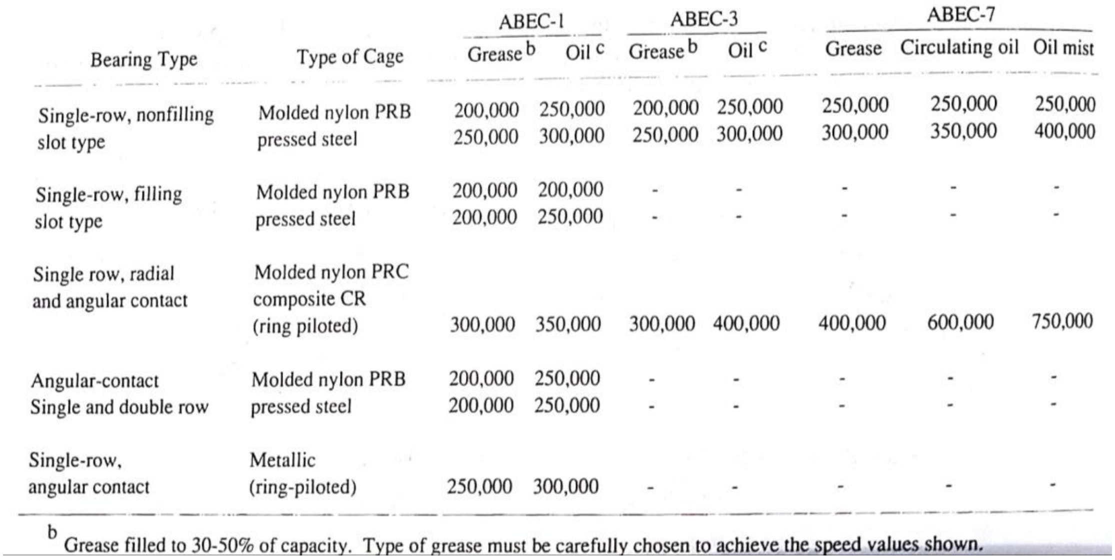
Precision Machine Design- Rolling Bearing

There are two types of rolling bearing: rolling bearing for rotary motion, and rolling bearing for linear motion

1. Rolling element for rotary motion bearing

Almost all rotating components need rolling bearings, and the following shows typical ball bearing and roller bearing for rotary motion bearings.



Bearing Type	Type of Cage	ABEC-1		ABEC-3		ABEC-7		
		Grease[b]	Oil[c]	Grease[b]	Oil[c]	Grease	Circulating oil	Oil mist
Single-row, nonfilling slot type	Molded nylon PRB	200,000	250,000	200,000	250,000	250,000	250,000	250,000
	pressed steel	250,000	300,000	250,000	300,000	300,000	350,000	400,000
Single-row, filling slot type	Molded nylon PRB	200,000	200,000	-	-	-	-	-
	pressed steel	200,000	250,000	-	-	-	-	-
Single row, radial and angular contact	Molded nylon PRC composite CR (ring piloted)	300,000	350,000	300,000	400,000	400,000	600,000	750,000
Angular-contact Single and double row	Molded nylon PRB	200,000	250,000	-	-	-	-	-
	pressed steel	200,000	250,000	-	-	-	-	-
Single-row, angular contact	Metallic (ring-piloted)	250,000	300,000	-	-	-	-	-

[b] Grease filled to 30-50% of capacity. Type of grease must be carefully chosen to achieve the speed values shown.

(source: Slocum's precision machine design and The Torrington Company)

DN speed values for ball brg

Each bearing type has DN speed value that is bore diameter in D[mm] X N[rpm] for various operating conditions, and it limits the maximum velocity of bearing in operation. Typically, 200,000-750,000 from grease, oil, circulating oil, to oil mist

Equivalent radial load, Fe

$Fe=K\omega KrFr+KaFa$

Where $K\omega$=rotation factor

=1 for rotating inner ring,

=2 for outer ring

Kr=radial load factor=1

Ka=axial load factor=1.4 for radial contact ball brgs,

=1.25 for shallow angular contact brg

=0.75 for steep angle angular contact brg

Load-Life equation

$La=a_1a_2a_3(C/Fe)^\gamma$

where La=millions of revolution

a_1=1.0 for 10% probability of failure

a_2=material factor

=1.0 for steel brgs, 3.0 for brgs with plated races

a_3=lubrication factor=1.0 for oil mist

C=Basic dynamic load ratings from catalogue

Fe=Equivalent radial load

γ=3 for balls, 10/3 for rollers

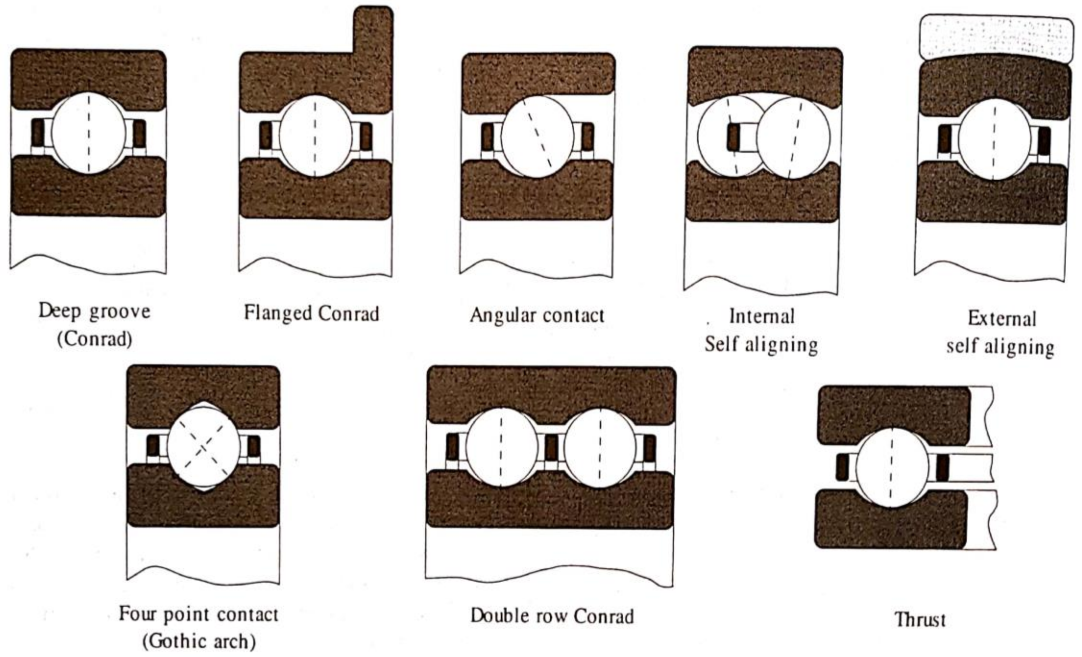
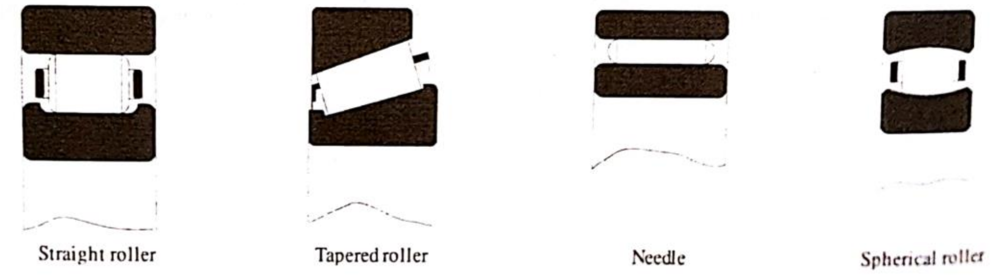


Figure 8.3.1 Typical ball bearing configurations for rotary motion bearings.



Ball and Roller bearings configurations

(source: Slocums' precision machine design)

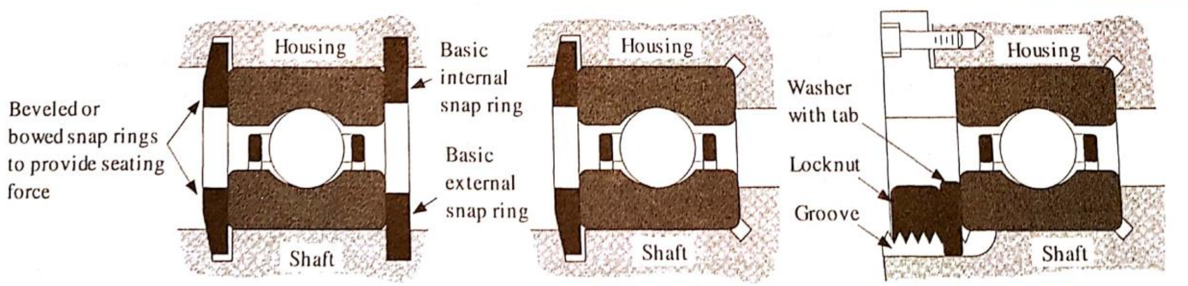
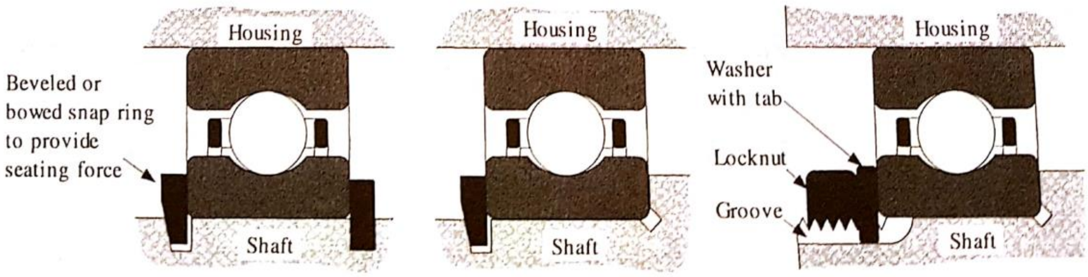


Figure 8.4.1 Methods for mounting Conrad bearings with full axial restraint in a bore and on a shaft.



Methods of mounting for ball bearings

(source:Slocum's precision machine design)

For rolling element bearings;

1) Radial contact brgs

Two types of radial contact brgs;

Shallow groove brg:

large radius of curvature, high radial stiffness with relatively lower axial stiffness

Deep groove brg:

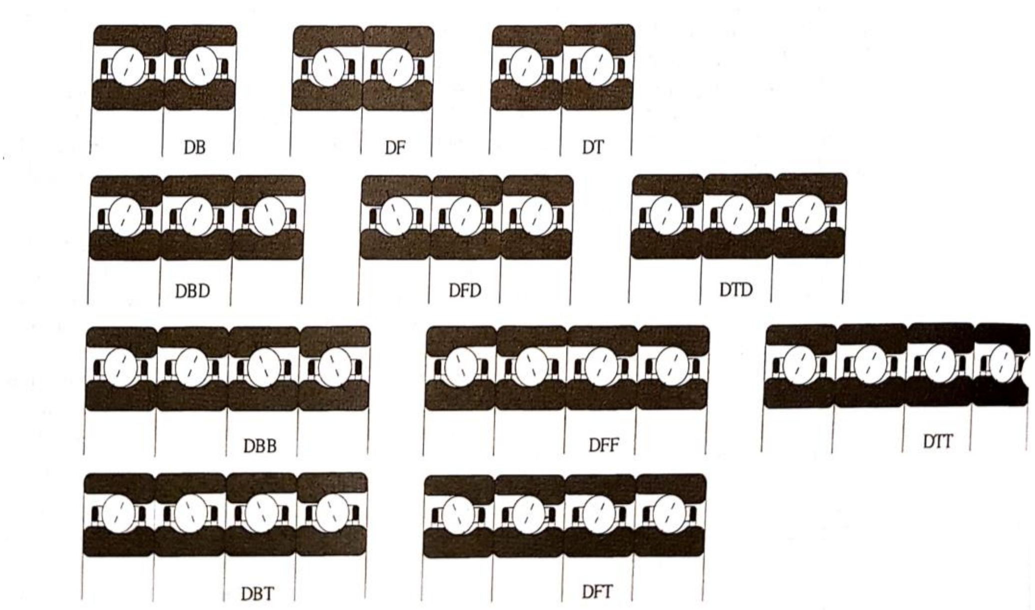
small radius of curvature, called Conrad brgs, very high radial stiffness with fairly high axial stiffness

Figs show the method of mounting for radial contact brgs. Full axial constraint on the shaft and axial freedom in the bore is a typical example for the thermal growth consideration.

Chamfers also help for the moderate stress concentration at the corners.

2) Angular contact brgs

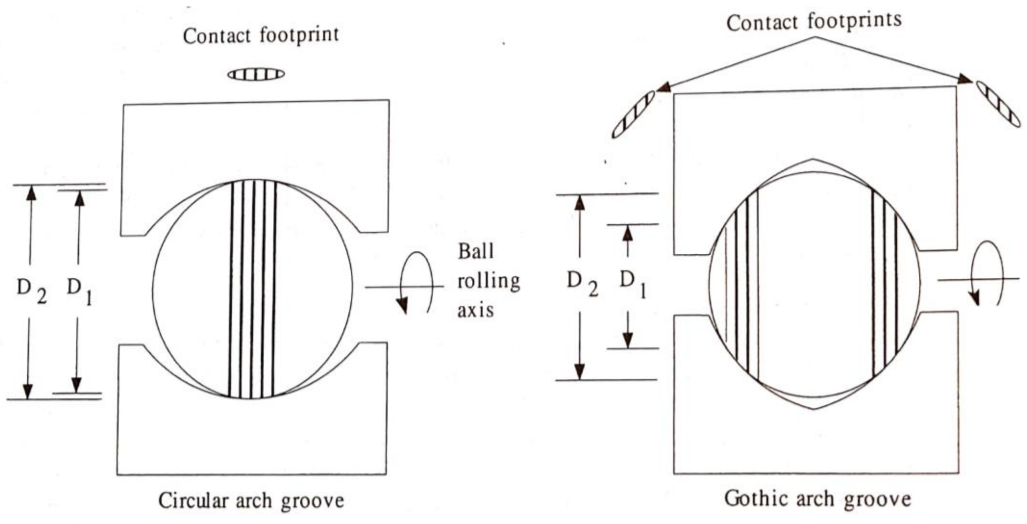
Balls contact to the races with inclination angle, in order to give high radial load capacity and thrust load capacity in one direction. For bidirectional thrust load, a second brg facing the opposite way is needed. Duplex, triplex, or qualdplex sets of angular contact brgs are used to give higher radial stiffness and higher thrust stiffness in a small space such as for main spindle of machine tools. Several possible configurations are shown in the fig.



Variable configurations for angular contact bearings (source:Slocum's precision machine design)

3) Four-points contact brgs

Contact brgs having Gothic arch shape groove in the inner and outer races; two points contact to inner race, two points contact to outer race, thus giving 4 points contact brg. This brg gives high radial, axial, and moment loads, and are conveniently can be used in robots or rotary turn tables under space constraints. Fig shows the circular arch groove and the Gothic arch groove, where the Gothic arch experiences higher stiffness but with more slips than the circular arch.



Circular arch groove and Gothic arch groove

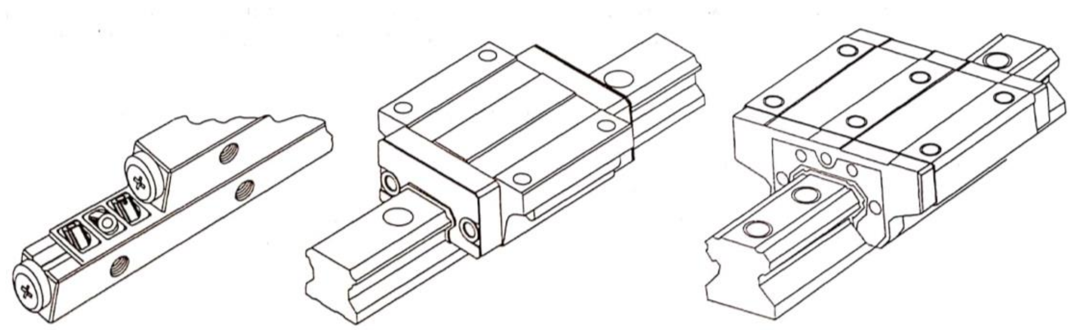
(source:Slocum's precision machine design)

4) Roller and needle brgs

Cylinders are rolling between cylindrical races, and very high radial stiffness can be achieved via the line contact on the cylinder. Straight roller brgs for very high radial load and tapered roller brgs are for high axial loads as well as high radial loads. Coupled use of the straight roller and tapered roller can give very high moment load capacity. Heavily loaded shafts in cars or heavy duty spindles in machine tools are typical examples.

2. Rolling element for linear motion brgs

Linear motion rolling brgs are among the most important elements, as shown in figs.



Nonrecirculating roller bearing Recirculating ball bearing Recirculating roller bearing

Various rolling element for linear motion bearing

(source:Slocum’s precision machine design)

Load-life equation for rolling balls in linear motion

$L=50(C/fwFc)^3$ in [Km]

Where C=basic dynamic load under which 90% of brgs will support while traveling a distance of 50Km

Fc=applied load

fw=service factor

=1.0-1.5 for smooth operation w/o impact or vibration (e.g. semiconductor equipments)

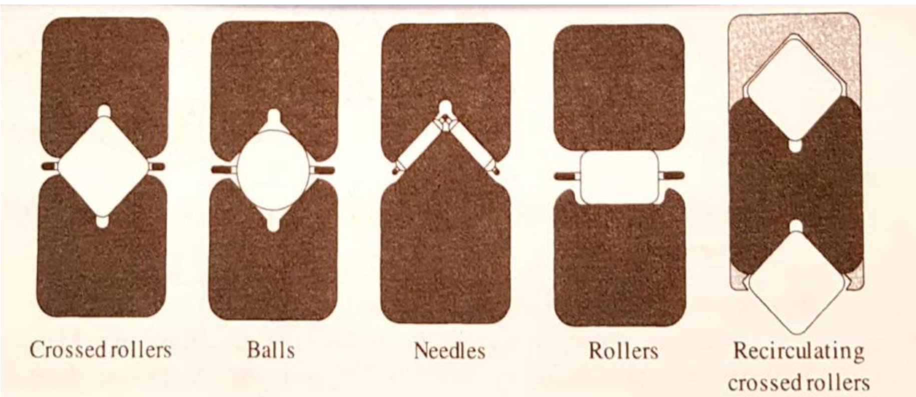
=1.5-2.0 for normal operation (e.g. CMM)

=2.0-3.5 under impact or vibration loads (e.g. machine tools)

The following figures show typical examples for the precision linear motion.

1) Non-recirculating ball or rollers in grooved rails

Various types of non-circulating ball or roller brgs in grooved rails are shown in the fig. When preloaded against each other, vertical horizontal and moment load can be withstood.



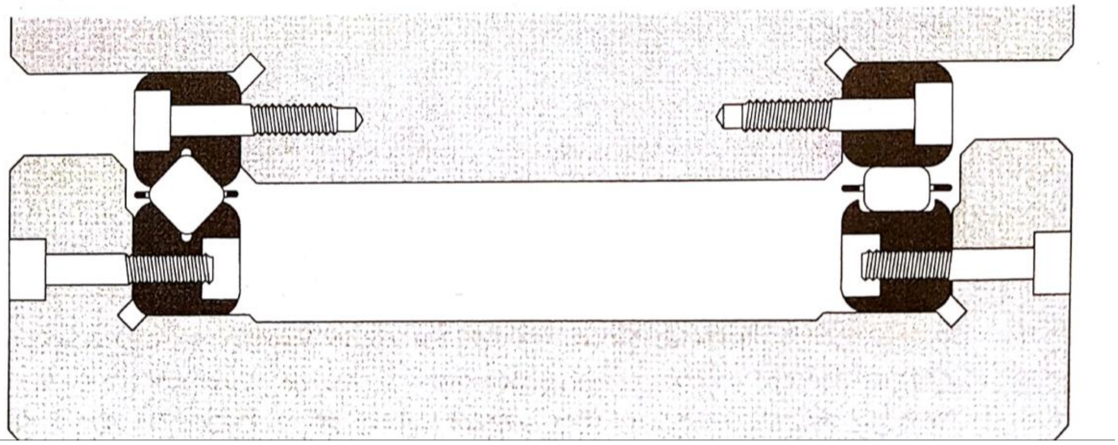
Noncirculating ball or roller bearings

(source:Slocum's precision machine design)

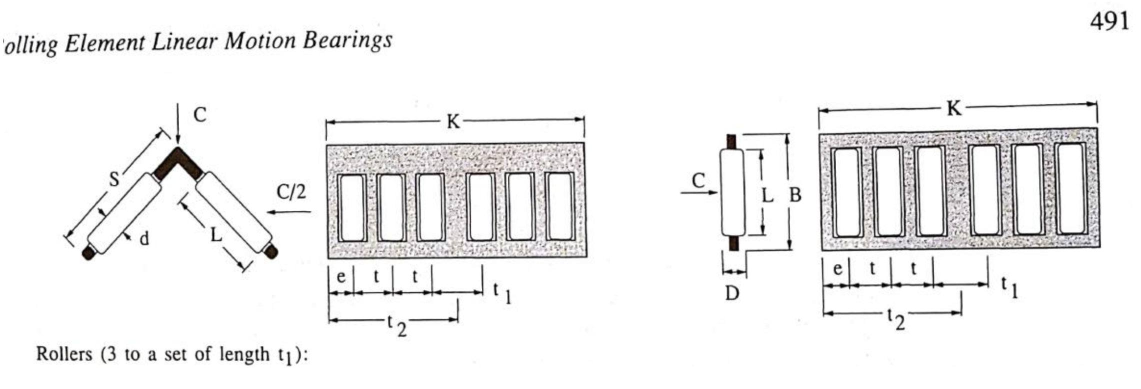
2) Rollers on Flat rail

Wherever a sliding bearing is used for linear motion, rollers in a cage with rolling on a flat rail can be used in such as T carriage, Dovetail, double V, and V and flat configurations.

The kinematic design is also possible with cross roller brgs and rollers on flat rails and some commercial modular non-circulating roller bearings are available.



Kinematic design with cross roller bearing and roller bearing (source:Slocum's precision machine design)

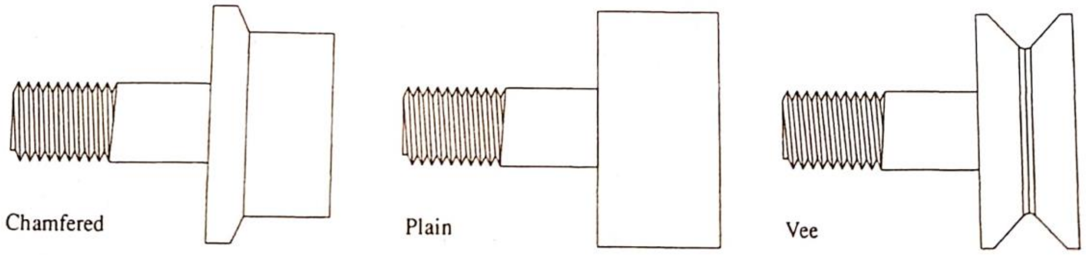


Commercial noncircular modular bearing

(source:Slocum's precision machine design)

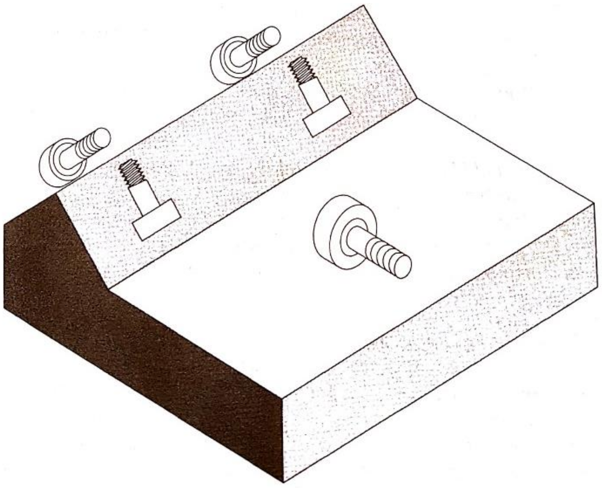
3) Cam followers; or wheel on rails as rotary motion brgs

The cam follower or wheels on rails can be a good rolling bearing. Fig shows various types of cam follwers, and kinematic configuration is also shown.



Various cam followers

(source:Slocum's precision machine design)

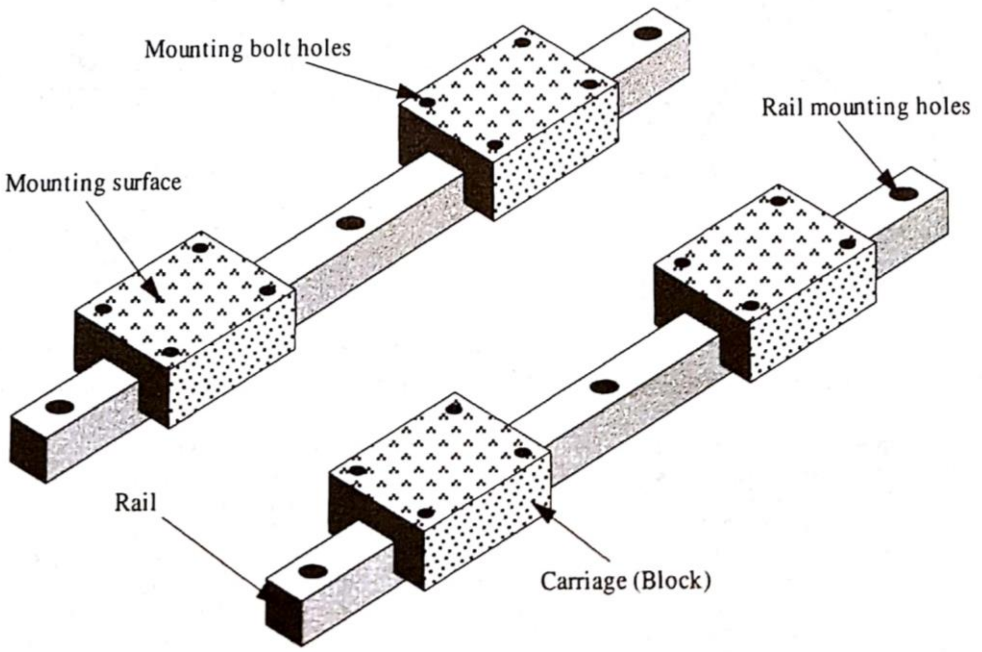


Kinematic design with rollers on V and Flat

(source:Slocum's precision machine design)

4) Linear motion guides

Linear motion guide consists of rectangular cross sectioned rail and rectangular box shaped carriage containing passages for recirculating balls. Two rails and four carriages are used for an axis motion, and this linear guides replacing the sliding contact linear bearings in many application, as it can provide heavier load capacity with larger sizes than before.



Typical linear motion guide bearing system

(source:Slocum's precision machine design)

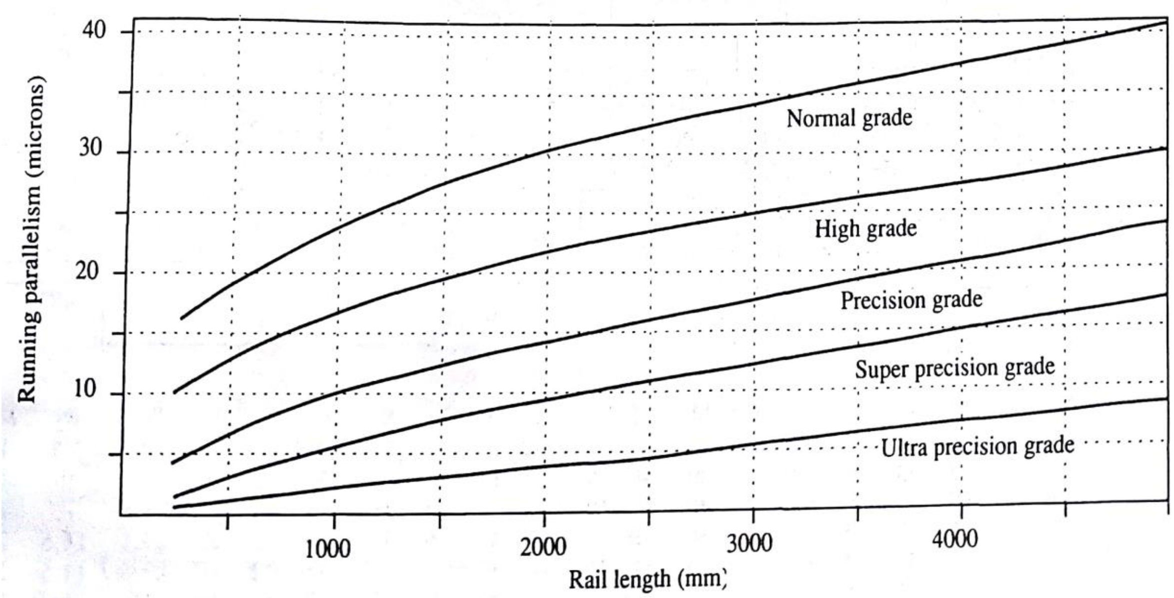
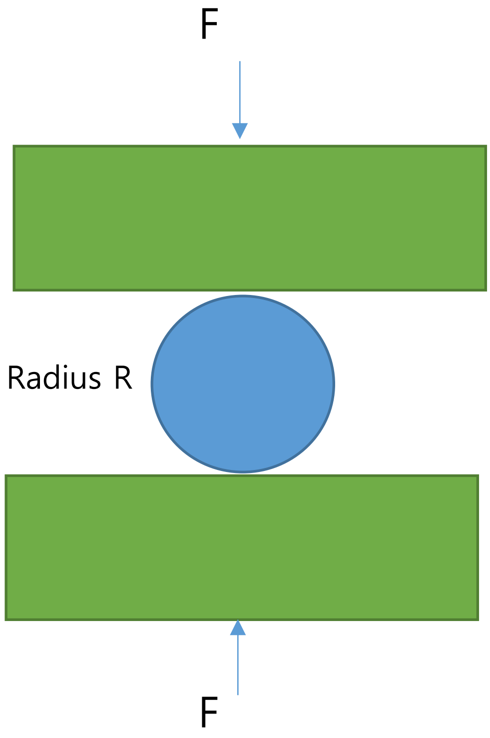
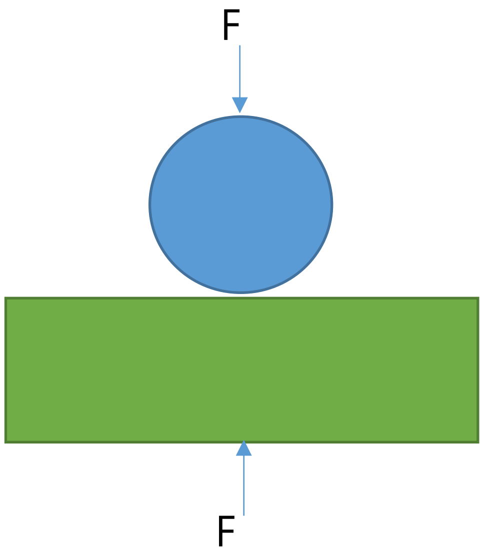


Figure 8.5.31 Typical running parallelism of upper and side surfaces of a linear guide bearing carriage with respect to upper and side surfaces of the bearing rail. (Courtesy of THK Co., LTD.)

Stiffness of balls between two parallel plates





Deflection of left system = Twice of Deflection of right system

From the contact mechanics, the deflection of left system is

$\delta=2\delta_{right}=(1/Re)^{1/3}(3F/2Ee)^{2/3}=(3/2)^{2/3}Re^{-1/3}(Ee)^{-2/3}F^{2/3}$

Compliance, $C=\partial\delta/\partial F=(3/2)^{2/3}\ Re^{-1/3}(Ee)^{-2/3}(2/3)F^{-1/3}$

$=(3/2)^{-1/3}\ Re^{-1/3}(Ee)^{-2/3}F^{-1/3}$

Thus, Stiffness, $K=1/C=1/(\partial\delta/\partial F)$

$=(3/2)^{1/3}\ Re^{1/3}(Ee)^{2/3}F^{1/3}$

When there are n balls engaged in averaging sense,

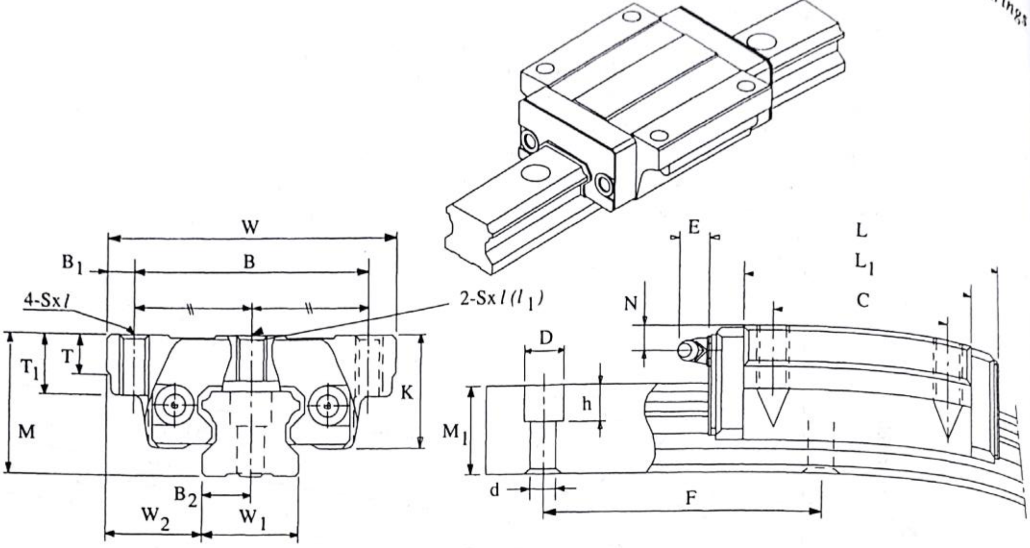
$Kn=n(3/2)^{1/3}\ Re^{1/3}(Ee)^{2/3}F^{1/3}$

For a steel ball of 5mm radius, and under F=300N preload;

$Ee=Es/[2(1-0.3^2)]\fallingdotseq 110GPa$, $Re=R/2=2.5mm=0.0025m$

$K=(3/2)^{1/3}(0.0025)^{1/3}(110E9)^{2/3}(300)^{1/3}=23.9MN/m=23.9N/um$

Ex) 40 balls (20 balls on each side) roll on flat guide under 300N preload gives 955 N/um stiffness, and it will give increase (about √2?) when the balls roll on V guide under preload, and will give another increase (about √2?) when the balls are preloaded with V roof. (cf. 55HTA model for stiffness)



Model	W	B	B_1	L	C	M	Sxl	A	T	T_1	K	L_1	E	W_1	W_2	B_2	M_1	F	d,D,H
15TA	47	38	4.5	53.5	30	24	M5x11	12.2	7	11	19.4	40.5	5.5	15	16	7.5	15	60	4.5,7.5,5.3
20TA	63	53	5	70	40	30	M6x10	14.5	10	10	25	50	12	20	21.5	10	18	60	6,9.5,8.5
20HTA	63	53	5	86	40	30	M6x10	14.5	10	10	25	66	12	20	21.5	10	18	60	6,9.5,8.5
25TA	70	57	6.5	79	45	36	M8x16	18	10	16	29.5	59	12	23	23.5	11.5	22	60	7,11,9
25HTA	70	57	6.5	103	45	36	M8x16	18	10	16	29.5	83	12	23	23.5	11.5	22	60	7,11,9
30TA	90	72	9	94	52	42	M10x18	21	10	18	35	72	12	28	31	14	26	80	9,14,12
30HTA	90	72	9	116	52	42	M10x18	21	10	18	35	94	12	28	31	14	26	80	9,14,12
35TA	100	82	9	105	62	48	M10x21	24	13	21	40	81.3	12	34	33	17	29	80	9,14,12
35HTA	100	82	9	134	62	48	M10x21	24	13	21	40	110	12	34	33	17	29	80	9,14,12
45TAX	120	100	10	139	80	60	M12x15	30	14	25	50	98	16	45	37.5	22.5	38	105	14,20,17
45HTA	120	100	10	171	80	60	M12x15	30	14	25	50	130	16	45	37.5	22.5	38	105	14,20,17
55TAX	140	116	12	163	95	70	M14x17	36	15	29	57	118	16	53	43.5	26.5	44	120	16,23,20
55HTA	140	116	12	201	95	70	M14x17	36	15	29	57	156	16	53	43.5	26.5	44	120	16,23,20
65TAX	170	142	14	186	110	90	M16x23	43	23	37	76	147	16	63	53.5	31.5	53	150	18,26,22
65HTA	170	142	14	246	110	90	M16x23	43	23	37	76	207	16	63	53.5	31.5	53	150	18,26,22
85TA	215	185	15	247	140	110	M20x30	51	30	55	94	179	16	85	65	42.5	65	180	24,35,28
85HTA	215	185	15	303	140	110	M20x30	51	30	55	94	236	16	85	65	42.5	65	180	24,35,28

*Prefix by HSR. All dimensions are in mm.

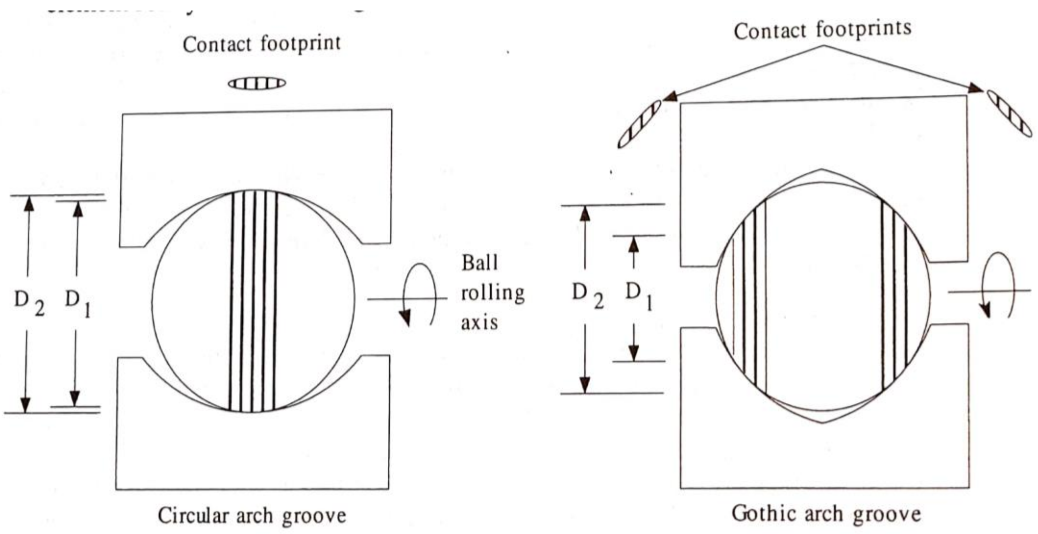
Figure 8.5.32 Face-to-face circular arch linear guides. (Courtesy of THK Co., LTD.)

Model	Stiffness (K_Y, K_Z) (N/μm) Medium preload	Load capacity (kgf)($F_Y = K_Z$)		Static moment capacity (kgf-m)		
		Dyn. C	Static C	Static M_X	Static M_X	Static M_X
HSR 15TA		760	1150	6.0	6.0	8.4
HSR 20TA	490	1230	1790	11.7	11.7	17.4
HSR 20HTA	686	1900	2380	20.2	20.2	23.2
HSR 25TA	647	1770	2580	20.2	20.2	29.4
HSR 25HTA	872	2420	3440	34.4	34.4	38.1
HSR 30TA	833	2500	3510	32.2	32.2	48.4
HSR 30HTA	1117	3320	4680	54.7	54.7	64.5
HSR 35TA	960	3320	4580	48.1	48.1	77.0
HSR 35HTA	1284	4470	6110	81.7	81.7	102.9
HSR 45TAX	1215	5350	7170	93.8	93.8	156.8
HSR 45HTA	1627	7170	9550	159.6	159.6	208.9
HSR 55TAX	1470	7890	10300	162.2	162.2	272.3
HSR 55 HTA	1960	10600	13800	275.5	275.5	363.7
HSR 65TAX	1842	12600	16100	316.7	316.7	497.6
HSR 65HTA	2479	17100	21500	538.4	538.4	664.5
HSR 85TA	2244	18700	23200	762.1	762.1	942.8
HSR 85HTA	2999	25200	30900	930.6	930.6	1255.0

Figure 8.5.33 Stiffness and load capacity of linear guides of Figure 8.5.32. (Courtesy of THK Co., LTD.)

(Source from Slocum's precision machine design)

Circular arch type and Gothic arch type linear guides are commercially available from several manufacturers



Circular arch groove and Gothic arch groove

(source:Slocum’s precision machine design)

Mounting method is of importance: one rail (or master rail) is fully constrained. The second rail is made parallel to the master rail using gage block or dial indicator, then just bolted without using any further fixation. After parallelism is checked, then bearing carriages are attached, and further fixing is followed when the parallelism is rechecked if it is needed.

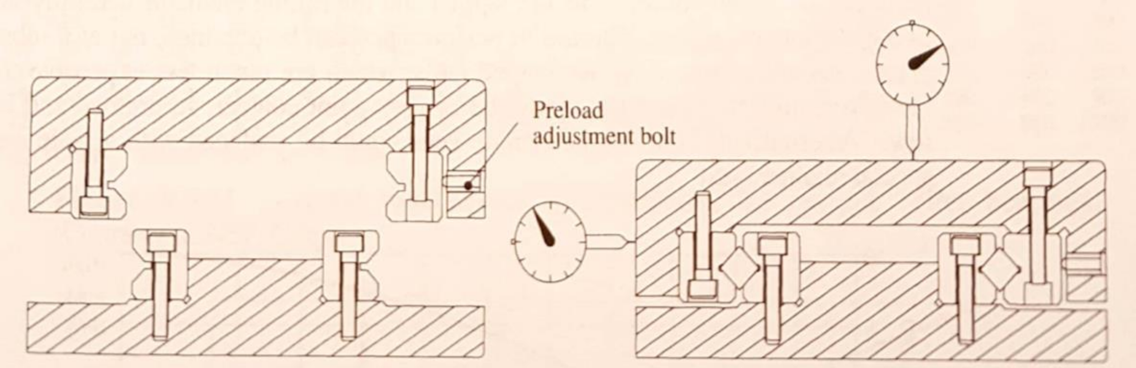
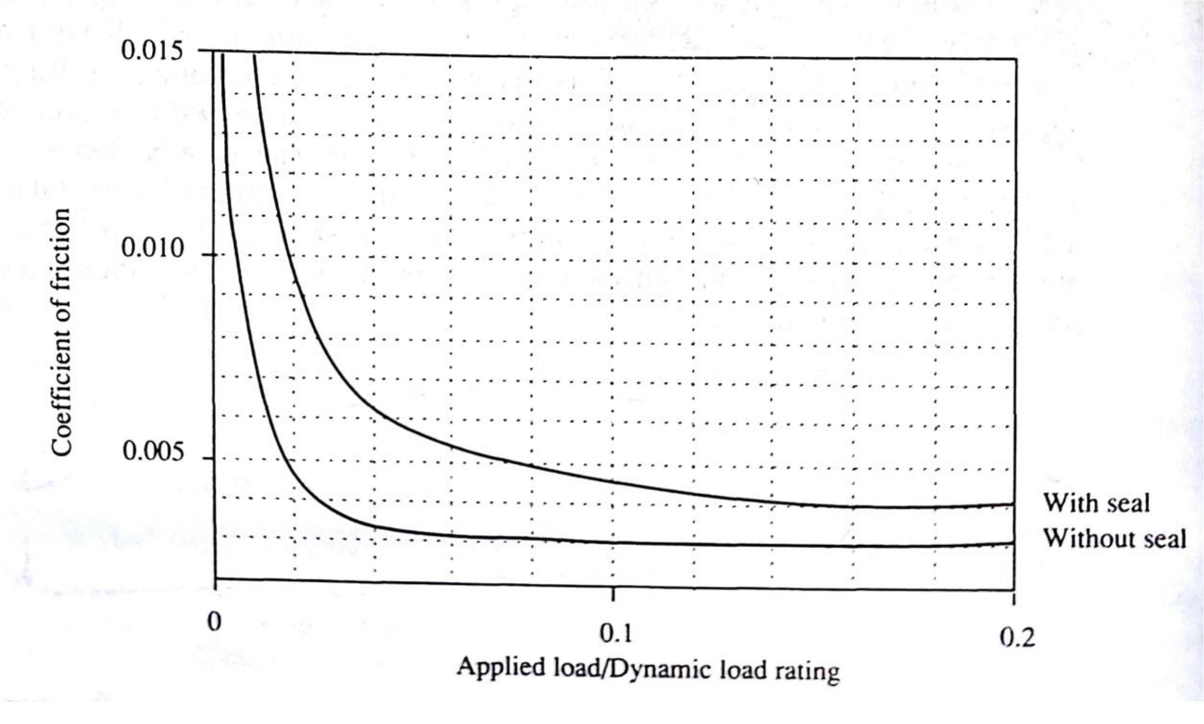


Figure 8.5.7 Typical assembly of crossed roller supported slide. (Courtesy of NSK Corp.)

Linear guide mounting methods

(source:Slocum's precision machine design)

Friction



Friction coefficient and applied load for typical recirculating ball linear guide

(source from THK, and Slocum's precision machine design)

Summary for Guidelines for Linear Motion

	Sliding	Rolling
Speed	≤0.25m/s	1-2m/s (linear) DN number (rotary)
Acceleration	≤0.1g	Not quoted
Range of motion	Typical few 10m No limit by assembly	Same
Loads	≤10 MPa	Load-Life eqn
Accuracy/ Precision	5-10um straightness 5um for highload ≤1um for light preload	Race/Rail's accuracy Averaging/Preload 30um Paraellism 10X higher by Lap
Repeatability	0.1-1.0 2um for heavy duty	0.25-1um radial 2-10X than accuracy
Resolution	2-10um ≤1um for PTFE	nrad-urad for rotary nm-um for linear
Stiffness	100-1000KPa/um	Maufacturers' Multi-brgs help

Preload	≒10% rated load	1-5% of static load
Damping	Same as fluid film	Lower damping
Friction	0.03-0.1 (static) 0.02-0.1(dynamic)	0.001-0.01(dynamic)
Life	5-10yrs	Load-Life equation