BS ISO 3408-4:2006

# Ball screws —

## Part 4: Static axial rigidity

ICS 25.060.99



British Standards

# National foreword

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INTERNATIONAL STANDARD

**ISO 3408-4**

First edition
2006-06-15

# Ball screws —

## Part 4: **Static axial rigidity**

*Vis à billes —*

*Partie 4: Rigidité axiale statique*

Reference number
ISO 3408-4:2006(E)

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# Foreword

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ISO 3408-4 was prepared by Technical Committee ISO/TC 39, *Machine tools*.

ISO 3408 consists of the following parts, under the general title *Ball screws*:

— *Part 1: Vocabulary and designation*

— *Part 2: Nominal diameters and nominal leads — Metric series*

— *Part 3: Acceptance conditions and acceptance tests*

— *Part 4: Static axial rigidity*

— *Part 5: Static and dynamic axial load ratings and operational life*

# Ball screws —

# Part 4:
# Static axial rigidity

## 1 Scope

This part of ISO 3408 sets forth terms and mathematical relations relevant to the determination of the static axial rigidity of the ball screw.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3408-1:2006, *Ball screws — Part 1: Vocabulary and designation*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3408-1 apply.

## 4 Symbols and subscripts

### 4.1 Symbols

| Symbol | Description | Unit |
|---|---|---|
| $\alpha$ | Contact angle | degrees, ° |
| $\rho$ | Reciprocal curvature radius | $mm^{-1}$ |
| $\tau$ | Ratio of the semi-major to the semi-minor axes of the contact ellipse | — |
| $\varphi$ | Lead angle | degrees, ° |
| $\Delta l$ | Elastic deflection | μm |
| $c_E$ | Material constant | — |
| $c_k$ | Geometry factor | $N^{-2/3}$ μm |
| $d_{bo}$ | Diameter of the deep hole bore | mm |
| $d_c$ | Diameter of load application on the ball screw shaft | mm |
| $D_c$ | Diameter of load application on the ball nut | mm |
| $D_{pw}$ | Ball pitch circle diameter | mm |
| $D_w$ | Ball diameter | mm |
| $D_1$ | Outer diameter of ball nut | mm |

| Symbol | Description | Unit |
|---|---|---|
| $E$ | Modulus of elasticity | N/mm$^2$ |
| $f_{ar}$ | Correction factor for accuracy classes (rigidity) | — |
| $f_{al}$ | Correction factor for load application | — |
| $f_{rs}, f_{rn}$ | Conformity (ratio of ball/balltrack radius to ball diameter) of ball screw shaft and ball nut | — |
| $F$ | Axial force, load | N |
| $i$ | Number of loaded turns | — |
| $k$ | Rigidity characteristic | N/μm$^{3/2}$ |
| $l$ | Length | mm |
| $l_s$ | Unsupported length of ball screw shaft | mm |
| $m$ | Poisson's constant (e.g. for steel $m$ = 10/3) | — |
| $n$ | Rotational speed | min$^{-1}$ |
| $P_h$ | Lead | mm |
| $q$ | Time percentage | % |
| $R$ | Rigidity | N/μm |
| $s_a$ | Backlash (axial play) | μm |
| $Y$ | Auxiliary value according to Hertz for the description of the elliptic integrals of the first and second kinds | N$^{-2/3}$·μm$^{4/3}$ |
| $z_1$ | Number of effectively loaded balls per turn | — |
| $z_2$ | Number of unloaded balls in the recirculation system, only for systems where balls will be recirculated after one turn | — |

## 4.2 Subscripts

| Symbol | Description |
|---|---|
| ar | refers to accuracy |
| b | refers to ball |
| bs | refers to ball screw |
| c | refers to nut body/ball screw shaft |
| e | refers to external load or the resulting deformation respectively |
| lim | refers to limit load (at this value the contact between balls and balltracks of ball screw shaft and ball nut is eliminated) |
| m | refers to equivalent |
| N | refers to normal load which acts upon balls and balltracks of the ball screw shaft and ball nut in the direction of the contact angle |
| n | refers to ball nut |
| pr | refers to preload |
| s | refers to ball screw shaft |
| b/t | refers to ball/balltrack area |
| nu | refers to ball screw within the loaded ball nut area |
| 1 | refers to ball nut 1 |
| 2 | refers to ball nut 2 |

# 5 Determination of static axial rigidity, $R$

## 5.1 General

The static axial rigidity of a ball screw exerts a major influence on its positioning accuracy. It is a function of the design of the ball screw, its support and bearing arrangement. For the purpose of the calculation given below support and bearing arrangement have been disregarded.

The static axial rigidity of ball screws is not linear. For the purpose of the study of rigidity, a ball screw can be conceived as a combination of several linear and non-linear spring elements. For this reason the rigidity value indicated is correct only for one load application.

The deflection to be determined is caused by

— axial deflections of the screw shaft and the ball nut body,

— radial deflections of the screw shaft and the ball nut body,

— deflections of the balls and the thread land.

The calculation of the deflections attributable to the ball contact is based on the theory related to Hertz stress. The following preconditions should be met as closely as possible:

— the material of the contacting partners shall be homogenous and isotropic,

— in addition, Hooke’s law applies, i.e., no plastic deformation, and

— in the contact area only normal stress shall be acting, i.e., a level pressure surface is generated.

Moreover, the applied simplified theory of Hertz specifies identical elasticity modulus and transversal contraction parameter for the material of ball screw shaft, ball nuts and balls.

When calculating axial rigidity it is important to differentiate between ball nuts that have backlash and those that have none, i.e. preloaded ball nuts.

It is possible to generate preload by different methods:

a) **Single ball nut with continuous thread**. Preloading by oversize balls, resulting in four-point-ball-contact.

See Figure 1.

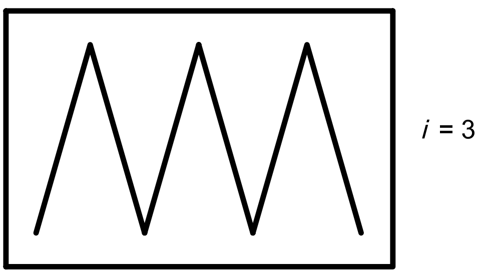



**Figure 1**

b) **Single ball nut with shifted thread between the preloaded areas**, achieving two-point-ball-contact.

See Figure 2.

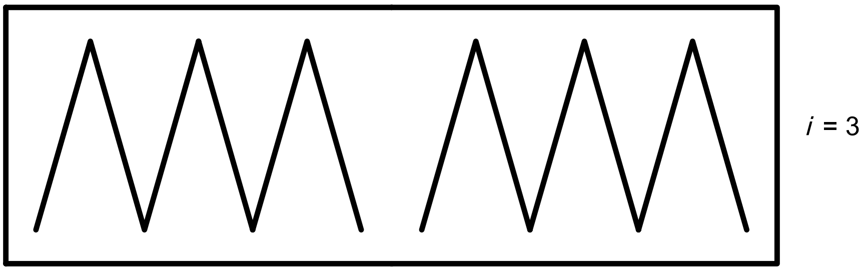



**Figure 2**

c) **Single ball nut with double start thread and shifted pitch** (two-point-ball-contact).

See Figure 3.

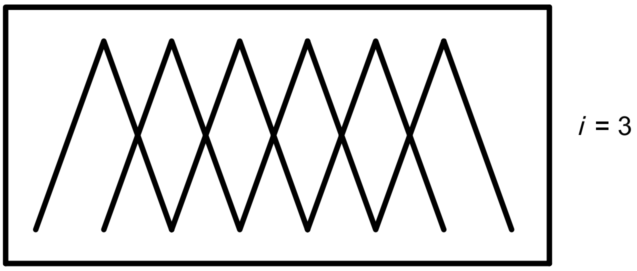



**Figure 3**

d) **Double ball nut consisting of two single ball nuts, each with continuous thread.** Axial displacement of the two single ball nuts against each other.

See Figure 4.

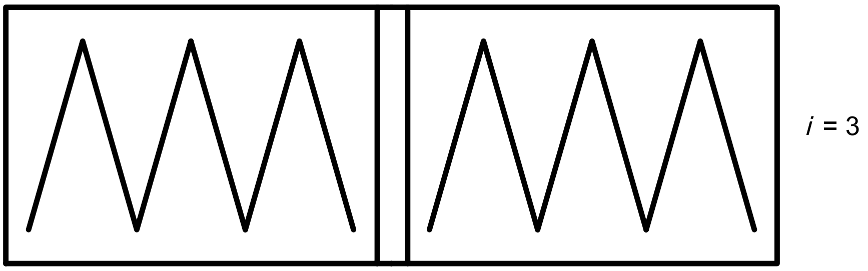



**Figure 4**

The rigidity calculation set forth in this standard can be applied to all preloading methods described.

As it is very time-consuming — and hence unsuitable for practical purposes — to determine the precise axial deflection on the basis of the corresponding formulae, a reasonably simplified calculation method is outlined below so that the calculation may be effected with a pocket calculator.

## 5.2 Static axial rigidity, $R$

The static axial rigidity, $R$, constitutes the resistance to deformation and denotes the force $\Delta F$, in newtons, which is required to effect a component deflection $\Delta l$ by 1 µm in the axial direction of load application:

$$R = \frac{\Delta F}{\Delta l} \quad (1)$$

## 5.3 Static axial rigidity of ball screw, $R_{bs}$

The overall rigidity, $R_{bs}$, is arrived at by adding the pertinent rigidity values of the components:

$$\frac{1}{R_{bs}} = \frac{1}{R_s} + \frac{1}{R_{nu,ar}} \quad (2)$$

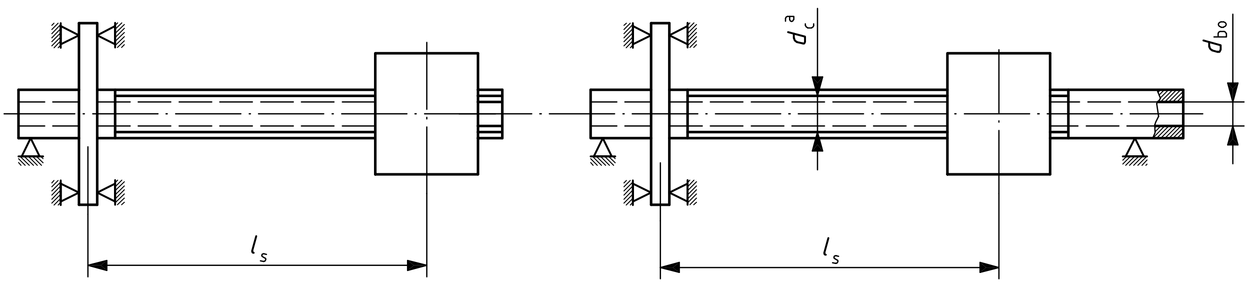
## 5.4 Static axial rigidity of ball screw shaft, $R_s$

### 5.4.1 General

The rigidity of the ball screw shaft follows from the elastic deflection of the ball screw shaft $\Delta l_s$ caused by an axial force $\Delta F$ and depends on the bearing arrangement.

### 5.4.2 Rigid mounting of ball screw shaft at one end

See Figure 5.




a) b)

a See Equation (4).

**Figure 5**

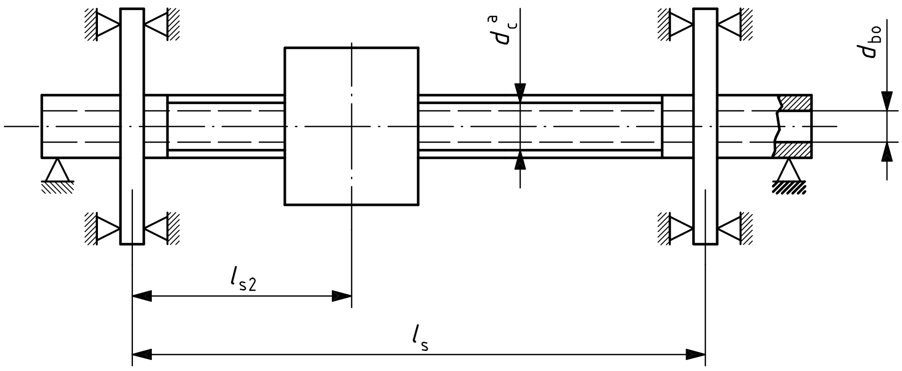
Where the rigidity is

$$R_{s1} = \frac{\pi \cdot \left(d_c^2 - d_{bo}^2\right) \cdot E}{4 \cdot l_s \cdot 10^3} \quad \text{in case of a solid shaft } d_{bo} = 0 \quad (3)$$

$$d_c = D_{pw} - D_w \cdot \cos\alpha \quad (4)$$

#### 5.4.3 Rigid mounting of ball screw shaft at both ends

See Figure 6.




a See Equation (4).

**Figure 6**

Where the rigidity is

$$R_{s2} = \frac{\pi \cdot \left(d_c^2 - d_{bo}^2\right) \cdot E}{4 \cdot l_{s2} \cdot 10^3} \cdot \frac{l_s}{l_s - l_{s2}} \tag{5}$$

the minimum of rigidity is obtained at

$$l_{s2} = \frac{l_s}{2}$$

and thus is

$$R_{s2,min} = \frac{\pi \cdot \left(d_c^2 - d_{bo}^2\right) \cdot E}{l_s \cdot 10^3} \tag{6}$$

## 5.5 Static axial rigidity of ball nut unit, $R_{nu}$

### 5.5.1 Static axial rigidity of ball nut unit with backlash, $R_{nu1}$

#### 5.5.1.1 Static axial rigidity of nut body and screw shaft under resulting radial components of load $R_{n/s}$

Determination of $R_{n/s}$:

$$R_{n/s} = \frac{\Delta F}{\Delta l_{n/s}} \tag{7}$$

$$\Delta l_{n/s} = \frac{\Delta F}{R_{n/s}} \tag{8}$$

Nut: thick-walled cylinder subjected to “internal pressure” (radial component of normal ball thrust).

Screw shaft: cylinder subjected to “external pressure” (radial component of normal ball thrust).

Premise:

— the ball screw shaft is either solid or deephole drilled;

— ball screw shaft and ball nut have the same Young’s modulus and Poisson’s ratio.

The axial rigidity of the nut body and screw shaft under this type of load is

$$R_{\text{n/s}} = \frac{2 \cdot \pi \cdot i \cdot P_{\text{h}} \cdot E \cdot \tan^2\alpha}{\left( \dfrac{D_1^2 + D_{\text{c}}^2}{D_1^2 - D_{\text{c}}^2} + \dfrac{d_{\text{c}}^2 + d_{\text{bo}}^2}{d_{\text{c}}^2 - d_{\text{bo}}^2} \right) \cdot 10^3} \tag{9}$$

where

$$D_{\text{c}} = D_{\text{pw}} + D_{\text{w}} \cdot \cos\alpha \tag{10}$$

#### 5.5.1.2 Static axial rigidity in ball/balltrack area, $R_{\text{b/t}}$

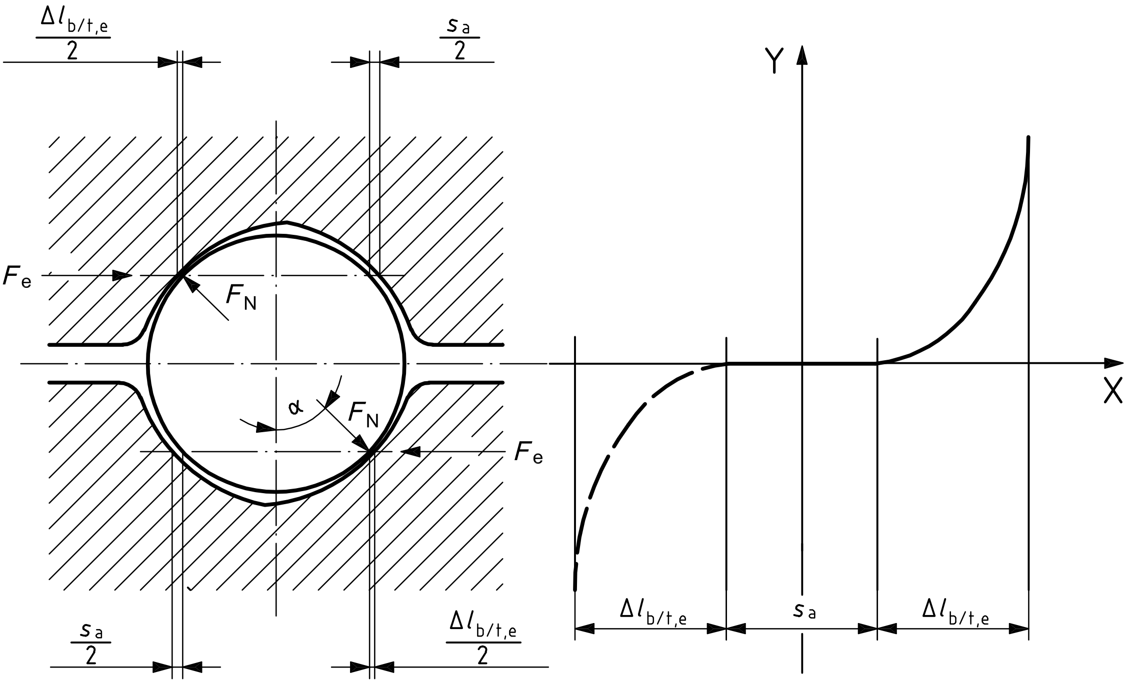
In order to simplify, the ball nut body and the screw shaft deformations have been disregarded in this calculation. The same applies to

— uneven distribution of load on the balls and threads,

— machining inaccuracies, and

— change of contact angle.

The relative displacement between ball nut and ball screw shaft due to the axial backlash has not been taken into account because it is not an elastic deflection [see Figure 7 a) and b)].




a) b)

X axial displacement between ball nut and ball screw shaft

Y external axial load, $F_e$

**Figure 7**

The extent of the axial deflection on the ball/balltrack area is a function of

— load applied,

— nominal diameter,

— ball size,

— number of loaded balls,

— conformity, and

— angle of load application.

Thus the axial deflection in the ball/balltrack area is sufficiently approximated by the following equation:

$$\Delta l_{\text{b/t}} = \frac{\Delta l_{\text{sb/t}} + \Delta l_{\text{nb/t}}}{\cos\varphi \cdot \sin\alpha} \qquad (11)$$

According to Hertz the approach of the components is calculated from:

$$\Delta l_{\text{s,nb/t}} = Y_{\text{s,n}} \cdot c_{\text{E}}^{2} \cdot \sqrt[3]{F_{\text{N}}^{2} \cdot \sum \rho_{\text{s,n}}} \qquad (12)$$

Where for the screw shaft balltrack/ball contact applies:

$$\sum \rho_{\mathrm{s}} = \frac{4}{D_{\mathrm{w}}} - \frac{1}{f_{\mathrm{rs}} \cdot D_{\mathrm{w}}} + \frac{2 \cdot \cos\alpha}{D_{\mathrm{pw}} - D_{\mathrm{w}} \cdot \cos\alpha} \tag{13}$$

For the nut balltrack/ball contact applies:

$$\sum \rho_{\mathrm{n}} = \frac{4}{D_{\mathrm{w}}} - \frac{1}{f_{\mathrm{rn}} \cdot D_{\mathrm{w}}} - \frac{2 \cdot \cos\alpha}{D_{\mathrm{pw}} + D_{\mathrm{w}} \cdot \cos\alpha} \tag{14}$$

The auxiliary values $Y_{\mathrm{s,n}}$ depend upon the ratio of the semi-major to the semi-minor axes of the contact ellipse cos $\tau$. The following equation makes use of sin $\tau$, which can be obtained by:

$$\sin\tau = \sqrt{1 - \cos^2\tau}$$

$$Y_{\mathrm{s,n}} = 1{,}282\left[-0{,}154(\sin\tau)^{1/4} + 1{,}348(\sin\tau)^{1/2} - 0{,}194\ \sin\tau\right] \tag{15}$$

$\cos\tau$ is solely conditioned by the contour of the rolling partners. It is described as follows:

$$\cos\tau_{\mathrm{s}} = \left| \frac{-\dfrac{1}{f_{\mathrm{rs}} \cdot D_{\mathrm{w}}} - \dfrac{2 \cdot \cos\alpha}{D_{\mathrm{pw}} - D_{\mathrm{w}} \cdot \cos\alpha}}{\sum \rho_{\mathrm{s}}} \right| \tag{16}$$

$$\cos\tau_{\mathrm{n}} = \left| \frac{-\dfrac{1}{f_{\mathrm{rn}} \cdot D_{\mathrm{w}}} + \dfrac{2 \cdot \cos\alpha}{D_{\mathrm{pw}} + D_{\mathrm{w}} \cdot \cos\alpha}}{\sum \rho_{\mathrm{n}}} \right| \tag{17}$$

$$c_{\mathrm{Es,n}} = \sqrt[3]{11\,550 \quad \frac{\mathrm{E}_{0\mathrm{s,n}} + E_{0\mathrm{b}}}{E_{0\mathrm{s,n}} \cdot E_{0\mathrm{b}}}} \tag{18}$$

with

$$E_{0\mathrm{s,n,b}} = \frac{E_{\mathrm{s,n,b}}}{1 - \dfrac{1}{m_{\mathrm{s,n,b}}^2}} \tag{19}$$

For ball bearing steel:

$$E_{\mathrm{s}} = E_{\mathrm{n}} = E_{\mathrm{b}} = 2{,}1 \cdot 10^5$$

$$m_{\mathrm{s}} = m_{\mathrm{n}} = m_{\mathrm{b}} = 10/3$$

$$E_{0\mathrm{s}} = E_{0\mathrm{n}} = E_{0\mathrm{b}} = E_0$$

$$c_{\mathrm{Es}} = c_{\mathrm{En}} = c_{\mathrm{Eb}} \approx c_{\mathrm{E}} = 0{,}4643$$

$$F_N = \frac{F}{i \cdot z_1 \cdot \cos\varphi \cdot \sin\alpha} \quad (20)$$

$$z_1 = \left( \frac{D_{pw} \cdot \pi}{\cos\varphi \cdot D_w} - z_2 \right)_{\text{integer}} \quad (21)$$

$$\varphi = \arctan \frac{P_h}{\pi \cdot D_{pw}} \quad (22)$$

The rigidity characteristic $k$ of one loaded turn of the ball screw is calculated from:

$$k = \frac{z_1 \cdot \sin^{5/2}\alpha \cdot \cos^{5/2}\varphi}{c_E^3 \cdot c_k^{3/2}} \quad (23)$$

and

$$c_k = Y_s \cdot \sqrt[3]{\sum \rho_s} + Y_n \cdot \sqrt[3]{\sum \rho_n} \quad (24)$$

Thus, the axial deflection due to Hertz stress exerted on a single nut can be calculated:

$$\Delta l_{b/t} = \left( \frac{F}{k \cdot i} \right)^{2/3} \quad (25)$$

$$\mathrm{d}\left(\Delta l_{b/t}\right) = \frac{2}{3} \cdot F^{-1/3} \cdot \left( \frac{1}{(k \cdot i)^{2/3}} \right) \cdot \mathrm{d}F \quad (26)$$

The static axial rigidity of the ball/balltrack area $R_{b/t}$ at the axial force $F$ is:

$$R_{b/t} = \frac{\mathrm{d}F}{\mathrm{d}\left(\Delta l_{b/t}\right)} = \frac{3}{2} \cdot \sqrt[3]{F_e \cdot (i \cdot k)^2} \quad (27)$$

This reveals the dependence of the spring rigidity on the load. The system rigidity may be increased by increasing the axial force exerted on the ball screw, e.g. by a preload force $F_{pr}$.

#### 5.5.1.3 Static axial rigidity of ball nut unit with backlash, $R_{nu1}$

$$\frac{1}{R_{nu1}} = \frac{1}{R_{b/t}} + \frac{1}{R_{n/s}} \quad (28)$$

### 5.5.2 Static axial rigidity of symmetrically preloaded ball nut unit, $R_{nu2,4}$

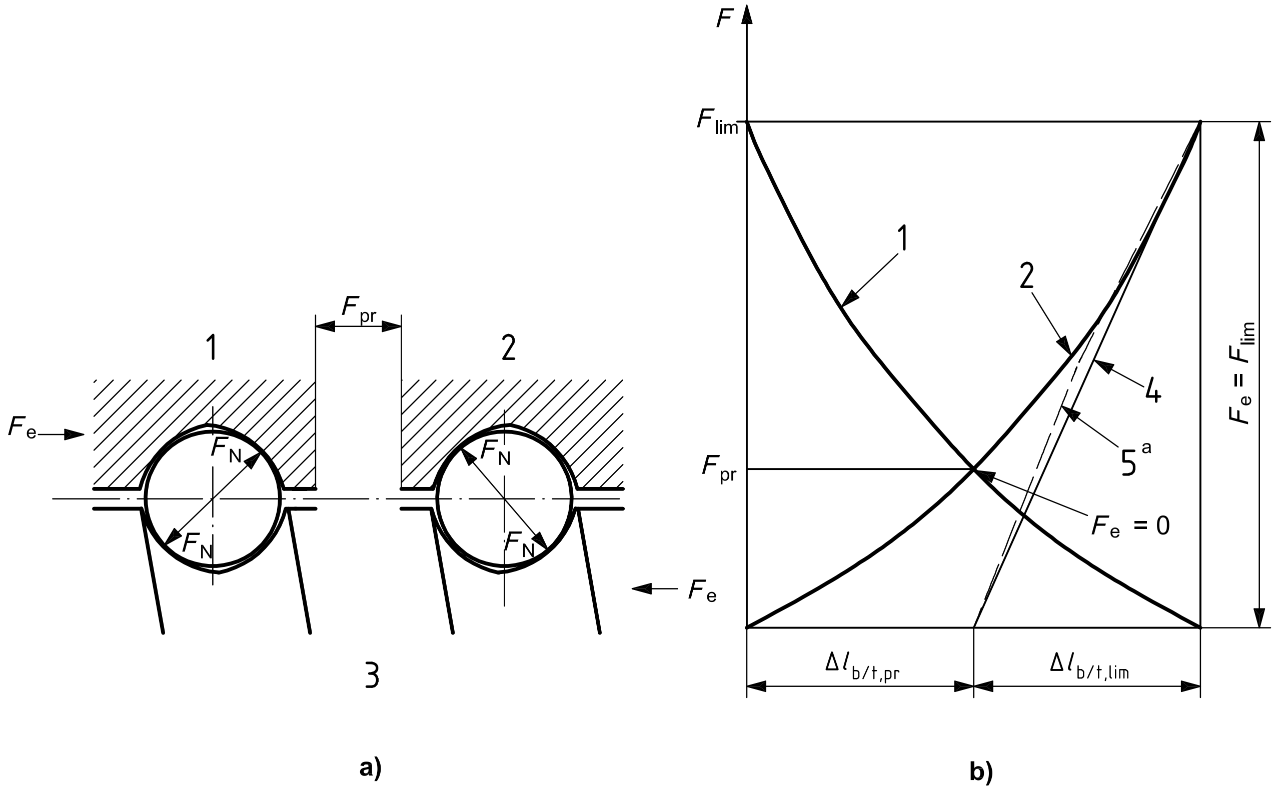
#### 5.5.2.1 Static axial rigidity of nut body and screw shaft under preload, $R_{n/s,pr}$

As both nut bodies act like preloaded rings, the rigidity, $R_{n/s,pr}$, of a double nut is twice as high as that of a single nut:

$$R_{n/s,pr} = 2 \cdot R_{n/s} \quad (29)$$

### 5.5.2.2 Static axial rigidity of ball/balltrack area under preload, $R_{n/t,pr}$ (see Figure 8)

In order to obtain high rigidity in the ball/balltrack area, nut systems are preloaded. Thus the backlash in the individual nut and the relatively large ball/balltrack deflection at low load are eliminated.




**Key**

1 ball nut 1

2 ball nut 2

3 ball screw shaft

4 straight approximation line

5 actual curve

[a] Actual curve of the axial deflection in the ball/balltrack area of the preloaded ball nut system if an additional external load between $F_c = 0$ and $F_c = F_{lim}$ is applied.

Maximum deviation between 4 and 5 is approximately 6 %.

**Figure 8**

The preload force to be applied has to be determined carefully, as excessive preload will reduce life.

The following equation will furnish a guide value for symmetric double nuts:

$$F_{pr} = \frac{F_m}{2^{3/2}} \tag{30}$$

The equivalent load $F_m$ is obtained from the following equation:

$$F_m = \sqrt[3]{\sum_{i=1}^{n} F_{ei}^3 \cdot \frac{n_i}{n_m} \cdot q_i} \tag{31}$$

The axial deflection of the ball/balltrack area due to the preload of a symmetrically preloaded nut system is calculated according to Equation (25):

$$\Delta l_{\text{b/t,pr}} = \left( \frac{F_{\text{pr}}}{k \cdot i} \right)^{2/3} \qquad (32)$$

For $0 < F_{\text{e}} \leqslant F_{\text{lim}}$, the rigidity $R_{\text{b/t}}$ in the ball/balltrack area is determined as follows:

— $\Delta l_{\text{b/t,pr}}$ for $F_{\text{pr}}$ is determined as for Equation (32),

— as there is

$$\Delta l_{\text{b/t,pr}} = \Delta l_{\text{b/t,lim}}$$

and

$$F_{\text{lim}} = 2^{3/2} \cdot F_{\text{pr}} \qquad (33)$$

— the approximation results in

$$R_{\text{b/t}} \approx \frac{F_{\text{lim}}}{\Delta l_{\text{b/t,pr}}} \qquad (34)$$

$$R_{\text{b/t}} \approx 2^{3/2} \cdot \sqrt[3]{F_{\text{pr}} \cdot (k \cdot i)^2} \qquad (35)$$

#### 5.5.2.3 Single or double ball nut preloaded by two-point-ball-contact, $R_{\text{nu2}}$

As both nut bodies act like preloaded rings, the rigidity $R_{\text{n/s}}$ of a double nut is twice as high as that of a single nut [see Equation (29)]:

$$\frac{1}{R_{\text{nu2}}} = \frac{1}{R_{\text{b/t}}} + \frac{1}{R_{\text{n/s,pr}}} \qquad (36)$$

#### 5.5.2.4 Single ball nut preloaded by four-point-ball-contact, $R_{\text{nu4}}$

The static axial rigidity $R_{\text{n/s}}$ of a nut preloaded by four-point-ball-contact is calculated according to that of a double ball nut preloaded by two-point-ball-contact:

$$\frac{1}{R_{\text{nu4}}} = \frac{1}{R_{\text{b/t}}} + \frac{1}{R_{\text{n/s,pr}}} \qquad (37)$$

### 5.5.3 Correction for accuracy, $f_{\text{ar}}$

As tolerances accumulate during the manufacturing process, differences occur in rigidity evaluations.

The correction factor takes into account the following influences:

— machining inaccuracies of balltrack (travel variations, groove, surface roughness, contact angle, diameter).

See Table 1.

**Table 1 — Correction factor for accuracy $f_{ar}$** (reference data)

| **Standard tolerance grade** | **0,1** | **3** | **5** |
|---|---|---|---|
| Factor $f_{ar}$ | 0,6 | 0,55 | 0,5 |

The static axial rigidity of the ball nut unit calculated with the corresponding correction factor is:

$$R_{nu,ar} = f_{ar} \cdot R_{nu} \quad (38)$$

# Annex A
(informative)

# Example calculation of static axial rigidity in preloaded symmetrical double nut system

## A.1 Givens

| | | |
|---|---|---|
| Ball pitch circle diameter | $D_{pw}$ | = 63,5 mm |
| Lead | $P_h$ | = 5 mm |
| Ball diameter | $D_w$ | = 3,5 mm |
| Number of loaded turns | $i$ | = 5 |
| Number of unloaded balls in the recirculation system | $z_2$ | = 3 |
| Conformity ratio of ball screw shaft and ball nut | $f_{rs}, f_{rn}$ | = 0,55 |
| Contact angle | $\alpha$ | = 45° |
| Outer diameter of ball nut | $D_1$ | = 75 mm |
| Equivalent axial load | $F_m$ | = 8 000 N |
| Preload Force | $F_{pr}$ | = 4 000 N |
| Unsupported length of ball screw shaft | $l_s$ | = 1 000 mm |
| Modulus of elasticity | $E$ | = 2,1 × $10^5$ N/mm$^2$ |
| Standard tolerance grad | | = 3 |

Ball screw shaft mounting according to Figure 2.

## A.2 Indication of screw shaft rigidity

Given: a screw shaft mounted rigidly at both ends, length $l_s$ = 1 000 mm

$$d_c = D_{pw} - D_w \cdot \cos\alpha \tag{4}$$

$$d_c = 63{,}5 - 3{,}5 \cdot \cos 45°$$

$$d_c = 61{,}03 \text{ mm}$$

According to Equation (6):

$$d_{b0} = 0$$

$$R_{s2\,min} = \frac{\pi \cdot 61^2 \cdot 21\,000}{1\,000 \cdot 10^3} = 2\,457 \text{ N/µm} \tag{6}$$

## A.3 Static axial rigidity of screw shaft and nut body $R_{n/s}$ due to resulting radial load

Given: outer diameter of ball nut $D_1$ = 75 mm, then:

$$D_c = 63{,}5 + 3{,}5 \cdot \cos 45° = 65{,}98 \qquad (10)$$

$$R_{n/s,pr} = 2 \cdot \frac{2 \cdot \pi \cdot 5 \cdot 5 \cdot 210\,000 \cdot \tan^2 45°}{\left(\frac{75^2 + 65{,}98^2}{75^2 - 65{,}98^2} + 1\right) \cdot 10^3} \qquad (9) + (29)$$

$$R_{n/s,pr} = 7\,458 \text{ N/µm}$$

## A.4 Determination of axial deflection due to preloading $\Delta l_{b/t,pr}$

Geometry factors:

$$\sum \rho_s = \frac{4}{3{,}5} - \frac{1}{0{,}55 \cdot 3{,}5} + \frac{2 \cdot \cos 45°}{63{,}5 - 3{,}5 \cdot \cos 45°} = 0{,}646\,55 \qquad (13)$$

$$\sum \rho_n = \frac{4}{3{,}5} - \frac{1}{0{,}55 \cdot 3{,}5} - \frac{2 \cdot \cos 45°}{63{,}5 + 3{,}5 \cdot \cos 45°} = 0{,}601\,94 \qquad (14)$$

$$\cos \tau_s = \left| \frac{-\frac{1}{0{,}55 \cdot 3{,}5} - \frac{2 \cdot \cos 45°}{63{,}5 - 3{,}5 \cdot \cos 45°}}{0{,}646\,55} \right| \qquad (16)$$

$$\cos \tau_s = \left| -0{,}839\,3 \right| = 0{,}839\,3$$

$$\cos \tau_n = \left| \frac{-\frac{1}{0{,}55 \cdot 3{,}5} + \frac{2 \cdot \cos 45°}{63{,}5 + 3{,}5 \cdot \cos 45°}}{0{,}601\,94} \right| \qquad (17)$$

$$\cos \tau_n = \left| -0{,}827\,4 \right| = 0{,}827\,4$$

$$Y_s = 1{,}282 \cdot \left[ -0{,}154 \cdot (0{,}543\,6)^{1/4} + 1{,}348 \cdot (0{,}543\,6)^{1/2} - 0{,}194 \cdot 0{,}543\,6 \right] \qquad (15)$$

$$Y_s = 0{,}969\,4$$

$$Y_n = 1{,}282 \cdot \left[ -0{,}154 \cdot (0{,}561\,6)^{1/4} + 1{,}348 \cdot (0{,}561\,6)^{1/2} - 0{,}194 \cdot 0{,}561\,6 \right] \qquad (15)$$

$$Y_n = 0{,}984\,5$$

$$c_E = 0{,}464\,3$$

$$z_1 = \left( \frac{63{,}5 \cdot \pi}{\cos 1{,}435\,7° \cdot 3{,}5} \right)_{\text{integer}} \qquad (21)$$

$z_1 = 54$ (rounded down)

$$\varphi = \arctan \frac{5}{\pi \cdot 63{,}5} \quad (22)$$

$$\varphi = 1{,}435\,7°$$

$$c_k = 0{,}969\,4 \cdot \sqrt[3]{0{,}646\,55} + 0{,}984\,5 \cdot \sqrt[3]{0{,}601\,94} \quad (24)$$

$$c_k = 1{,}669\,5$$

$$k = \frac{54 \cdot \sin^{5/2} 45° \cdot \cos^{5/2} 1{,}435\,7°}{0{,}464\,3^3 \cdot 1{,}669\,5^{3/2}} \quad (23)$$

$$k = 105{,}07$$

For $F_m < F_{lim}$ $\left( F_{lim} = 4\,000 \cdot 2^{3/2} = 11\,313 \text{ N} \right)$

$$R_{b/t} \approx 2^{3/2} \cdot \sqrt[3]{4\,000 \cdot (105{,}07 \cdot 5)^2} = 2\,923 \text{ N/µm} \quad (35)$$

## A.5 Rigidity $R_{nu,ar}$ of ball screw/ball nut system over loaded area

$$R_{nu,ar} = \frac{2\,923 \cdot 7\,458}{2\,923 + 7\,458} \cdot 0{,}55 = 1\,155 \text{ N/µm} \quad (36) + (38)$$

Overall rigidity $R_{bs}$:

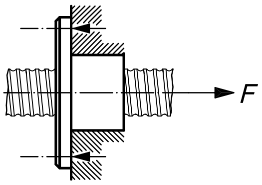
$$\frac{1}{R_{bs}} = \frac{1}{2\,457} + \frac{1}{1\,155} \quad (2)$$

$$R_{bs} = 785{,}7 \text{ N/µm}$$

# Annex B
(informative)

## Correction for load application, $f_{al}$

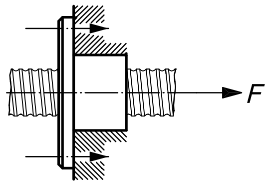
The correction load application factor, $f_{al}$, given in Table B.1, takes into account different loadings as shown in Figures B.1 a) and b) and B.2 a) and b).




Screw shaft — Tensile condition

Nut sleeve — Tensile condition

**a) T-T loading condition**

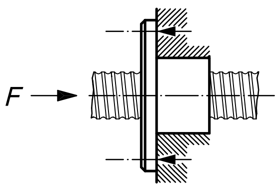



Screw shaft — Compressive condition

Nut sleeve — Compressive condition

**b) C-C loading condition**

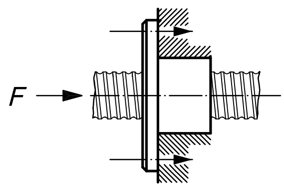
**Figure B.1**




Screw shaft — Compressive condition

Nut sleeve — Tensile condition

**a) T-C loading condition**




Screw shaft — Tensile condition

Nut sleeve — Compressive condition

**b) T-C loading condition**

**Figure B.2**

**Table B.1 — Correction factor for load application** $f_{al}$ (reference data)

| **Load application** | **T-T loading<br>C-C loading** | **T-C loading** |
|---|---|---|
| Factor $f_{al}$ | 0,9 | 0,7 |

The correction factor for accuracy will be modified to the values according to Table B.2.

**Table B.2 — Modified correction factor for accuracy $f'_{ar}$ (reference data)**

| **Standard tolerance grade** | **0, 1** | **3** | **5** |
|---|---|---|---|
| Factor $f'_{ar}$ | 1,0 | 0,9 | 0,8 |

The static axial rigidity of the ball nut unit with the correction factor is then:

$$R_{nu,ar} = f_{al} \cdot f'_{ar} \cdot R_{nu}$$

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