EPFL

Introduction to the Design of Space Mechanisms

© ADR

Theme 6 part 1:

Components

Ball-bearing

Gilles Feusier

Components

- Existing and, if possible, **qualified components** used in mechanisms:
  - Ball bearings, ball screws
  - Flex-pivots
  - Actuators, motors
  - Electrical, Electronic and Electromechanical (EEE) components:
    - Connectors,
    - Cables,
    - Switches,
    - Sensors (e.g. position sensors) and gauges,
    - Electrical and electronic components (including thermistors and heaters)

- **Use of Commercial Off-The-Shelf** (COTS) components
  + Low cost, short lead time, large series (well known in defined constrains)
  - Batch variabilities, change of specification/manufacturing processes, obsolescence, requirements outside of the design specifications

EEE Components

- Acc. to **ECSS-Q-ST-60C Rev.3** [6.1]
- This standard defines the requirements of EEE components for space projects for
  - selection,
  - control,
  - procurement,
  - usage.

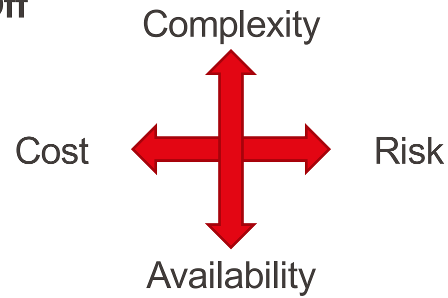
EEE: Electrical, Electronic and Electromechanical components

- Components are divided into 3 classes:
  - Class 1 Highest assurance, lowest risk, highest cost
  - Class 2
  - Class 3 Lowest assurance, highest risk, lowest cost
- The project objectives, definition and constraints determine which class or classes of components are appropriate to be utilized within the system and subsystems.

EEE Components

- EEE components maybe
  - Available and space qualified from a catalogue (should be used in priority for ESA projects or depending on requirements).
  - Available from a catalogue but requiring a space qualification or an extension of their qualification (e.g. COTS).
  - Specifically developed for the purpose of the project. This later case requiring a full qualification program.

Trade-Off



Availability includes lead time and export restrictions

EEE Components

- Each class of EEE components requires a specific associated documentation (acc. to **ECSS-Q-ST-60C Rev.3**):
  - Tables 4-1, 5-1, 6-1 of ECSS-Q-ST-60C Rev.3
  - Main normative documents associated to EEE components, according to the Document Requirement Definition (DRD) in annexes A to D of ECSS-Q-ST-60C Rev.2
    - Component Control Plan (CCP). Class 1 components only.
    - Declared Component List (DCL)
    - Procurement Specification
    - Part Approval Document (PAD)
    - …
- ESCC system for the specification, qualification and procurement of EEE parts for use in Space programs (European Space Components Coordination / https://spacecomponents.org).
- For commercial components: ECSS-Q-ST-60-13C Rev.1 "Space product assurance - Commercial electrical, electronic and electromechanical (EEE) components"

What is your experience with ball-bearings?

- Which type of ball-bearings do you know?
- What type of configuration do you know?
- Where are ball-bearings used in a spacecraft?

- Turn to your neighbors (3-5 people teams)
- **5 minutes**
- Present the results of your discussion

Ball Bearing Applications in Space


©Collins Aerospace


©TAS-CH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©ESA/RUAG


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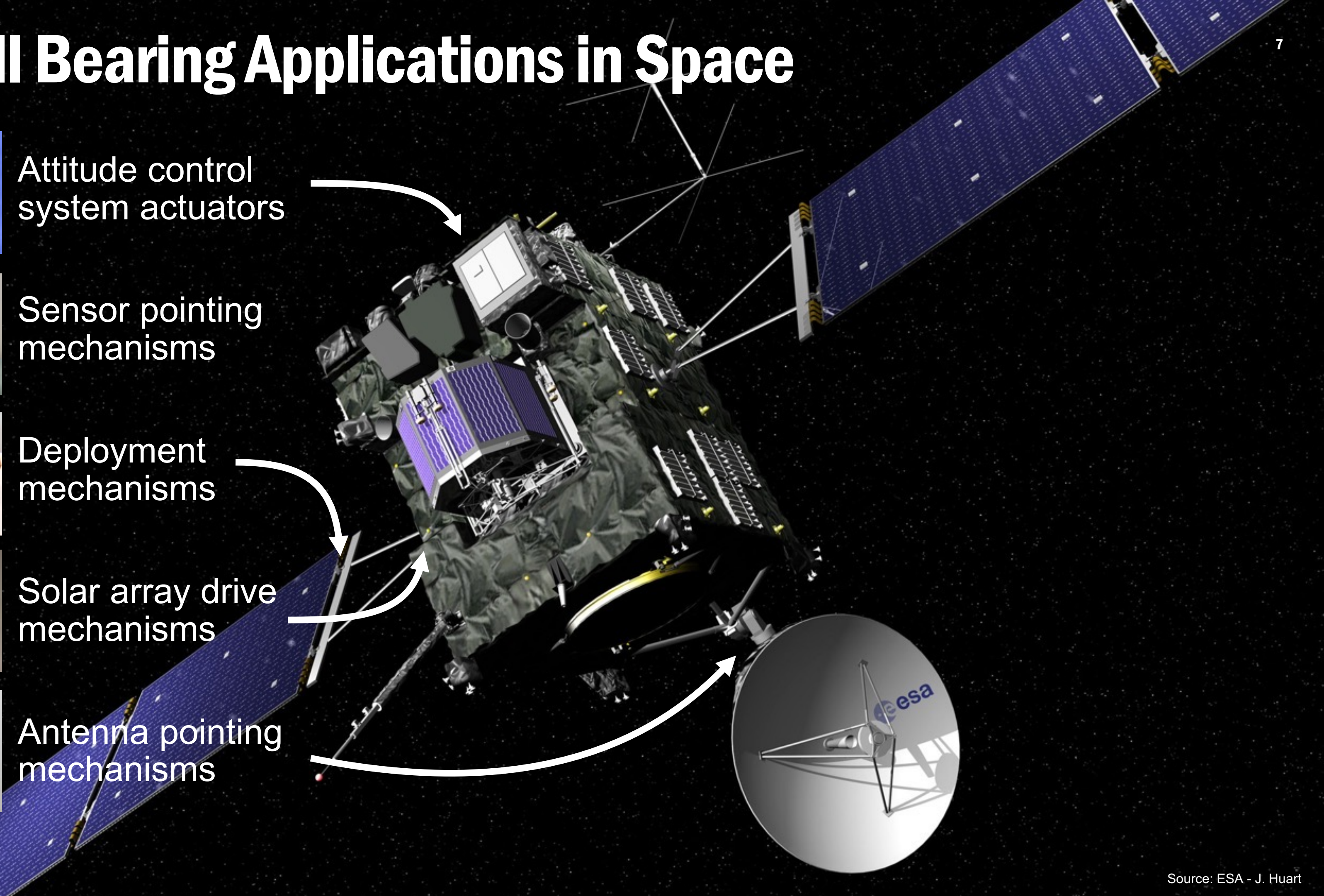
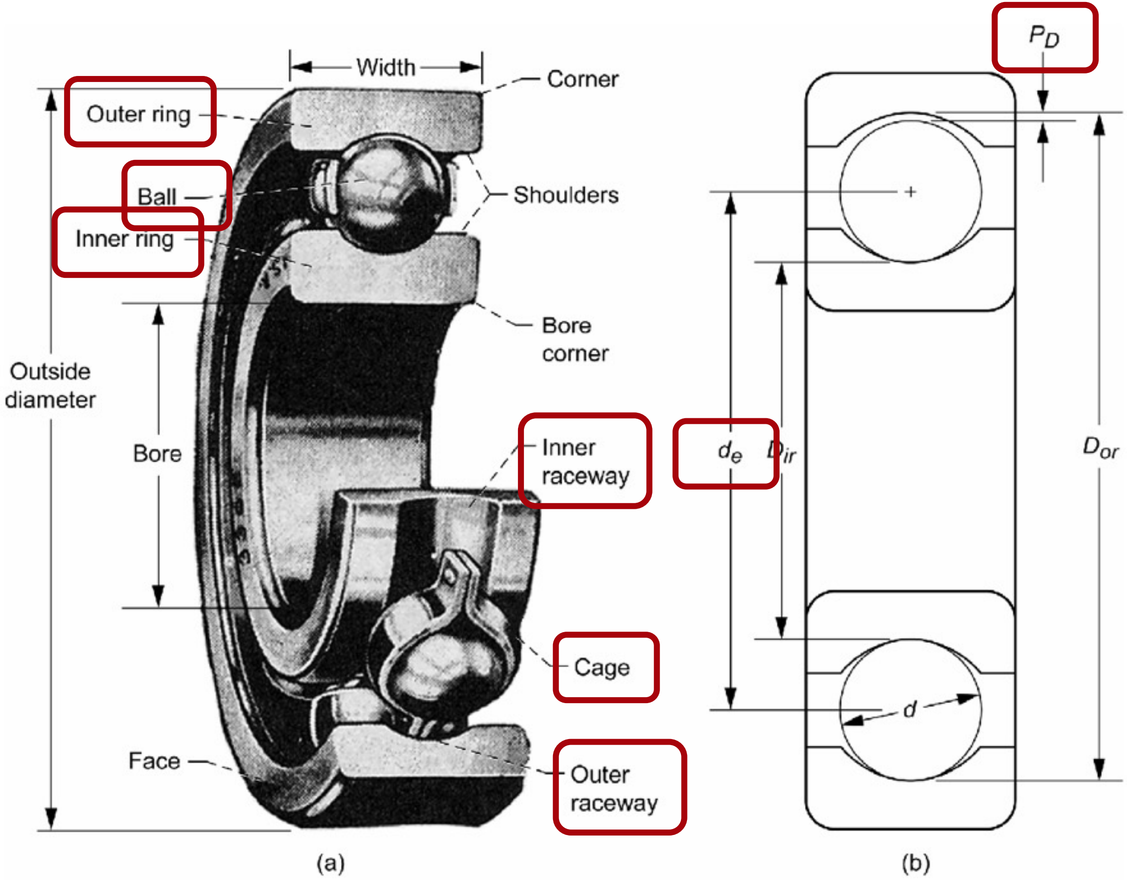


Ball Bearing Parts



Source: NASA/TM—2008-214265 [6.5]

P_D: diametral clearance

D_{ir}: raceway diameter at ball-race contact of inner race

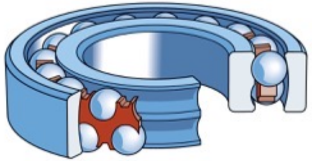
D_{or}: raceway diameter at ball-race contact of outer race

Pitch diameter:

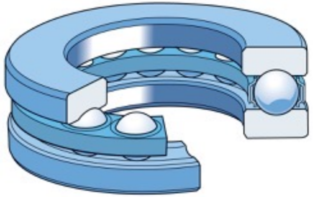
$$d_e = \frac{D_{or} + D_{ir}}{2}$$

Bearing Types and Geometry

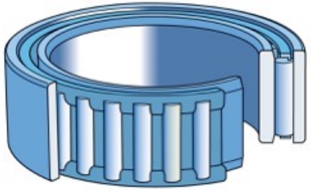
Deep groove bearing



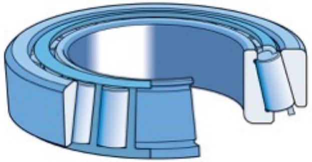
Self-aligning ball bearing



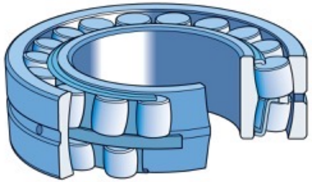
Thrust ball bearing



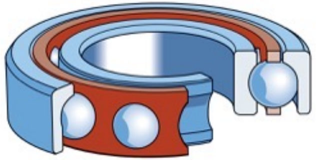
Needle roller bearing



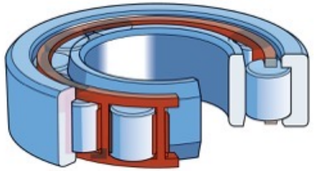
Tapered roller bearing



Spherical roller bearing



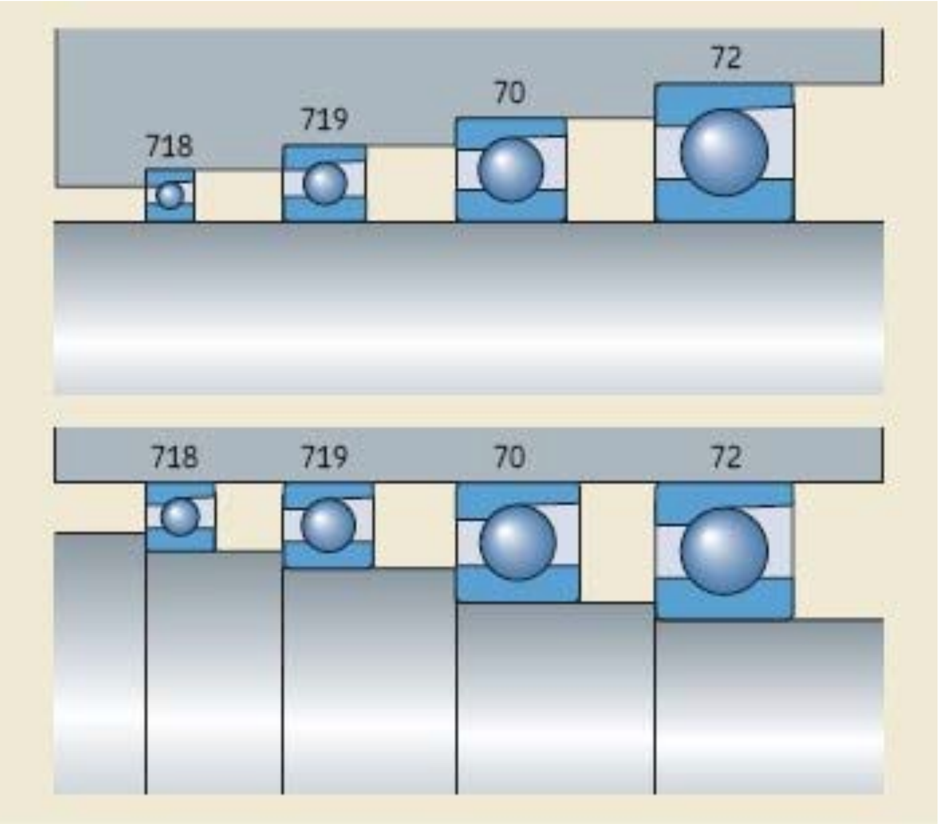
Angular contact ball bearing



Cylindrical roller bearing

Source: https://www.phase-trans.msm.cam.ac.uk/2010/types/index.html

Bearing Types and Geometry - Sizes

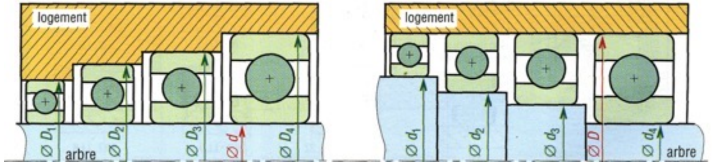


Source: SKF documentation

Use of coding.
In general a code for the series of ball-bearing (type) followed by the dimension codes (ISO).

7 = angular contact ball bearing

Diameter of axis and load will permit to define the size of the bearing.

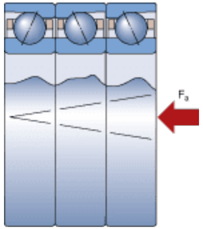


Source: http://www.zpag.net/Tecnologies_Indistrielles/Roulements_Etude.htm

Bearing Marking Example

Thrust face mark (punched)

“V-shaped” marking
(matched bearing sets only)



Deviation of the mean bore diameter Δd_m [µm], and position of the maximum eccentricity of the inner ring

Deviation of the mean outside diameter ΔD_m [µm], and position of the maximum eccentricity of the outer ring

Trademark

Complete designation of the bearing

Date of manufacture, coded

Country of manufacture

Serial number (bearing sets only)

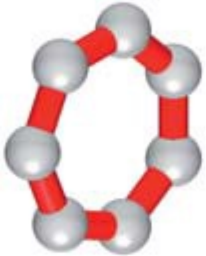
Source: SKF documentation

Bearing Types and Geometry - Cage

Pressed metal
(Steel, copper)

Massive ring
(organic, composite, bronze)

Crown type
(organic, composite …)



Spacers (cylindres)
(PTFE typ.)

Spacers (rings)
(PTFE typ.)

Full balls

Trade-Off

Mechanical strength ⟷ Friction torque

Source: ADR catalogue

Materials for Ball Bearings for Space Applications

EN standard (chemical composition)	AISI	Standard	Remarks
X105CrMo17	440	AMS 5630, 5880, 5618	Z100CD17
X40CrMonVN16.2	-	AMS 5925	XD15NW™
X30CrMoN15.1	-	AMS 5898	CRONIDUR® 30
100Cr6	SAE 52100	AMS 6440, 6444	100C6
HS 18-0-1	T1	AMS 5626	High-speed steel
80MoCrV40	M50	AMS 6490, 6491	Semi high-speed steel
X115CrMoV14.4.1	-	AMS 5749	BG42®
CoCr30W8	-	-	ALACRITE 554
CoCr32W13	-	-	ALACRITE 505
Ti 6Al-4V	-	AMS 4911, 4928, 4935, 4965, 4967	Titanium alloy TA6-V
Si_3N_4	-	-	Silicon nitride (ceramic)

Source: ADR catalogue. List is not exhaustive

Stainless steels: suitable for Space applications

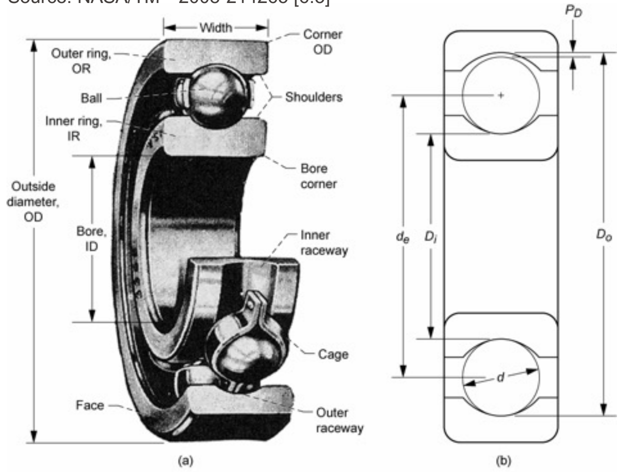
Standard steels: Corrosion (not suitable for Space)

Light weight: Low load capacity

Ceramics: Fragile (suitable for Space with precautions)

Ball Bearings

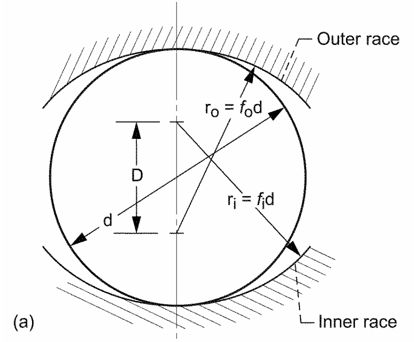
Source: NASA/TM—2008-214265 [6.5]



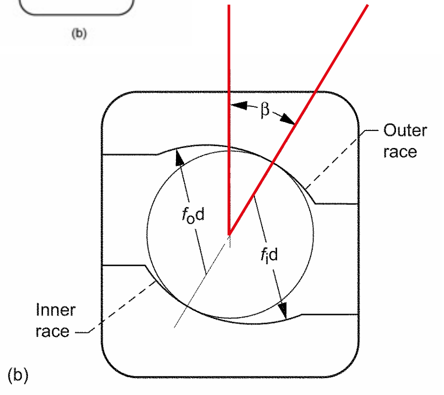
Conformity: $f = \frac{r}{d} \quad (\approx 0.52)$

Pitch diameter: $d_e = \frac{D_o + D_i}{2}$

Contact angle: β between 10° and 30°
The choice depends on the load case



Deep-groove ball bearing



Angular contact ball bearing

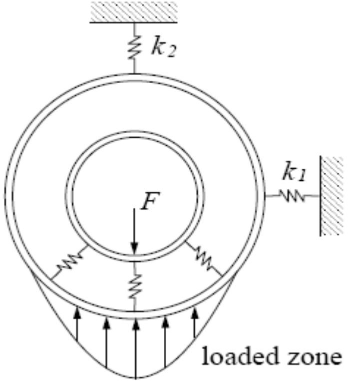
With:

- d : diameter of the ball
- r : race-groove radius (r_o or r_i)
- f : shall be > 0.5 for geometric reasons (f_o or f_i)
- P_D: diametral clearance

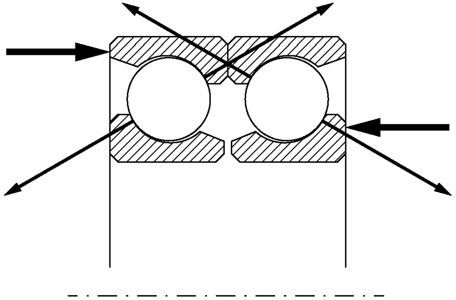
Ball Bearings

- The forces are distributed on the ball as a function of the load direction
  - **Radial load** *(distributed)*
  - **Axial load** *(uniformly)*
  - **Combined load**
    - Combination of radial and axial loads
    - Calculation of an equivalent load P_{eq} producing a stress equivalent to the combined load.
- Standard mathematical model for predicting ball bearing lifetime:
  - **Lundberg-Palmgren** theory (1947/1952)
    - Takes into account stresses and fatigue theories
    - Use of many experimental measures
    - Statistic analysis based on Weibull method

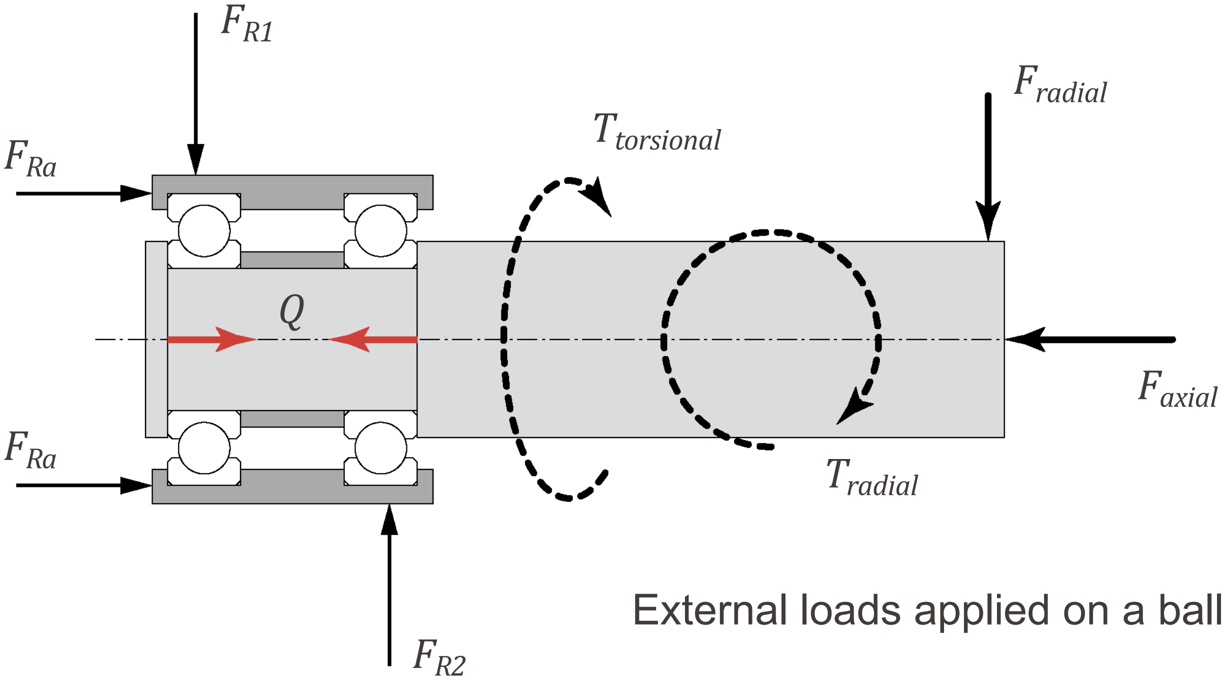
Radial load: only few balls are loaded not uniformly



Axial load: all balls are uniformly loaded



Functional Parameters



External loads applied on a ball bearing system

- F_{axial}, F_{radial}, $T_{torsional}$, T_{radial}: Functional applied forces and torques
- F_{R1}, F_{R2}, F_{Ra}: Reaction forces acting on the mechanism
- Q: Preload (also participates to the ball bearing stressing loads

References for the Lundberg-Palmgren Theory

- NASA Technical Memorandum 107440 [6.2]

  A. Palmgren Revisited - A Basis for Bearing Life Prediction

  Erwin V. Zaretsky
  Lewis Research Center
  Cleveland, Ohio
  Prepared for the
  STLE Annual Meeting
  sponsored by the Society of Tribologists and Lubrication Engineers
  Kansas City, Missouri, May 18–22, 1997

- See also ADR catalogue for practical use of the theory

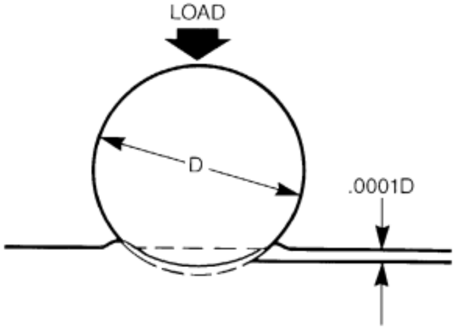
  Cf. [6.3] ADR-catalog.pdf on the MOODLE

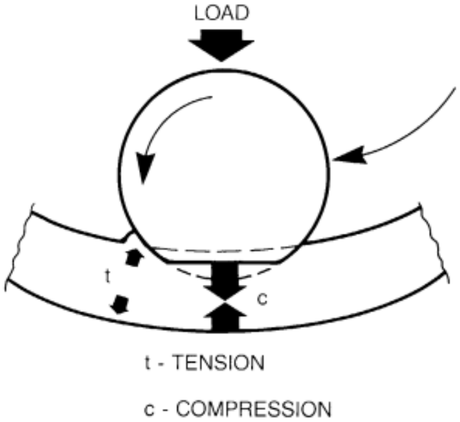
Ball Bearing Life Evaluation

- Some important definitions
  - Basic static radial load rating C_o:
    - value of the static radial load which will cause a total permanent deformation (ball and raceway) on the most heavily stressed ball/raceway contact (4’200 MPa for ground applications) of approximately 0.0001 of the ball diameter.
  - Basic dynamic radial load rating C:
    - value of the radial load of constant strength and direction that can be theoretically sustained for a nominal bearing life of 1 million revolutions.
  - Equivalent static radial load P_o:
    - a static radial load that would cause the same total permanent deformation on the most loaded contact as that obtained under effectively applied loads.
  - Equivalent dynamic radial load P:
    - a dynamic radial load that is constant in magnitude and direction under which the reached life would be the same as that with effectively applied loads.

Ball Bearing Life Evaluation

- Definition of the load ratings





Basic static radial load C_o

- No or very slow rotation
- Very slow oscillations
- Shocks

Permanent deformation of rolling element and raceway (0.0001 x D)

Basic dynamic radial load C

- Rotation under load

➢ Cyclic stresses (fatigue)

Basic rating life of 10^6 revolutions

Source: https://www.ahrinternational.com/PDF_catalogues/MRC/definitionOF_LOAD_RATINGS.pdf [6.4]

Ball Bearing Life Evaluation

- Equivalent load ratings

$$P = X \cdot F_{radial} + Y \cdot F_{axial} \qquad [\mathrm{N}]$$

where: X radial coefficient of the bearing
Y axial coefficient of the bearing

Cf. tables given by manufacturer (e.g. ADR catalogue)

Contact[3] angle	F_a[1]/C_o	e	Single bearing or DT pair: $F_a/F_r \leqslant e$ X	Y	$F_a/F_r > e$ X	Y	X_o[2]	Y_o[2]	DO or DX pairs: $F_a/F_r \leqslant e$ X	Y	$F_a/F_r > e$ X	Y
	0.014	0.23				2.30				2.78		3.74
	0.028	0.26				1.99				2.40		3.23
	0.056	0.30				1.71				2.07		2.78
	0.085	0.34				1.55				1.87		2.52
5°	0.110	0.36	1	0	0.56	1.45	0.6	0.5	1	1.75	0.78	2.36
	0.170	0.40				1.31				1.58		2.13
	0.280	0.45				1.15				1.39		1.87
	0.420	0.50				1.04				1.26		1.69
	0.560	0.52				1.00				1.21		1.63
	0.014	0.29				1.88				2.18		3.06
	0.029	0.32				1.71				1.98		2.78
	0.057	0.36				1.52				1.76		2.47
	0.086	0.38				1.41				1.63		2.29
10°	0.110	0.40	1	0	0.46	1.34	0.6	0.5	1	1.55	0.75	2.18
	0.170	0.44				1.23				1.42		2.00
	0.290	0.49				1.10				1.27		1.79
	0.430	0.54				1.01				1.17		1.64
	0.570	0.54				1.00				1.16		1.63
	0.015	0.38				1.47				1.65		2.39
	0.029	0.40				1.40				1.57		2.28
	0.058	0.43				1.30				1.46		2.11
	0.087	0.46				1.23				1.38		2.00
15°	0.120	0.47	1	0	0.44	1.19	0.5	0.46	1	1.34	0.72	1.93
	0.170	0.50				1.12				1.26		1.82
	0.290	0.55				1.02				1.14		1.66
	0.440	0.56				1.00				1.12		1.63
	0.580	0.56				1.00				1.12		1.63
20°	—	0.57			0.43	1.00		0.42		1.09	0.70	1.63
25°	—	0.68	1	0	0.41	0.87	0.5	0.38	1	0.92	0.67	1.41
30°	—	0.80			0.39	0.76		0.33		0.78	0.63	1.24
35°	—	0.95			0.37	0.66		0.29		0.66	0.60	1.07

Source: ADR catalogue

- Nominal life for individual bearings (Lundberg-Palmgren) L_{10}:

$$L_{10} = \left(\frac{C}{P}\right)^{p} \qquad [10^6 \text{ rev.}] \qquad \text{where} \quad p = 3 \quad \text{for ball bearings}$$

The **life associated with a reliability of 90%** (90% probability of survival)

Ball Bearing Life Evaluation

Reading: E. Zaretsky et al. “Relation Between Hertz Stress-Life Exponent, Ball-Race Conformity, and Ball Bearing Life”, NASA/TM-2008-214265 [6.5]

- The lifetime depends mainly on:
  - The Hertz pressure at ball-races contact points, function of:
    - Conformity f
    - Ball diameter d
    - Number of balls
    - Direction of the load
  - The materials
  - The travelled distance (number of revolutions)
  - The lubrication

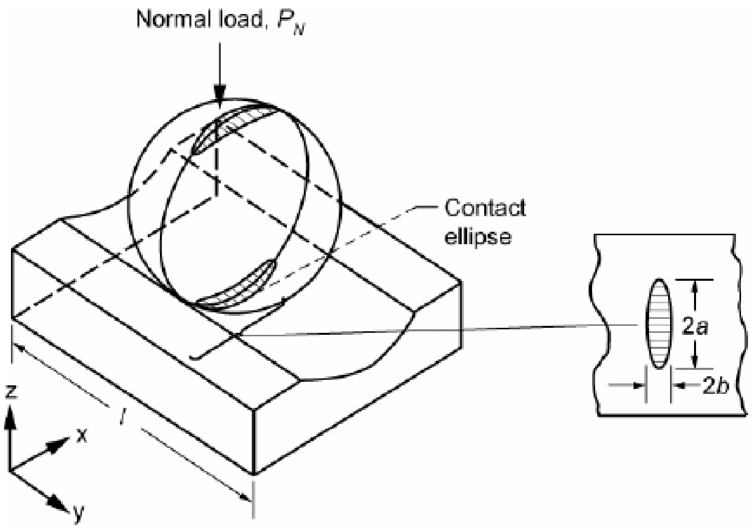
Ball Bearing Life Evaluation

- Hertz Pressure (in GPa)
  - Radial load (deep groove)

$$S_{max\ j} = K \cdot \frac{\left[\frac{2\cdot(-1)^{j+1}}{D_j} + \frac{4}{d} - \frac{1}{f_j d}\right]^{2/3}}{(\mu \cdot \nu)_j} P_{N_{max}}^{1/3}$$

  - Axial load (angular-contact)

$$S_{max\ j} = K \cdot \frac{\left[\frac{2\cdot\cos(\beta)}{d_e + (-1)^j d \cdot \cos(\beta)} + \frac{4}{d} - \frac{1}{f_j d}\right]^{2/3}}{(\mu \cdot \nu)_j} P_N^{1/3}$$



μ and ν: transcendental functions from Hertz theory

with:
- D_j: diameter of the grooves
- j = 0: outer race
- j = 1: inner race
- d: diameter of the balls
- P_N: normal load on the balls
- $P_{N_{max}}$: normal load on the most loaded ball
- f_j: conformity
- β: contact angle
- d_e: pitch diameter

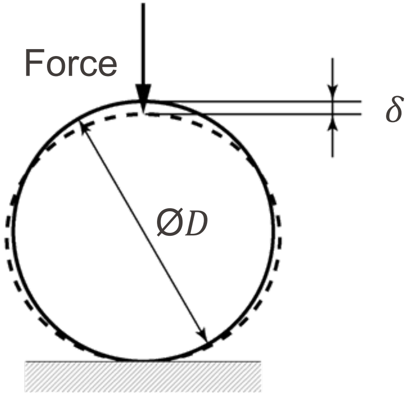
K : geometry-load constant (K = 1.58·10^{-3} for bearing steel on bearing steel, S_{max} in GPa)

Source: E. Zaretsky et al. "Relation Between Hertz Stress-Life Exponent, Ball-Race Conformity, and Ball Bearing Life", NASA/TM-2008-214265 [6.5]

Ball Bearing Life Evaluation

- Allowable Hertz pressure
  - **For terrestrial, lubricated applications (ISO 76)**[1] $P_H \leq$ 4'200 MPa
    - Corresponds to a total permanent deformation of the rolling element of diameter D of:

$$\frac{\delta}{D} = {}^{1}\!/_{10'000}$$



  - **Space applications**
    - According to ECSS-E-ST-33-01C[1] $P_H \leq$ 3'360 MPa
    - Other applicable standards (e.g. in-house standards):
      - Under vibrations (for sizing): $P_H \leq$ 2'414 MPa
      - In orbit: $P_H \leq$ 1'034 MPa
      - Permissible actual loads may reach 1.5 x P_H (safety factor)
      - …

[1] for SAE 52100

Ball Bearing Preload

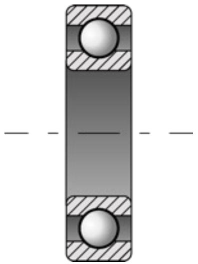
- Preload
  - Always required for precision mechanisms using ball bearings
    - Control of the stiffness of the bearing assembly
    - Assembly without play (axial and radial)
    - Stability in vibration (gapping allowed or not)

  - **Drawbacks**
    - The permanent axial force is detrimental for:
      - Lifetime
      - Resistive torque

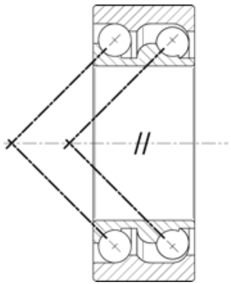
  - Types of assembly (consequences will be discussed later on)
    - Without any spring: **Hard preload**
    - With a spring: **Soft preload**

Ball bearing Assembly

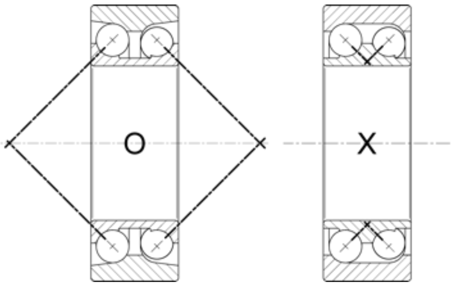
- One single ball bearing (deep groove) with radial contact
  - Barely used: axial and radial instability, problems in vibrations
  - Could be useful for laterally supporting a bearing, a pulley, for centering …



- Tandem configuration
  - Used for doubling or multiplying the load capacity
  - Barely used for space mechanisms
  - Generally combined in a Tandem-Duplex configuration



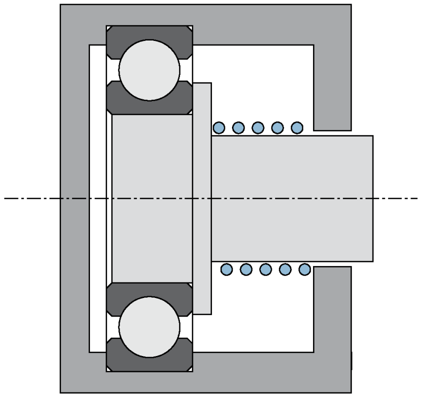
- Duplex configuration
  - Assembly of a pair of ball bearings with a preload
  - Main assembly configuration for precision mechanisms



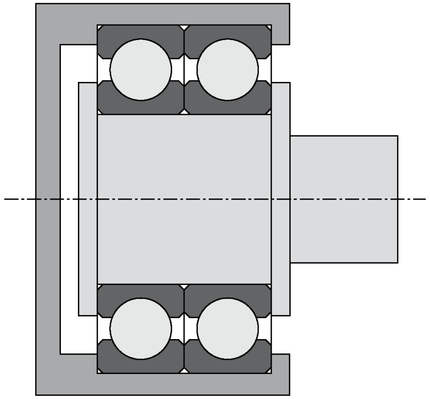
Source: Cdang - Wikipedia

Ball bearing Assembly

- Single ball bearing with elastic preload
  - Simple assembly
  - Low stiffness (not favorable in vibration)



- Ball bearing pair with rigid preload
  - Back to back assembly (**O-mount**)
  - Face to face assembly (**X-mount**)
  - Requires high mechanical accuracy
  - Very rigid (good behavior in vibration)



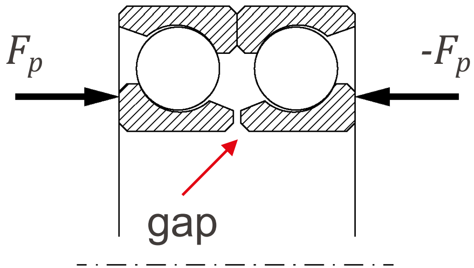
- Multiple ball bearings assembly
  - More than two ball bearing on the shaft
  - High loads capacity

Ball bearing Preload Control

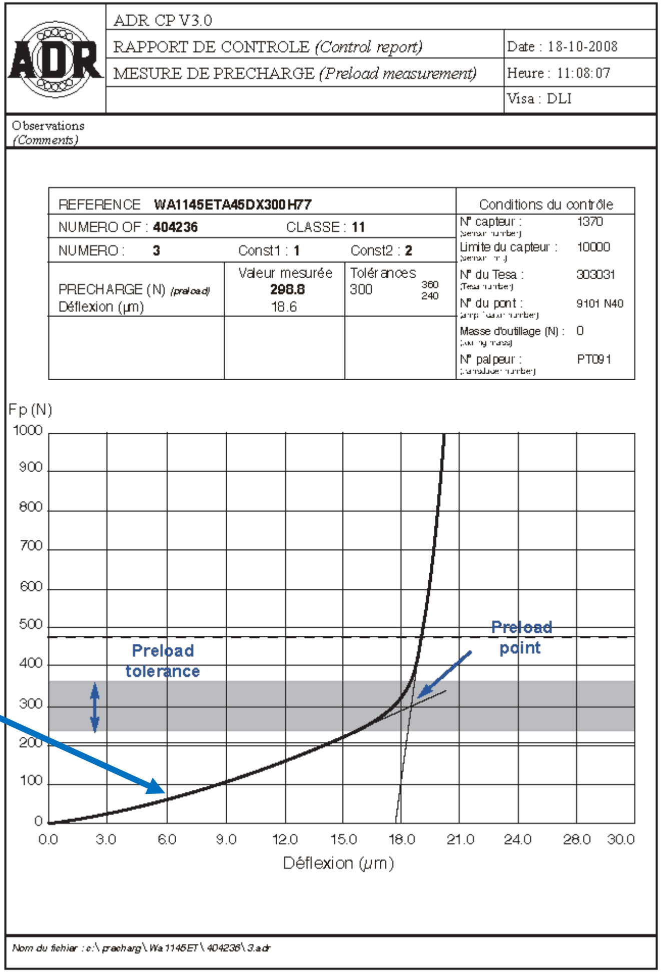
- Elastic preload (Q)
  - k: spring stiffness
  - δ: spring deflection

$$Q = k \cdot \delta$$

- Hard preload
  - Non-linear stiffness
  - Sharp stiffness change when gap reduced to 0
  - Measured from the record: F_p vs. δ



Example of a preload measurement



ADR	ADR CP V3.0	
	RAPPORT DE CONTROLE *(Control report)*	Date : 18-10-2008
	MESURE DE PRECHARGE *(Preload measurement)*	Heure : 11:08:07
		Visa : DLI

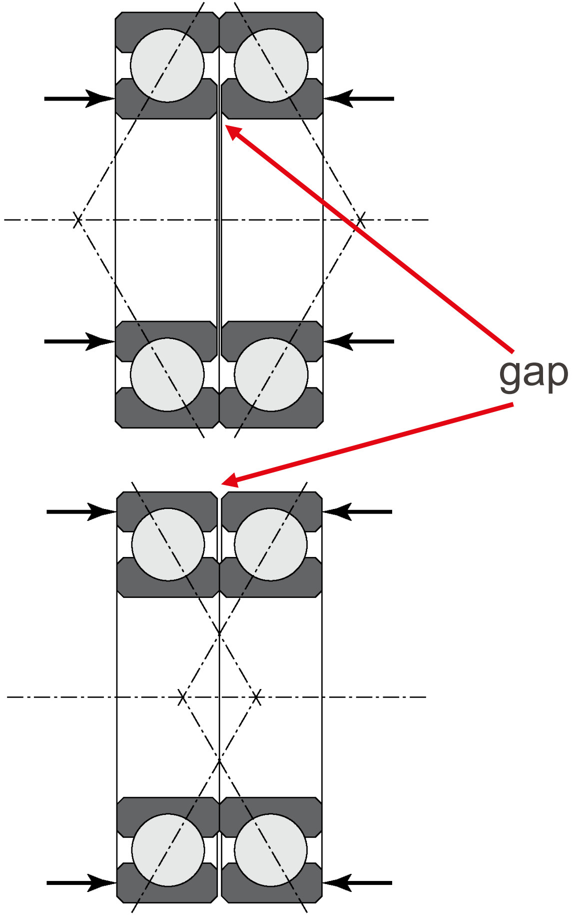
Observations
(Comments)

REFERENCE WA1145ETA45DX300H77			Conditions du contrôle
NUMERO OF : **404236**	CLASSE : **11**		N° capteur : 1370
NUMERO : **3**	Const1 : **1**	Const2 : **2**	Limite du capteur : 10000
	Valeur mesurée	Tolérances	N° du Tesa : 303031
PRECHARGE (N) *(preload)*	**298.8**	300 360 240	N° du pont : 9101 N40
Déflexion (µm)	18.6		Masse d'outillage (N) : 0
			N° palpeur : PT091

Nom du fichier : e:\precharg\Wa1145ET\404236\3.adr

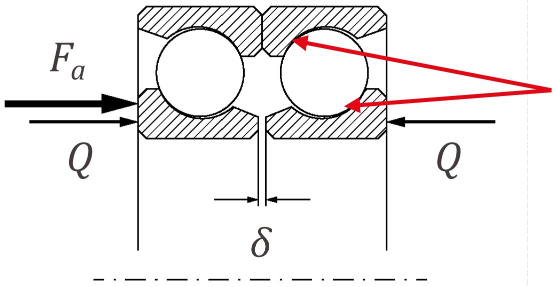
Ball bearing Assembly (duplex)

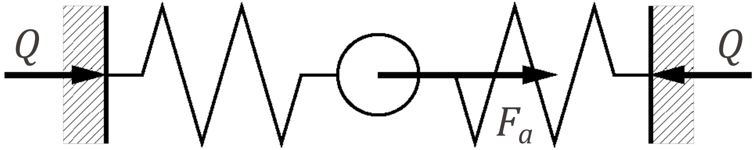
- **O-Mount** (back to back)
  - Very stiff
  - Able to carry high moments
  - Requires a very accurate alignment in order to avoid torque variations and wear
- **X-Mount** (face to face)
  - More tolerant to misalignment
  - Used for a regular torque
  - Not appropriate for carrying high moments

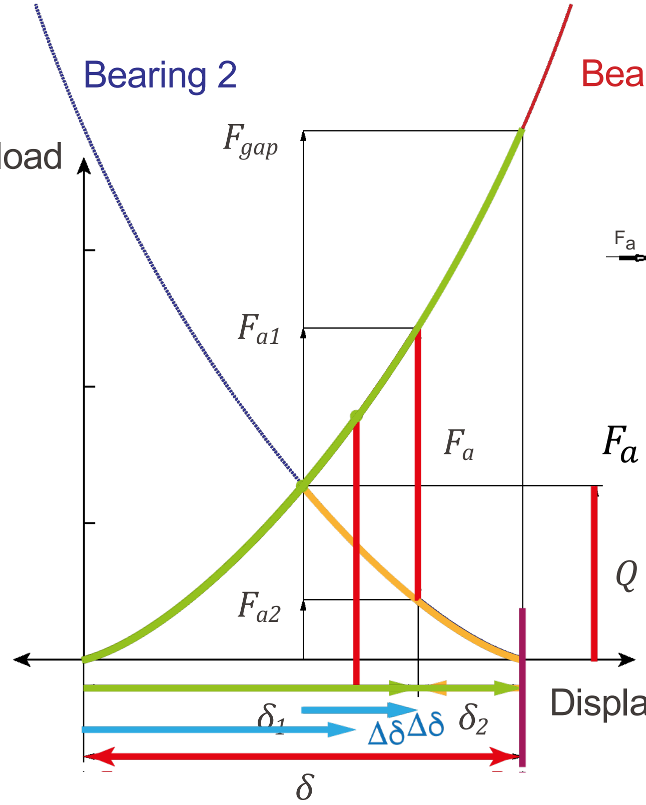


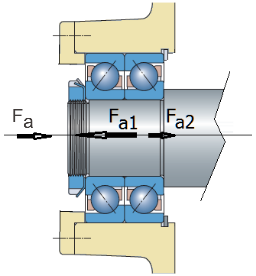
Ball bearing Assembly

- Duplex ball bearing stiffness
  - Non-linear stiffness
    - ⇒ Better load capacity









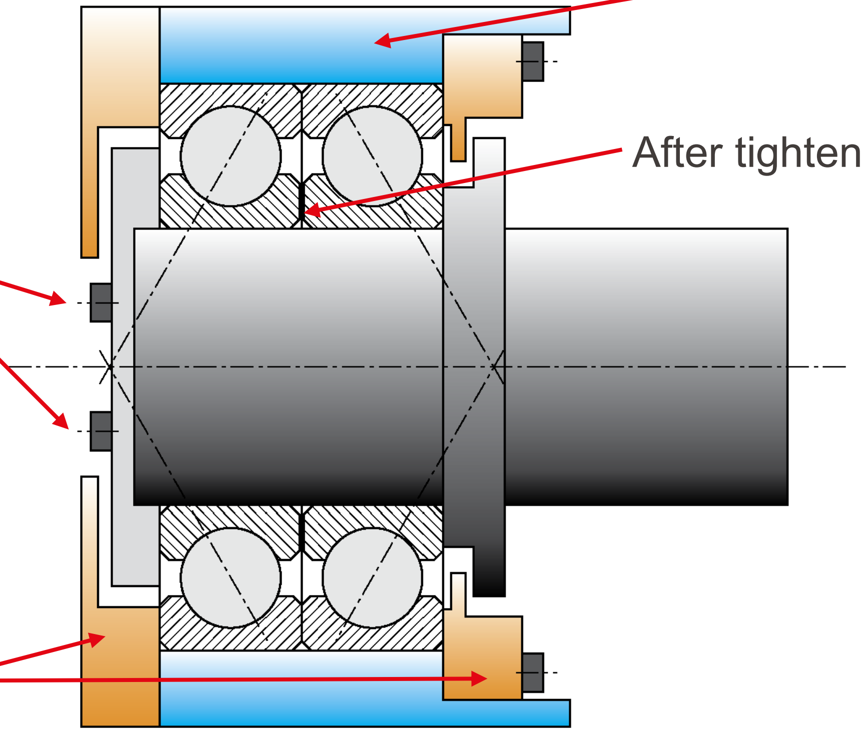
$$F_a = F_{a1} - F_{a2}$$

$$\delta \propto Q^{2/3} \quad \Rightarrow \quad \frac{F_{gap}}{Q} \approx 2.83$$

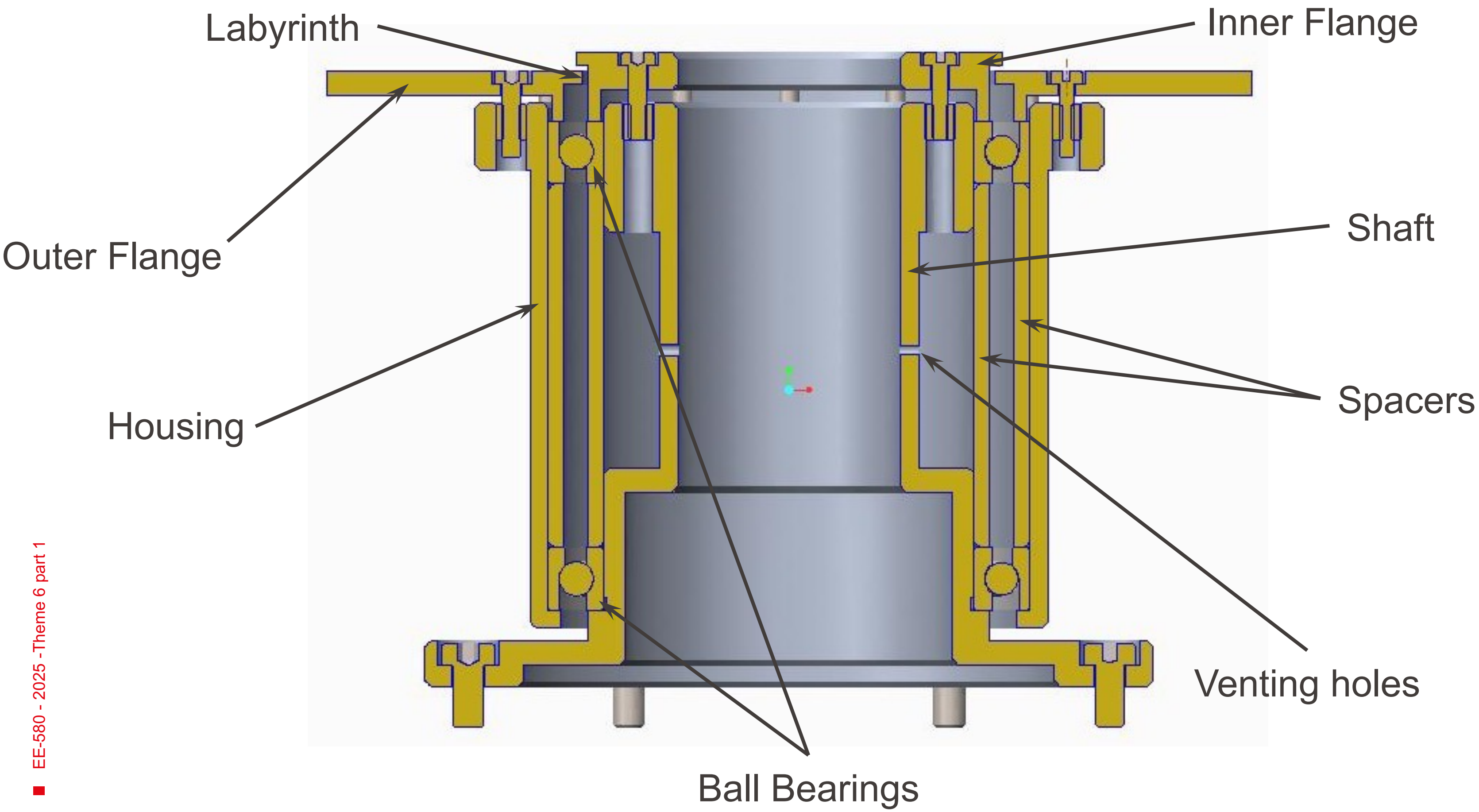
Reading: P. Guay et al. “Ball Bearing Stiffness. A New Approach Offering Analytical Expressions”, Proceedings of the 16th European Space Mechanisms and Tribology Symposium (ESMATS 2015), September 2015. [6.6]

Ball bearing Assembly

- Duplex Assembly (O-Mount, hard preload)

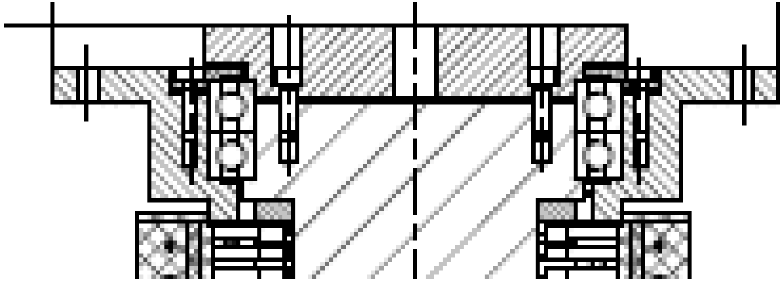


Ball bearing – Example of Duplex O-Mount

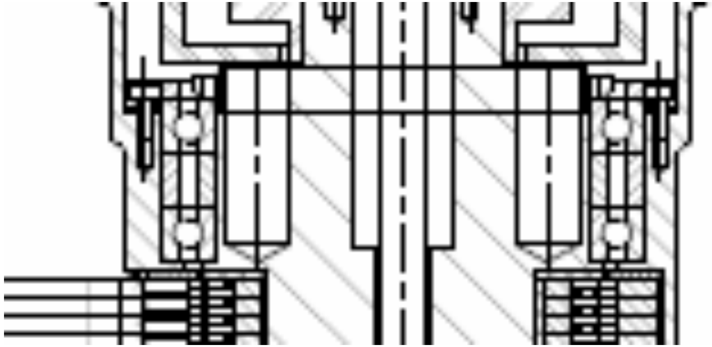


EPFL

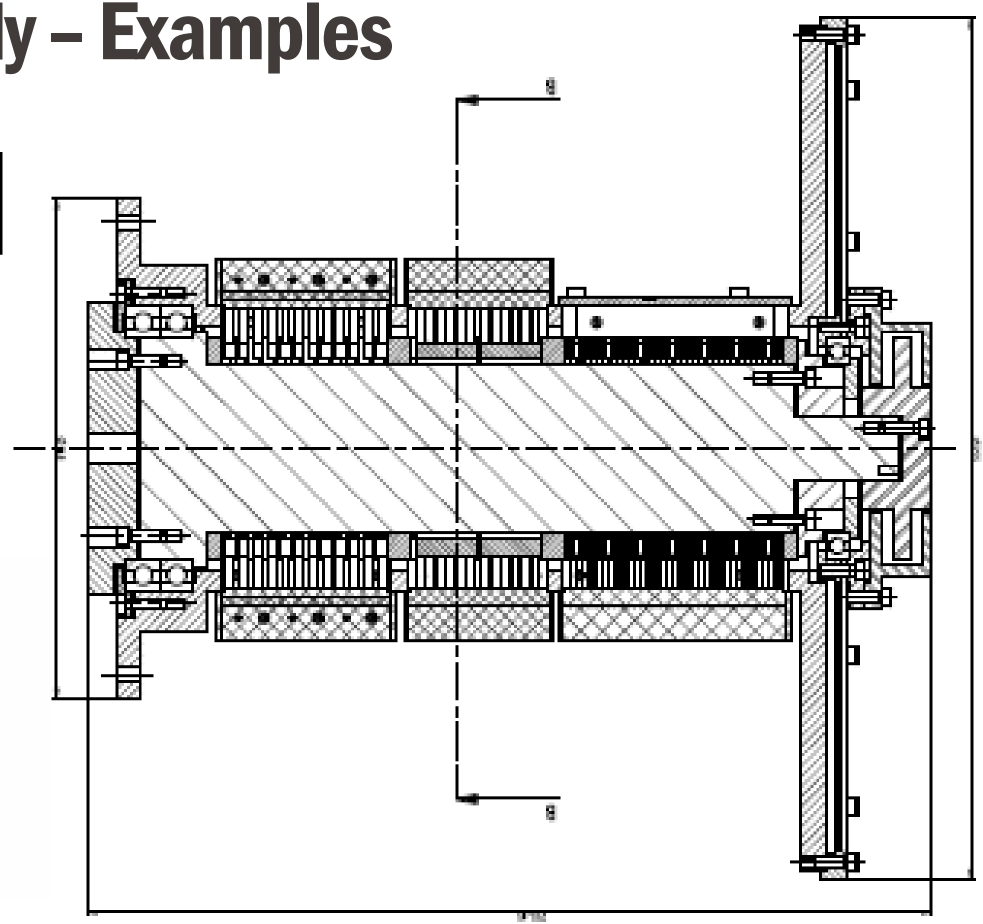
Ball bearing Assembly – Examples



Hard mount



Hard mount with spacers



Hard mount on one side, supported by a membrane on the other side

Theme 6 Part 1 Summary

- Various type of components
  - Mechanical components (bearings, actuators, …)
  - EEE components (cables, connectors, sensors, …)
    - According to ECSS-Q-ST-60C Rev.3 and ECSS-Q-ST-60-13C Rev.1
    - Classified: three classes
    - Use of COTS
- Ball-bearings
  - Usages
  - Types
  - Materials
  - Lundberg-Palmgren, life evaluation
  - Assembly
  - Preload

Next Week

- Theme 6 – Components (continued): Ball-bearings, Motors and Actuators

Note:

- Mini Project part 3 Concept
  (cf. EE580_MP3_2025_v1 Concept.pdf)
  Deadline **May 1^{2t}, 16:00**