ME 216: Engineering Metrology

Fundamentals of Limits and Fits

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Product Design for Manufacturing

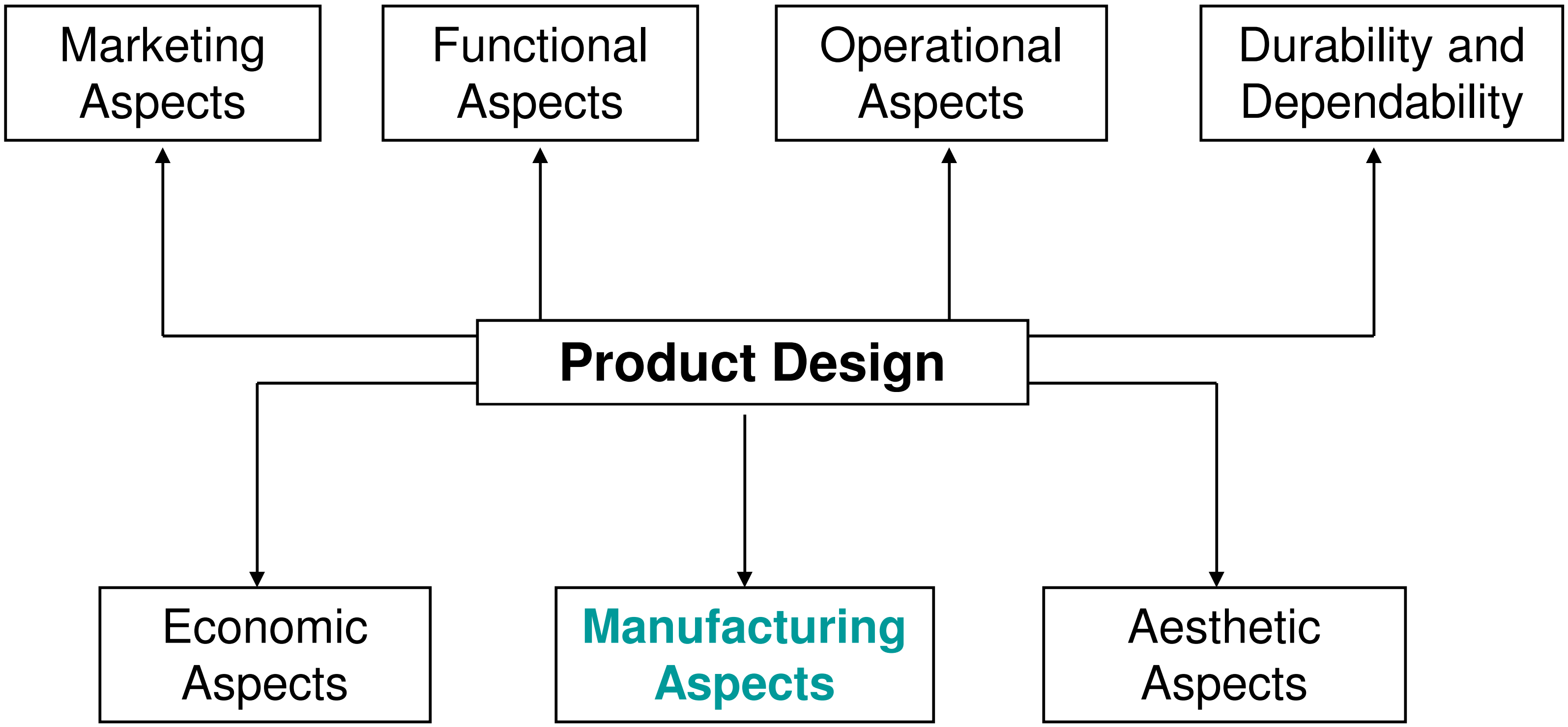

Fig. 1 Typical Stages in a Product Life Cycle

Role of Metrology in Design for Manufacturing

Manufacturing Aspect

- Key Functional Requirements
- Fit between the mating parts
- Tolerances, dimensions on mating parts
- Manufacturing Processes & Sequences
- Cost of Manufacturing

Fit: It is the interrelation between dimensions of mating parts before their assembly

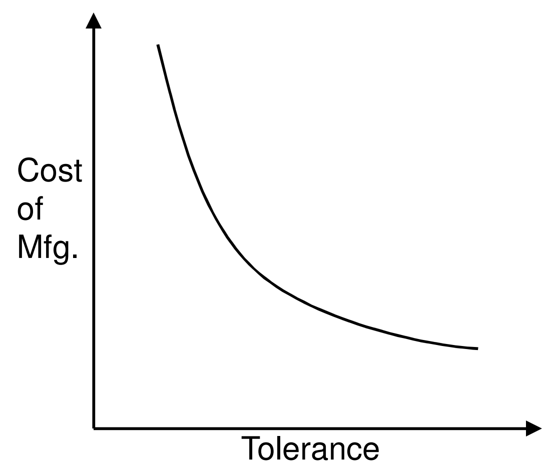

Fig. 2 Implications of Manufacturing aspects

Evaluation for Limits and Fits

Steps involved in the Evaluation of Limits of Tolerances

Selection of an Appropriate FIT based on functional requirement

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Selection of Type of Shaft and Hole

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Selection of Tolerance Grade for shaft and hole

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Evaluation of standard Tolerance

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Evaluation of Limits of Tolerances

Fig. 3 Evaluation of Limits of Tolerances

Introduction

- Precision and Accuracy:
  - Precision refers to repeatability
  - Accuracy refers of result to the true value

- Accuracy can be found by

$$Accuracy = \sqrt{(\text{Repeatability})^2 + (Systematic\ error)^2}$$

where, systematic error =True value- mean of set of readings

Limits and Fits - Definitions

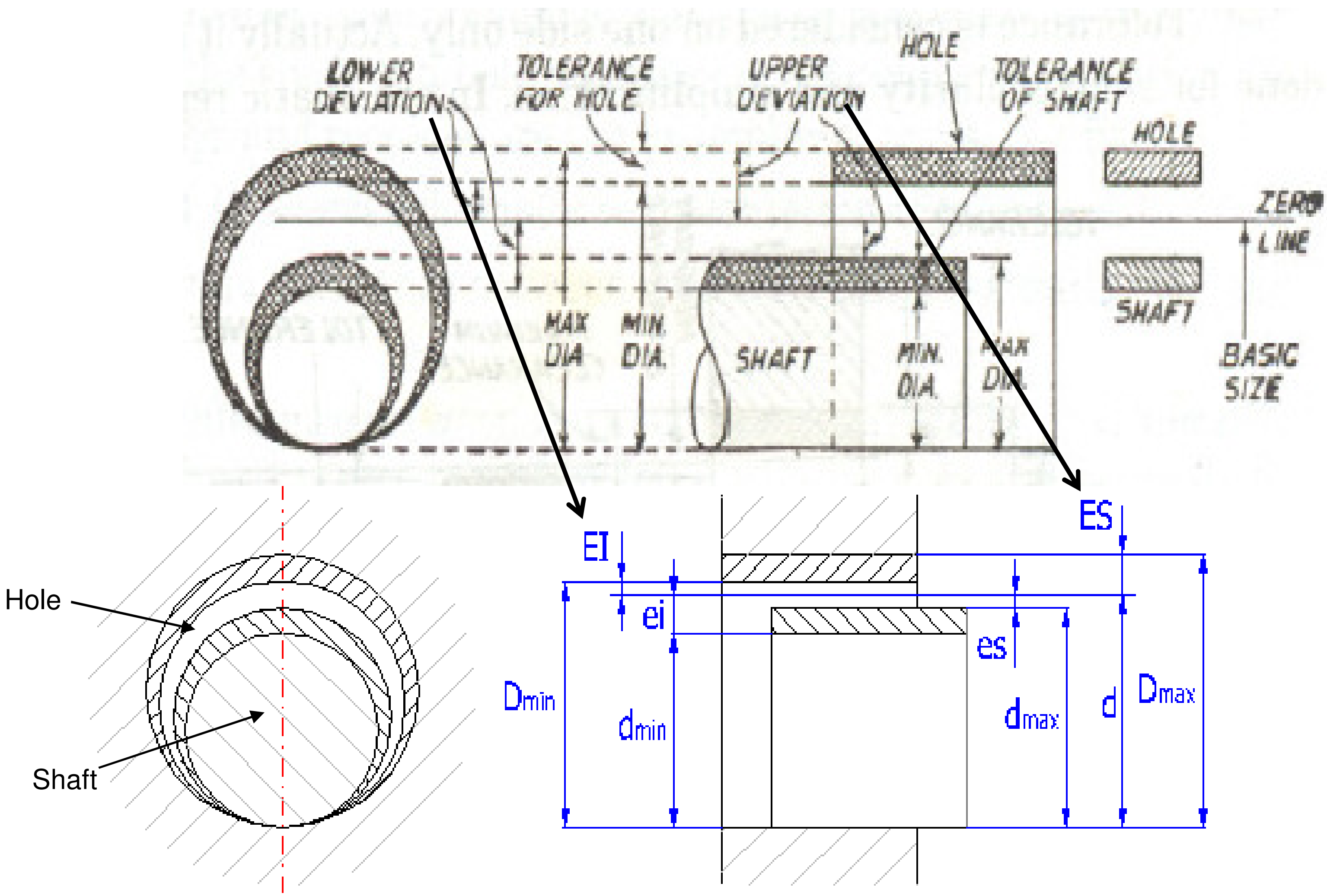


Fig. 4 Tolerance Zones [1]

Limits and Fits - Definitions

Zero Line: It is a line along which represents the basic size and zero (or initial point) for measurement of upper or lower deviations.

Basic Size: It is the size with reference to which upper or lower limits of size are defined.

Shaft and Hole: These terms are used to designate all the external and internal features of any shape and not necessarily cylindrical.

Hole Designation: By upper case letters from A, B, … Z, Za, Zb, Zc (excluding I, L, O, Q, W and adding Js, Za, Zb, Zc) - 25 nos. Indian Stds

Shaft Designation: By lower case letters from a, b, … z, za, zb, zc (excluding i, l, o, q, w and adding js, za, zb, zc) - 25 nos.

Definitions

Upper Deviation: The algebraic difference between the maximum limit of size (of either hole or shaft) and the corresponding basic size, like *ES*, *es*.

Lower Deviation: The algebraic difference between the minimum limit of size (of either hole or shaft) and the corresponding basic size, like *EI*, *ei*.

Fundamental Deviation: It is one of the two deviations which is chosen to define the position of the tolerance zone.

Tolerance: The algebraic difference between upper and lower deviations. It is an absolute value.

Limits of Size: There are two permissible sizes for any particular dimension between which the actual size lies, maximum and minimum

Basic Shaft and Basic hole: The shafts and holes that have zero fundamental deviations. The basic hole has zero lower deviation whereas, the basic shaft has zero upper deviation.

Selection of Fits

Definition of Fit: It is the relation between dimensions of two mating parts before their assembly.

Selection of Fits

Systems of Fit: There are two systems by which a fits can be accomplished –

1. Hole basis system
2. Shaft basis system

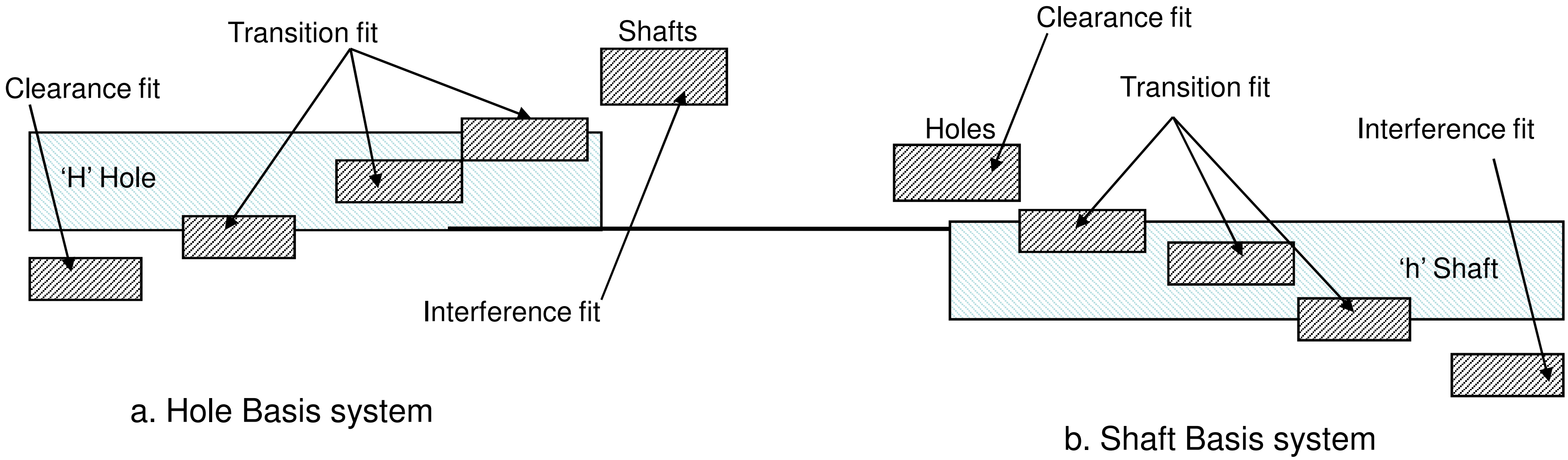
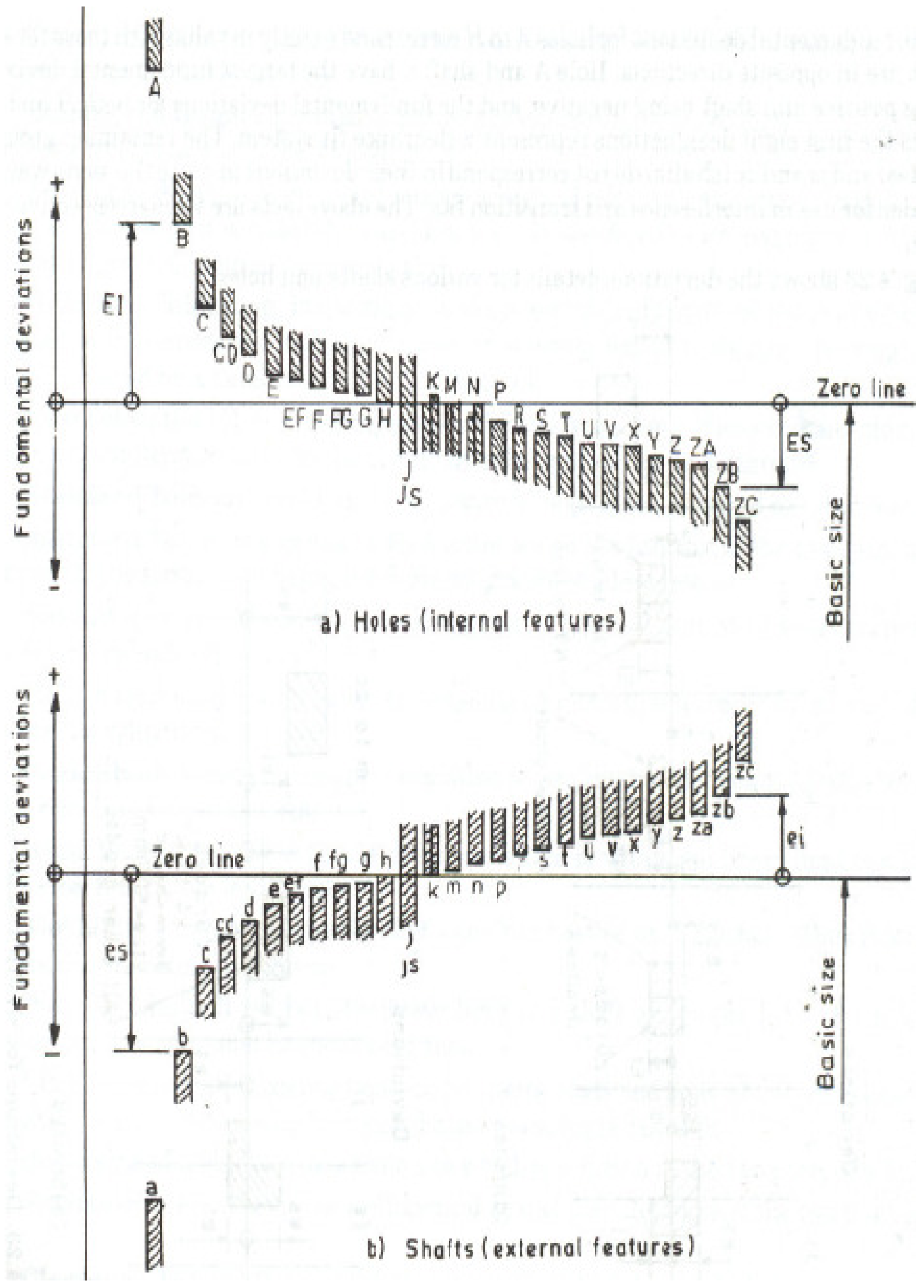


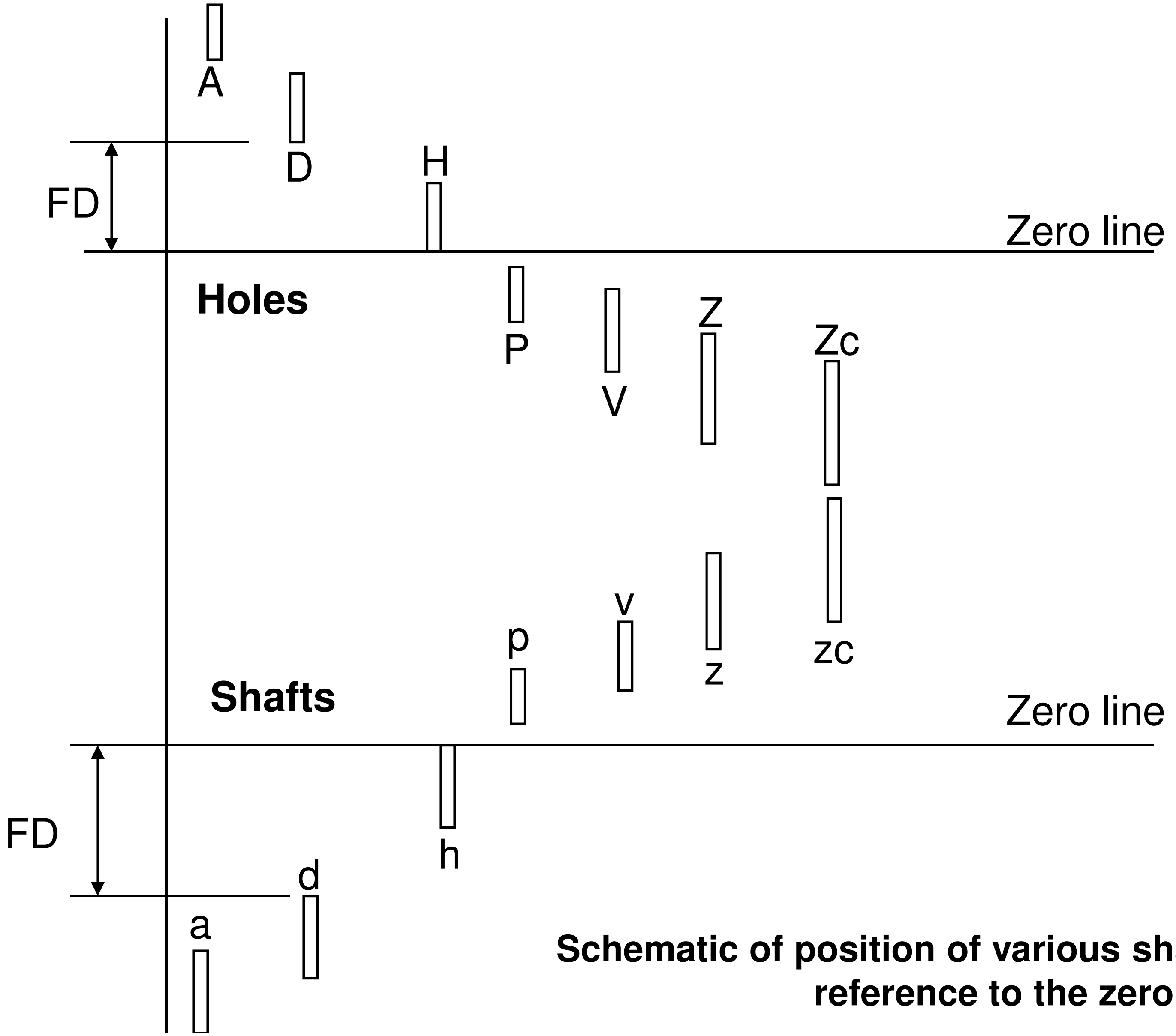
Fig. 7 [a-b] Systems of Fit



Schematic for grades in Indian Stds.

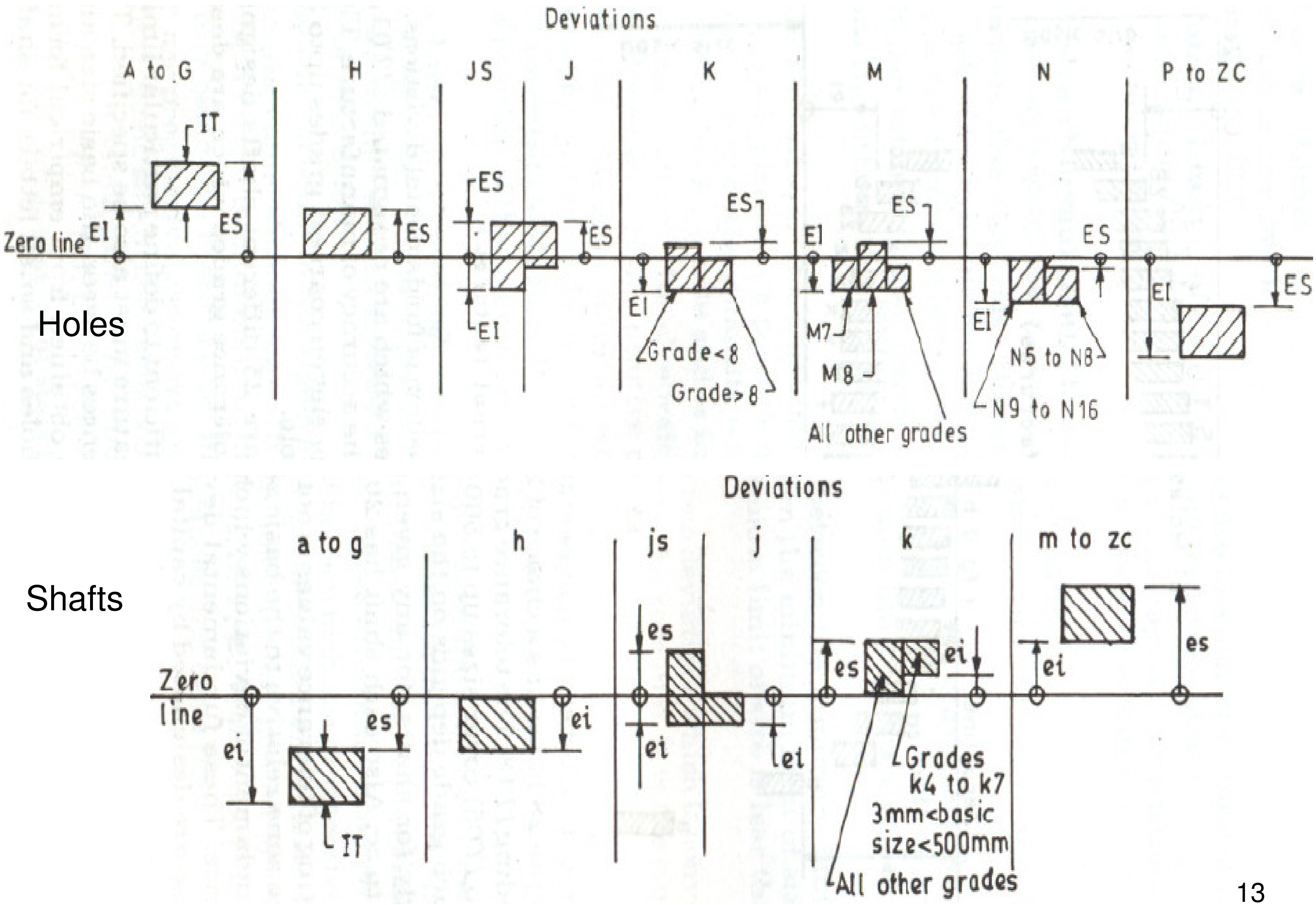
Disposition of all the shafts and holes with reference to the zero line

Limits and Fits - Definitions



Schematic of position of various shafts and holes with reference to the zero line

Fig. 7 Fundamental deviations for various shafts and holes



Grades of Tolerance

Grade of Tolerance: It is an indication of the level of accuracy. There are 18 grades of tolerances – IT01, IT0, IT1 to IT16

IT01 to IT4 - For production of gauges, plug gauges, measuring instruments

IT5 to IT 7 - For fits in precision engineering applications

IT8 to IT11 – For General Engineering

IT12 to IT14 – For Sheet metal working or press working

IT15 to IT16 – For processes like casting, general cutting work

Grades of Tolerance

Standard Tolerance: Various grades of tolerances are defined using the 'standard tolerance unit', (i) in µm, which is a function of basic size [3].

$$i = 0.45\sqrt[3]{D} + 0.001D$$

where, D *(mm)* is the geometric mean of the lower and upper diameters of a particular diameter step within which the chosen the diameter D lies.

Diameter steps in I.S.I are: (a-b, where a is above and b is up to, Refer Table in the following sheet)

1-3, 3-6, 6-10, 10-18, 18-30, 30-50, 50-80, 80-120, 120-180, 180-250, 250-315, 315-400 and 400-500 mm

Table for Sizes

Values in millimetres

a) Basic sizes up to 500 mm (incl.)			
Main steps		Intermediate steps [1)]	
Above	Up to and including	Above	Up to and including
–	3	No subdivision	
3	6		
6	10		
10	18	10 14	14 18
18	30	18 24	24 30
30	50	30 40	40 50
50	80	50 65	65 80
80	120	80 100	100 120
120	180	120 140 160	140 160 180
180	250	180 200 225	200 225 250
250	315	250 280	280 315
315	400	315 355	355 400
400	500	400 450	450 500

Grades of Tolerance

It is understood that the tolerances have parabolic relationship with the size of the products. As the size increases, the tolerance within which a part can be manufactured also increases.

IT01 – 0.3 + 0.008D

IT0 – 0.5 + 0.012 D

IT1 – 0.8 + 0.020D

IT2 to IT4 – the values of tolerance grades are placed geometrically between the tolerance grades of IT1 and IT5.

IT6 – 10 i; IT7 – 16i; IT8 – 25i; IT9 – 40i; IT10 – 64i; IT11 – 100i; IT12 – 160i; IT13 – 250i; IT14 – 400i; IT15 – 640i; IT16 – 1000i.

Formulae for fundamental deviations of shafts up to size 500 mm

Upper Deviation (es)	
Shaft Designation	*In microns (for D in mm)*
a	$= -(265 + 1.3D)$ for $D \leq 120$ and $= -3.5D$ for $D > 120$
b	$= -(140 + 0.85D)$ for $D \leq 160$ $= -1.8D$ for $D > 160$
c	$= -52D^{0.2}$ for $D \leq 40$ $= -(95 + 0.8D)$ for $D > 40$
cd	G.M. of values for c and d
d	$= -16D^{0.44}$
e	$= -11D^{0.41}$
ef	G.M. of values for e and f
f	$= -5.5D^{0.41}$
fg	G.M. of values for f and g
g	$= -2.5D^{0.34}$
h	$= 0$

Lower Deviation (ei)	
Shaft Designation	*In microns (for D in mm)*
j	No formula
js	$ITI/2$
$k4$ to $k7$	$= +0.6\sqrt[3]{D}$
k for grade ≤ 3 and ≥ 7	
m	$= +(IT7 - IT6)$
n	$= +5D^{0.34}$
p	$= +IT7 + 0$ to 5
r	= geometric mean of values for p and s
s	$= IT8 + 1$ to 4 for $D \leq 50$ $= +IT7$ to $+0.4D$ for $D > 50$
t	$= +IT7 + 0.63D$
u	$= +IT7 + D$
v	$= +IT7 + 1.25D$
x	$= +IT7 + 1.6D$

Formulae for fundamental deviations of shafts up to size 500 mm

y	$= + IT7 + 2D$
z	$= + IT7 + 2.5D$
za	$= IT8 + 3 + 3.15D$
zb	$= + IT9 + 4D$
zc	$= + IT10 + 5D$

<table>
<tr><td colspan="3">All deviations except those given below :</td><td>General rule :
Hole limits are identical with the shaft limits of the same symbol (letter and grade) but disposed on the other side of the zero line.
EI = Upper deviationes of shaft of the same letter symbol but of opposite sign.</td></tr>
<tr><td rowspan="2"></td><td>N</td><td>9 and coarser grades</td><td>$ES = 0$</td></tr>
<tr><td>J, K, M and N</td><td>Up to Grade 8 inclusive</td><td rowspan="3">Special rule :
ES = Lower deviation ei of the shaft of the same letter symbol but one grade finer and of opposite sign increased by the difference between the telerances of the two grades in question. i.e. $ei + IT_{n-1} = ES + IT_n$ and $ei - IT_n = ES - IT_{n-1}$.</td></tr>
<tr><td>For size above 3 mm</td><td>K, M and N</td><td>Up to grades</td></tr>
<tr><td>For sizes above 3 mm</td><td>P to ZC</td><td>Up to Grade 0 inclusive</td></tr>
</table>

Formulae for fundamental deviations of shafts up to size 500 - 3150 mm

Shafts			Holes			Formula for deviations in μ
Type	Fund Deviation	Sign	Type	Fund Deviation	Sign	(For D in mm)
d	s	—	D	EI	+	$16D^{0.44}$
e	"	—	E	"	+	$11D^{0.41}$
f	"	—	F	"	+	$5.5D^{0.41}$
g	"	—	G	"	+	$2.5D^{0.34}$
h	"	No sign	H	"	No sign	0
js	ei	—	JS	ES	+	$0.5ITn$
k	"	+	K	"	—	0
m	"	+	M	"	—	$0.024D + 12.6$
n	"	+	N	"	—	$0.04D + 21$
p	"	+	P	"	—	$0.072D + 37.8$
r	"	+	R	"	—	Geometric mean of the values for p and s or P and S
s	"	+	S	"	—	$IT7 + 0.4D$
t	"	+	T	"	—	$IT7 + 0.63D$
u	"	+	U	"	—	$IT7 + D$

Selection of Holes

Letter Symbol → / Grade ↓	A	B	C	CD	D	E	EF	F	FG	G	H	J	JS	K	M	N	P	R	S	T	U	V	X	Y	Z	ZA	ZB	ZC
0 & 01											×		×															
1											×		×															
2											×		×															
3							×		×	×	×		×	×	×	×	×	×	×									
4							×	×	×	×	×		×	×	×	×	×	×	×									
5					×	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×					
6				×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		
7				×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
8		×	×	×	×	×	×	×	×		×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
9	×	×	×	×	×	×	×	×	×		×		×	×	×	×	×	×		×		×	×	×	×	×	×	×
10	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×		×		×	×	×	×	×	×	×
11	×	×	×		×						×		×			×									×	×	×	×
12	×	×	×		×						×		×															
13	×	×	×		×						×		×															
14											×		×															
15											×		×															
16											×		×															
17											×		×															
18											×		×															

Notes : Holes *A* and *B* are provided only for basic sizes greater than 1 mm. Holes *K* in tolerance grades above *IT*8 are provided only for basic sizes less than or equal to 3 mm.

Holes *T*, *V* and *Y* are only provided for basic sizes greater than 24, 18 and 18 mm.

Holes *N* of tolerance grades above *IT*8 only are only provided for basic sizes greater than 1 mm. Tolerance grades *IT*14 to *IT*18 are only provided for basic sizes greater than 1 mm.

Selection of Shafts

Letter Symbol → / Grade ↓	*a*	*b*	*c*	*cd*	*d*	*e*	*ef*	*f*	*fg*	*g*	*h*	*j*	*js*	*k*	*m*	*n*	*p*	*r*	*s*	*t*	*u*	*v*	*x*	*y*	*z*	*za*	*zb*	*zc*
0 & 10											×	×																
1											×		×															
2											×		×															
3							×	×	×	×	×		×	×	×	×	×	×	×									
4							×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×					
5				×		×	×	×	×	×	×		×	×	×	×	×	×	×									
6				×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		
7				×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
8			×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
9	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×		×		×	×	×	×	×	×
10	×	×	×	×	×	×	×	×	×	×	×		×	×			×	×	×				×	×	×	×	×	×
11	×	×	×		×						×		×	×		×									×	×	×	×
12	×	×	×		×								×	×													×	×
13	×	×			×						×		×	×														
14											×		×															
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16											×		×															
17											×		×															
18											×		×															

Notes : Shaft *a* and *b* are provided only for basic size greater than 1 mm.

Shafts *j*8 are provided only for basic sizes less than or equal to 3 mm.

Shafts *t*, *v* and *y* are provided for basic sizes greater than 24, 14 and 18 mm respectively.

Tolerance grades *IT*14 to *IT*18 are only provided for basic sizes greater than 1 mm.

Selection of Fits

Clearance Fits (Hole Basis System):

Shafts	Grades	Description of fit	Application
a, b, c	11	Very large clearance	Generally not used
d	8, 9, 10	Loose running	Loose pulleys
e	7, 8, 9	Loose clearance	Electric motor bearings, heavily loaded bearing
f	6, 7, 8	Normal running	Lubricated bearings (with oil or grease), pumps and smaller motors, gear boxes
g	5, 6	Precision running	Lightly loaded shafts, sliding spools, accurate bearings
h	5 to 11	Extreme clearance (preferably for non-running parts)	Sockets and spigots of joints

Preferred Clearance fits (in practice) [1] : H11/c11, H9/d9, H8/f7, H7/g6 (Guide Fit), H7/h6, C11/h11, D9/h9, F8/h7, G7/h6

Selection of Fits

Transition Fits (Hole Basis System):

Shafts	Grades	Description of fit	Application
js	5, 6, 7	Slight clearance to slight interference	Very accurate location, couplings, spigots, gears,
k	5, 6, 7	No clearance to little clearance	Precision joints likely to be subjected to vibrations
m	5, 6, 7	Slight interference (on average)	Forced assembly is required
n	5, 6, 7	Slight interference and very little clearance	Semi-permanent or tight fit assemblies

Preferred Transition fits [1]: H7/k6, H7/n6, K7/h6, N7/h6

Selection of Fits

Interference Fits (Hole Basis System):

Shafts	Grades	Description of fit	Application
p	6, 7, 8,	True interference (light)	Fixing bushes, standard press fit
r	5, 6, 7	Interference (but can be dismantled)	Tight press fit. Keys in key ways
s	5, 6, 7	Semi permanent/ permanent fit	Valve seating, collars on shafts
t, u	----	High degree of interference	Permanent assemblies

Preferred Interference fits [1]: H7/p6 (Press fit), H7/s6, H7/u6, P7/h6, S7/h6, U7/h6

Example #1

Evaluate limits and fits for a pair of – Diameter 6 H7/g6

Solution: The size 6 mm lies in the diametral step of 3-6, therefore, D is given by –

$$D = \sqrt{3 \times 6} = 4.24mm$$

The value of fundamental tolerance unit is given by –

$$i = 0.45\sqrt[3]{D} + 0.001D$$

$$i = 0.45\sqrt[3]{4.24} + 0.001 \times 4.24$$

$$i = 0.7327\mu m$$

Limits of tolerance for hole H7

The standard tolerance is – 16 i = *16x0.7327 = 11.72 = 12* μm

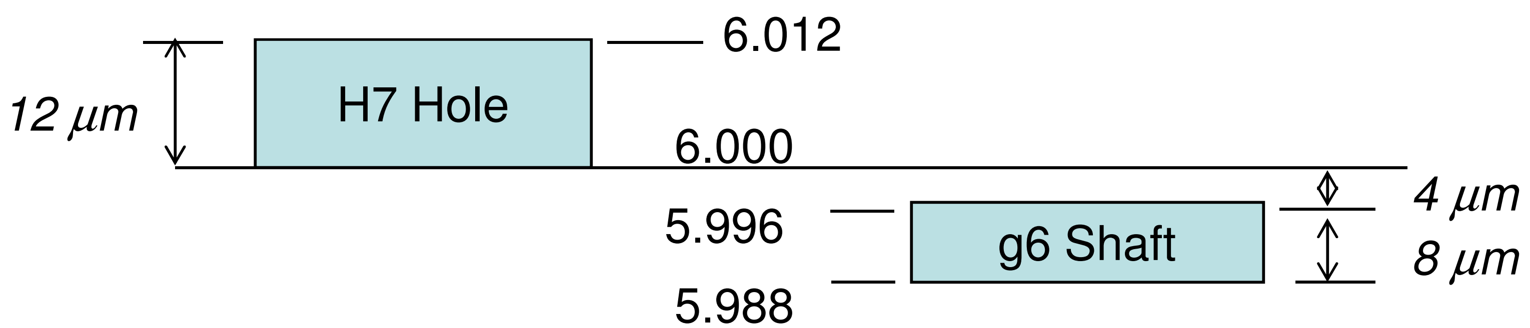
The fundamental deviation H hole is – 0

Limits of tolerance for g6 shaft

The standard tolerance is – 10 i *10x0.7327 = 7.327 = 8* μm

Fundamental deviation for g shaft $= -2.5D^{0.34} = -2.5(4.24)^{0.34} = -4.085 = -4\mu m$

Example #1



Disposition of tolerance zone around the zero line

Fit

Maximum clearance = Maximum size of hole - Minimum size of shaft

$$= 6.012 – 6.988 = 0.024 \text{ mm} = 24\ \mu m$$

Minimum clearance = Minimum size of hole - Maximum size of shaft

$$= 6.000 - 6.996 = 0.004 \text{ mm} = 4\ \mu m$$

The type of fit is Clearance.

Example #2

Calculate the limits of sizes for ϕ 20 P7/h6 and identify the fit.

Therefore, D is given by –

$$D = \sqrt{18 \times 24} = 20.78mm$$

The fundamental tolerance unit i is given by –

$$i = 0.45\sqrt[3]{20.78} + 0.001 \times 20.78 = 1.258\mu m$$

Limits evaluation for P7 Hole

The fundamental deviation for p shaft is – IT7 + 0 to 5

The fundamental deviation P7 hole – IT6 + 0 to 5 =10 i + 5

$$10 \times 1.258 + 5 = 17.58 = 18\mu m$$

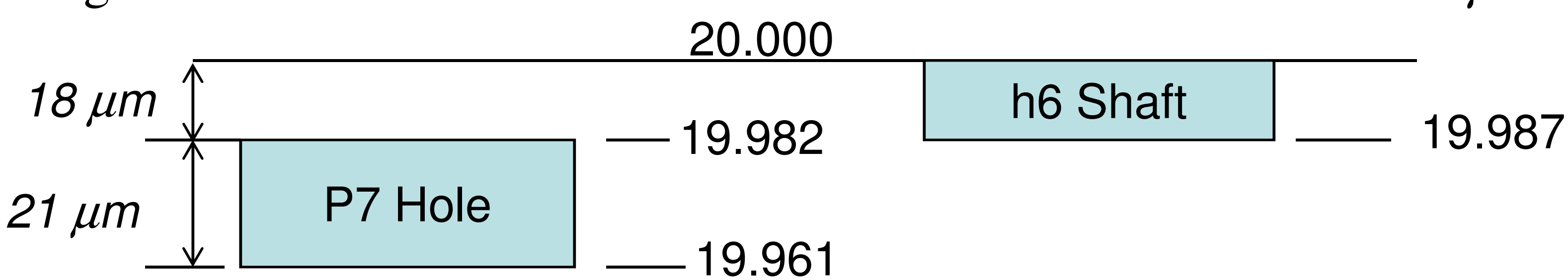
For grade 7 the standard tolerance is – 16 i = *16x1.258* = *20.128* = *21* μm

Example #2

Limits evaluation for h6 Shaft

The fundamental deviation for h shaft is – 0

For grade 6 the standard tolerance is – 10 i = $10 \times 1.258 = 12.58 = 13\ \mu m$



Disposition of tolerance zone around the zero line

Fit

Maximum clearance = Maximum size of hole - Minimum size of shaft

$$= 19.982 – 19.987 = - 0.005 = - 5\ \mu m$$

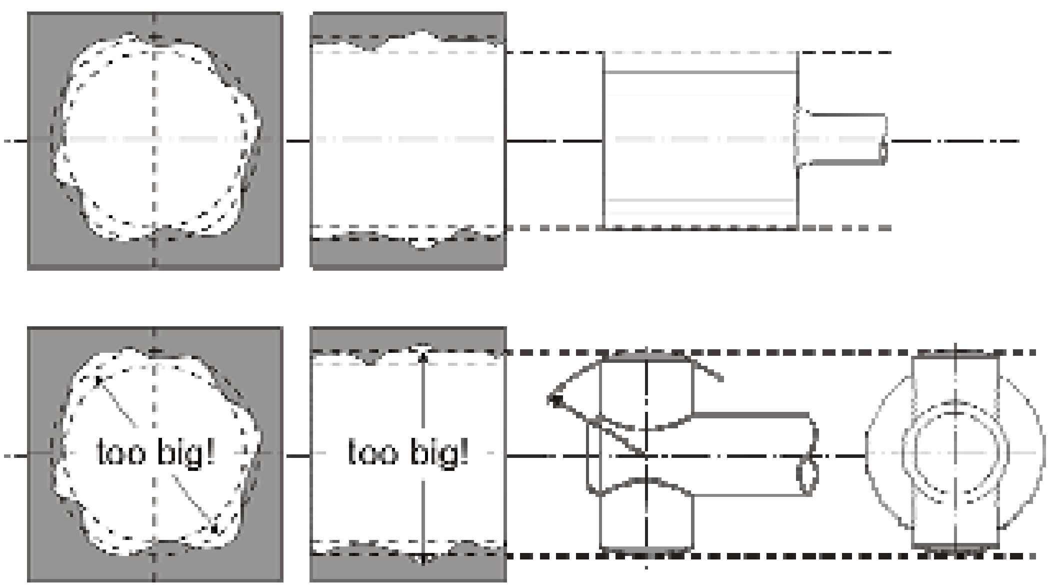
Maximum Interference = Minimum size of hole - Maximum size of shaft

$$= 19.961\ \ - 20.000 –= - 0.039 \text{ mm} = - 39\ \mu m$$

The fit is Interference. But it can become Transition if you choose some value of FD for p shaft between IT7 + 1 to 5 μm

Taylor's Principle of Gaging

- The go gage should be designed to check the form
- The no-go gage checks the individual sections



Go gage:
- Plug gage for maximum material dimension, i.e., smallest hole
- Testing the function, i.e., shape and pairing dimension

No Go gage:
- Ball gage for minimum material dimension, biggest hole
- Testing the maximum dimension

References

References and other study material are available at –

1.http://www.mitcalc.com/doc/tolerances/help/en/tolerances.htm

2. http://www.ecs.umass.edu/mie/labs/mda/dlib/fit_tol/fitandtol.html

3. R. K. Jain, Engineering Metrology, Khanna Publishers, New Delhi (India)