f_c}{f_w} \times \frac{C}{P_m}\right)^3 \times 50$$

L = Nominal life (km)

C = Basic dynamic load rating (N)

P_m = Average dynamic load (N)

f_h = Hardness factor

f_t = Temperature factor

f_c = Contact factor

f_w = Load factor

$f_h = f_t = f_c = 1$

considering moderate vibrations, $f_w = 1.2$

C_{0a} = 3480 N

nominal life, **L = 155729 km**

$$\boldsymbol{L_h = 43.25 \times 10^4\ hours}$$

for 8 hours per day, the service life of the ball screw in years is 148 years.

❑ Validation of assembly

- **Service life of the system:**

Component name	Ball screw & nut (L_B)	Fixed side support (L_F)	Supported side support (L_S)	LM guide (L_L)
Service life (million revolution)	29841.1	86310.23	80977.79	77850
Service life (hours)	16.57×10^4	47.95×10^4	44.98×10^4	43.25×10^4
Service life (years)	57	164	154	148

$$\frac{1}{L} = \frac{1}{L_B} + \frac{1}{L_F} + \frac{1}{L_S} + \frac{1}{L_L}$$

$$\mathbf{L = 27.1\ years.}$$

❑ Validation of assembly

- **Rigidity of the system:**

$$\delta = \frac{F_a}{K}$$

$\delta =$ Elastic displacement of a feed screw system in the axial direction (µm)
$K =$ Axial rigidity of ball screw
$F_a =$ Applied axial load

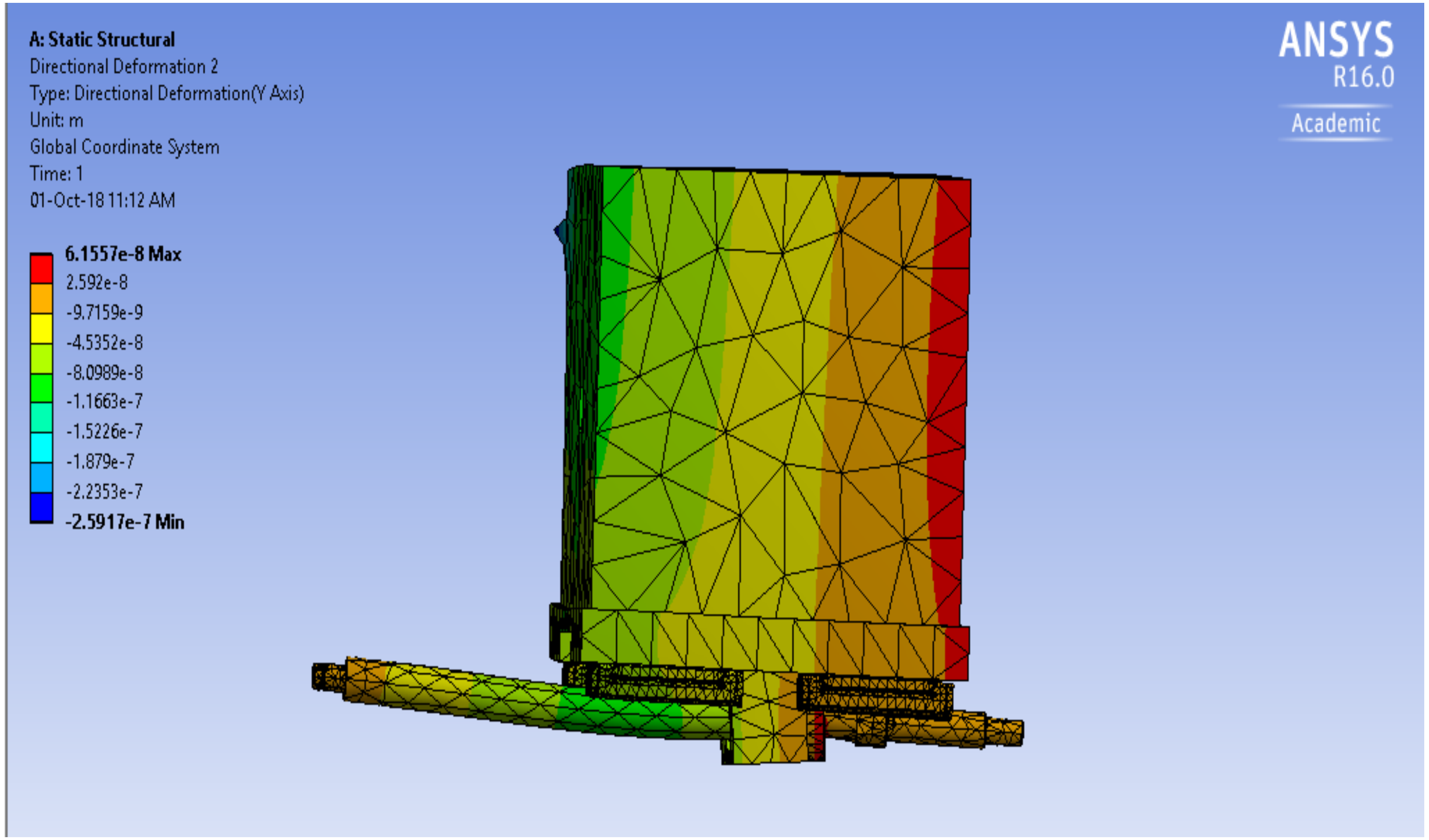
$$\frac{1}{k} = \frac{1}{k_s} + \frac{1}{k_n} + \frac{1}{k_b}$$

k = Axial rigidity of the system
k_s = Axial rigidity of screw shaft
k_n = Axial rigidity of the nut
k_b = Axial rigidity of the bearings

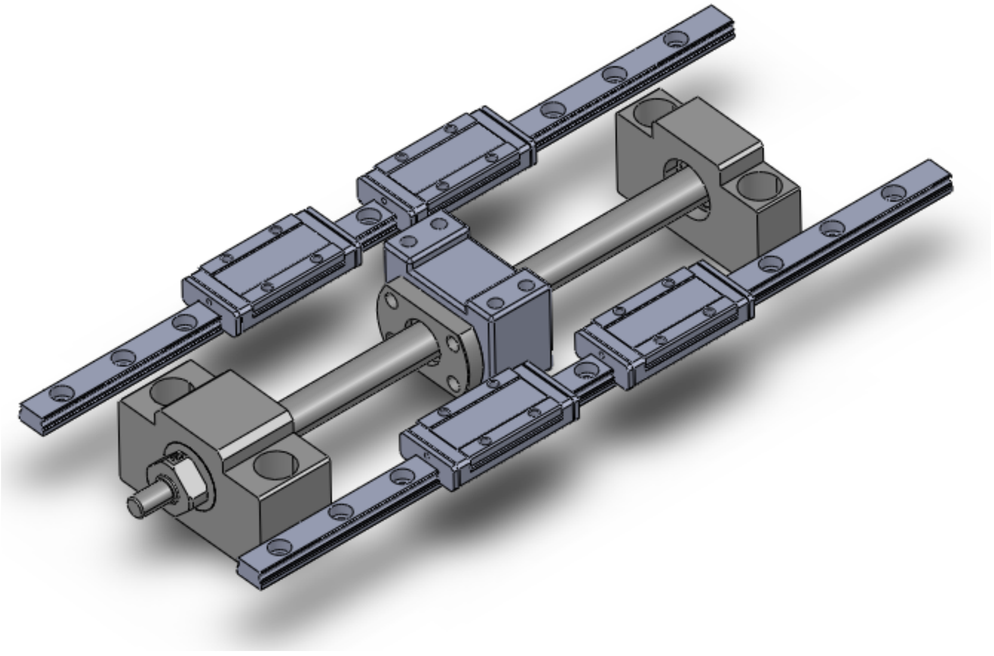
k = ***32.88 N/µm***
$\delta = \mathbf{1.84\ \mu m}$

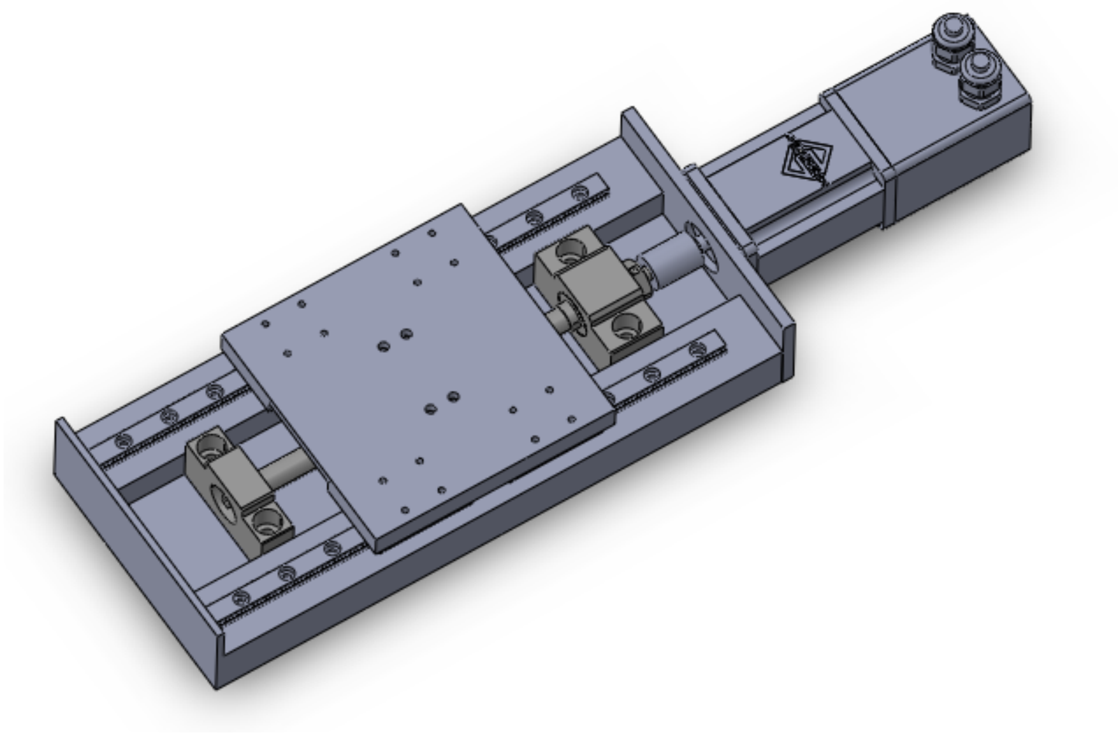
❑ Validation of assembly

- **Deflection of the system:** **(deflection is in the range of 10^{-9} to 10^{-8} m)**

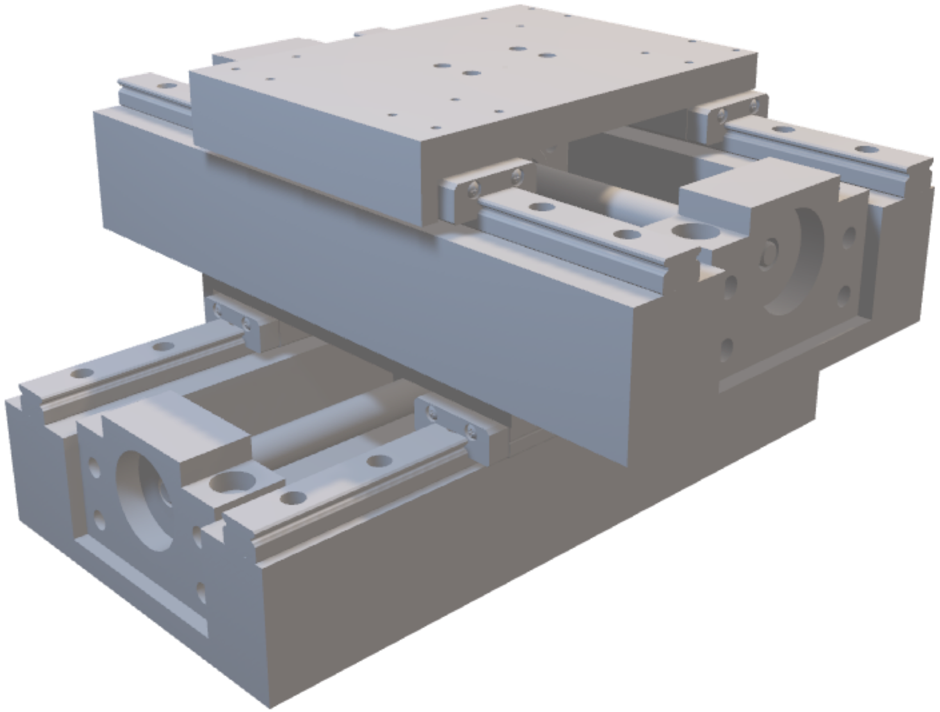


- CAD model





❑ Stacked stages CAD model



THANK YOU