Precision Machine Design-Fundamental Concepts

Why Design?

"Design determines more than 70% of the whole machine's performance, or Machine's Destiny" (H.J.Pahk)

Why Preision?

-To achieve greater miniaturization and packing densities in Semiconductor and Flat Panel Display

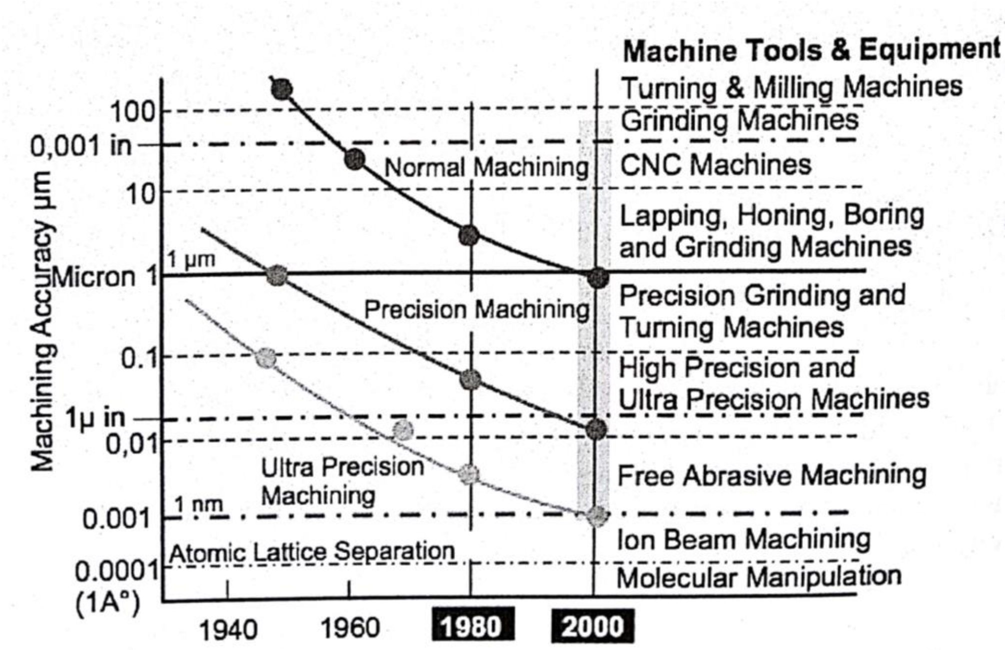
-To achieve further advances in science and technology such as Nano/Bio/MEMS application

-To improve quality control via higher manufacturing accuracy capabilities; thence to reduce scrap, rework, and inspection; to reduce manufacturing cost

-To eliminate 'field-fitting' and promote assembly in auto/machine assembly

-To improve interchageability of components

-To achieve longer wear/fatigue life of components



Progress in machining accuracy from Prof. Taniguchi

	1920	1940	1960	1980	2000	2020 (Extrapolated[1])
Normal machining	—	60	30	5	1	0.1
Precision machining	—	75	5	0.5	0.1	0.03
High-precision machining	75	5	0.5	0.05	0.01	>0.003
Ultrahigh-precision machining	5	0.5	0.05	0.005	0.001	<0.3 nm

Precision machining — High-precision machining — Ultrahigh-precision machining

COLOR FIGURE 4.1 Evolution of machine required precision over the last century. Extrapolation from Prof. Tanigushi's graph, University of Tokyo. Values are indicated in micrometer.

(Source: S.Mekid, Introduction to precision machine design an error assessment, CRC press)

	Tolerance band	Mechanical	Optical
Normal machining	200 μm	Normal domestic appliances and automotive parts, etc.	Camera, telescope and binocular bodies
	50 μm	General purpose mechanical parts for typewriters, engines, etc.	Camera shutters
			Lens holders for cameras and microscopes
Precision machining	5 μm	Mechanical watch parts	Lenses
		Machine tool bearings	Prisms
		Gears	Optical fiber and connectors (multi-mode)
		Ballscrews	
		Rotary compressor parts	
	0.5 μm	Ball and roller bearings	Precision lenses
		Precision drawn wire	Optical scales
		Hydraulic servo valves	IC exposure masks (photo, X-ray)
		Aerostatic bearings	Laser polygon mirrors
		Ink-jet nozzles	X-ray mirrors
		Aerodynamic gyro bearings	Elastic deflection mirrors
			Monomode optical fibre and connectors
Ultra-precision machining	0.05 μm	Gauge blocks	Optical flats
		Diamond indentor tip radius	Precision Fresnel lenses
		Microtome cutter edge radius	Optical diffraction gratings
		Ultra-precision X-Y tables	Optical video disks
	0.005 μm		Ultra-precision diffraction gratings

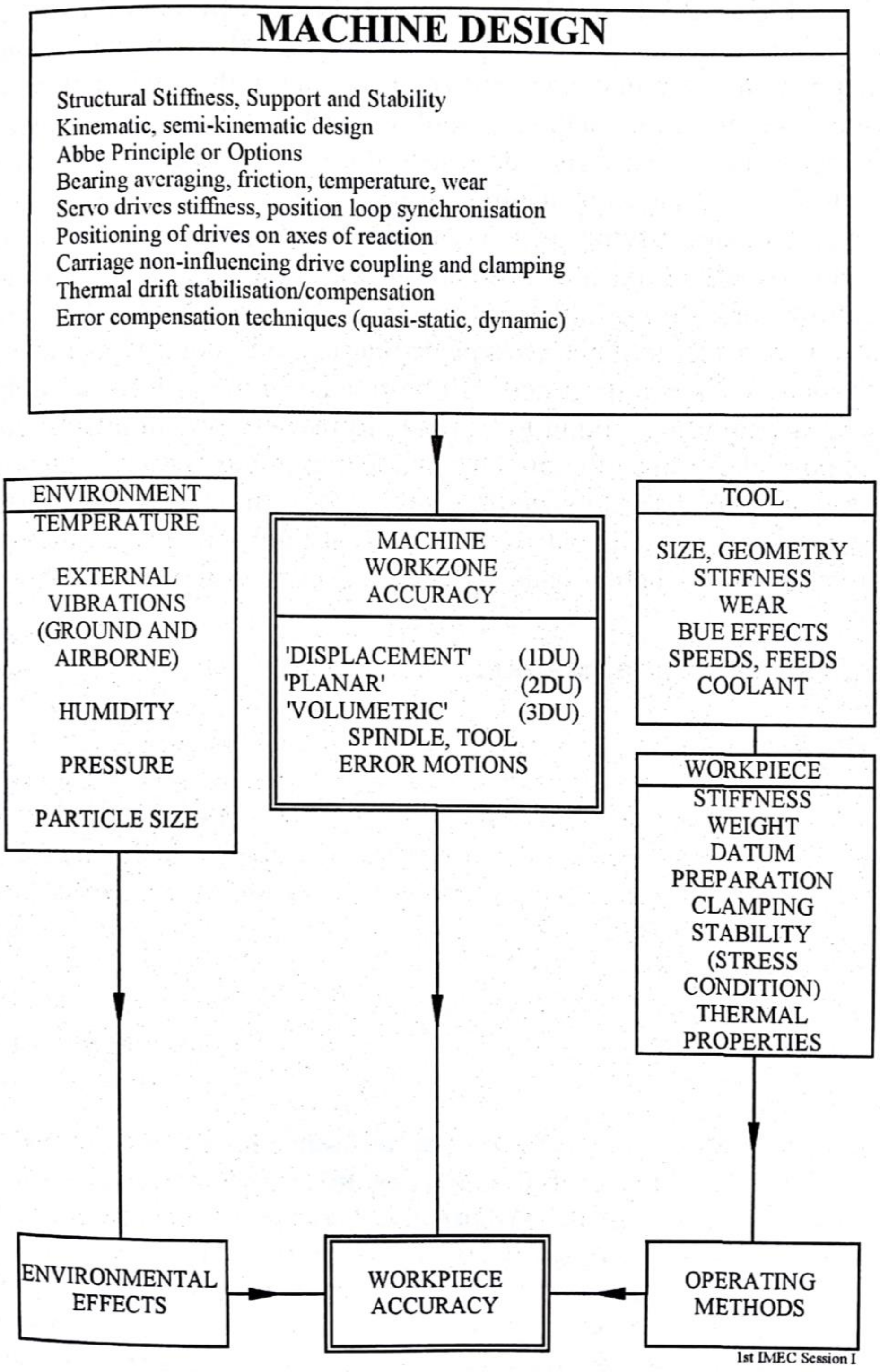
Tolerances on mechanical and optical products (from Prof. Taniguchi)

Factors affecting Precision and Accuracy

1. Machine : Accuracy*
2. Operation:

   Process Condition, Tool, Workpiece, Operator
3. Environment:
   (1) Temperature(change, gradient, frequency, radiation)
   (2) Vibration(Ground, Acoustic)
   (3) Humidity and pressure(wavelength change)

(*This accuracy is already determined from the design stage)



Factors affecting workpiece accuracy from Wada

(Source: Dornfeld etal., Precision manufacturing, Springer)

Terminology for Precision Machine Design

Error: Difference between the actual position and the nominal position of a machine

Repeatability of positioning: Quantitative expression of the closeness of successive positioning of the same quantity under the same conditions

Deviation: Divergence (or difference) of a value from the standard or reference value

Standard deviation: RMS (root mean square) deviation, or average deviation

Spread, scatter, dispersion: Difference between the largest and the smallest values for the same quantity

Resolution: Ability to respond to the smallest changes of quantity, or smallest display of instrument

Error classification in terms of reproducibility

Systematic error:

An error which, in the course of a number of measurements of the same quantity under the effectively same conditions, remains constant in absolute value and sign. Or, it varies according to a definite law when conditions change. Practically, the systematic error can be evaluated as the average value of the errors from the repeat measurements. Wherever systematic errors have been established, they may be used for correction or compensation for the value measured.

Random error (or random uncertainty):

An error varies in unpredictable manner in absolute value and in sign under effectively identical conditions. It is only possible to fix limits within which the error will lie with a stated probability. Standard deviation, k times σ, of the repeat measurements can be used for the random error. It would be 2σ for 95%, 3σ for 99% typically

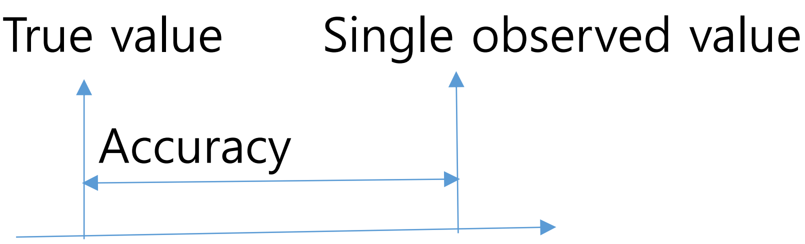
Hysteresis error (reversal or backlash error)

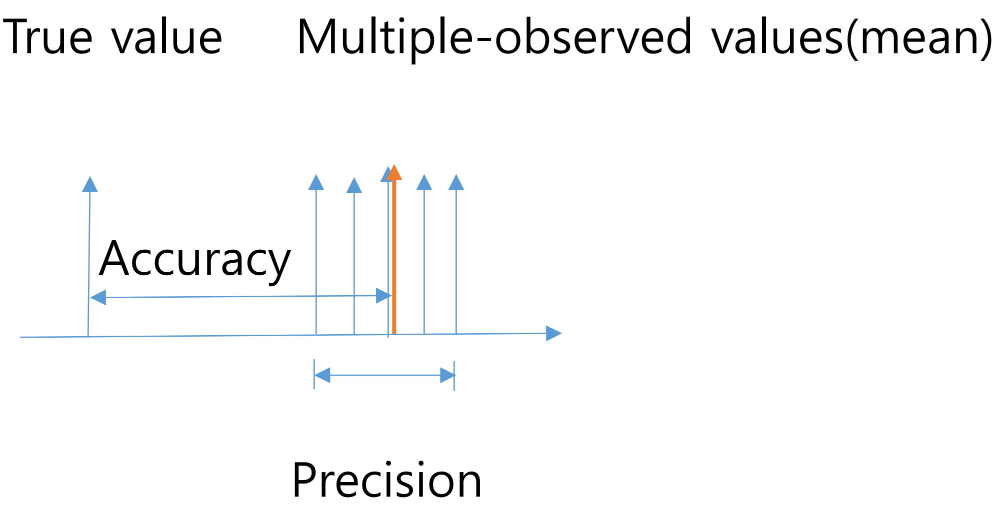
A highly reproducible error, being governed by the play in the transmission components and the friction forces, and it is sign dependent on the direction of approach.

Accuracy and Precision

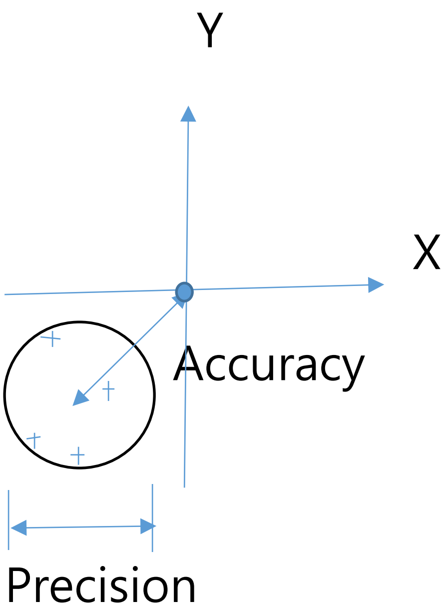
Accuracy: The closeness of an observed quantity to the true value (by ISO). It can be evaluated as the systematic error.

Precision: The closeness of agreement between the repeat measurement results (by ISO). It can be evaluated as the random error(random uncertainty), or repeatability.





Accuracy and Precision in 2D plane



"The smaller the random error, the more precise, and higher repeatability"

"The smaller the systematic error, the more accurate"

Ex) Precision Machine, Precision Engineering, Machine Accuracy

6 DOF errors

6 DOFs(Degree of Freedoms) errors are introduced for the linear motion of a machine axis on the guideway, or slider.

(DOFs=Degree of Freedoms

=Number of Independent Coordinates)

How many DOFs for "a free body in 3D space"?

3 translational errors; δx, δy, δz

x,y,z indicate the direction of translational errors

3 rotational errors; Ex, Ey, Ez

x,y,z indicate the direction of rotational errors, or axis of rotation;

For the Y axis of slide; y is added to the notation in the bracket such as (y)

$\delta x(y)$, $\delta y(y)$, $\delta z(y)$; Ex(y), Ey(y), Ez(y)

Positional error; $\delta y(y)$

Horizontal straightness error; $\delta x(y)$

Vertical straightness error; δz(y)

Pitch angular error; Ex(y)

Yaw angular error; Ez(y)

Roll angular error; Ey(y)

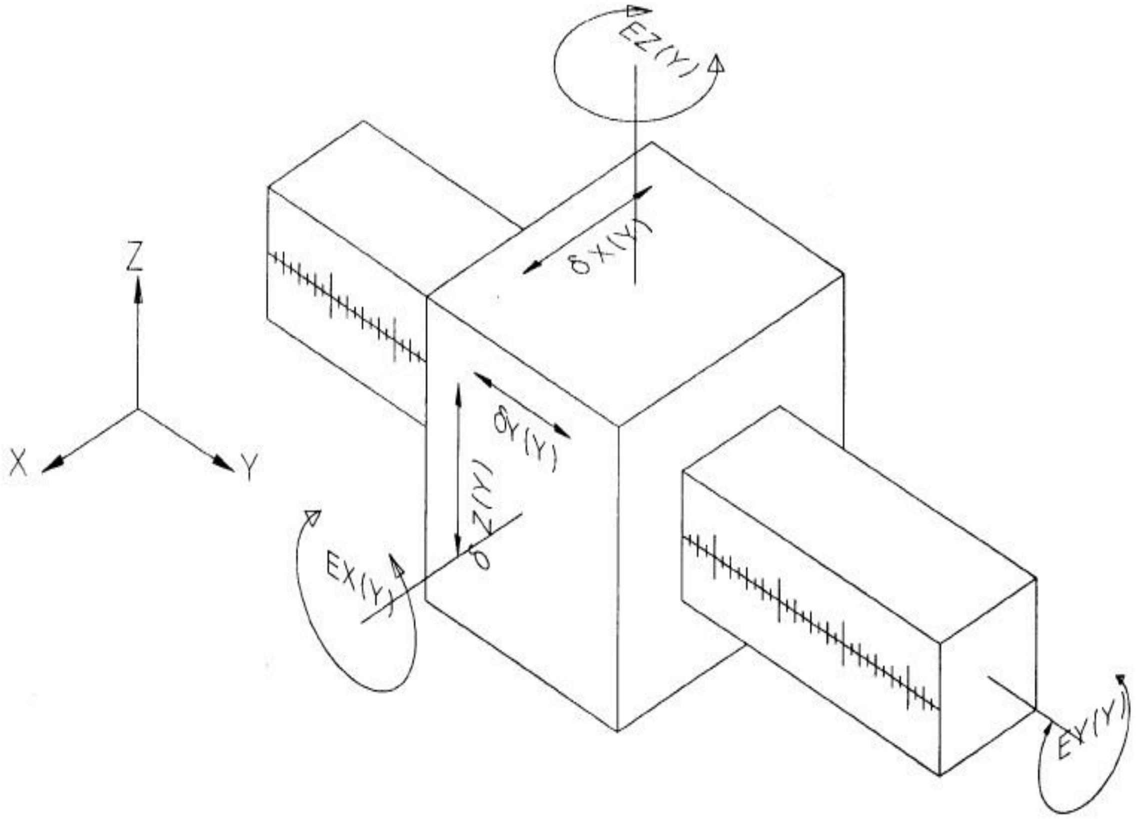


FIG.3.1 6 DEGREE OF FREEDOMS OF ONE GUIDE WAY

(*Source: Ph.D Thesis of Dr. H.J.Pahk, University of Manchester)

(1)Positional error, δy(y)

: Errors observed along the direction of travel, due to thermal expansion of slide, lead screw error, scale error, wavelength error, interpolation error, etc, and typically few 10um.

(2)Straightness error; δx(y), δz(y)

:Errors observed in the transverse direction that perpendicular to the direction of travel, and is mainly due to the non-straight of the guideway from manufacturing defects, thermal deformation, or wear. Typically, few um for 1 m travel. Horizontal straightness error observed in the xy plane, and vertical straightness error in the yz plane.

(3)Anglular error; Ex(y), Ey(y), Ez(y)

Angular error, or errors of axis of rotation observed along the guideway.

Ex(y):Pitch angular error observed in the horizontal transverse direction(X) along the guideway. It can be due to vertical straightness error, $\delta z(y)$; or thermal deformation(thermal bending) of guideway.

Ez(y):Yaw angular error observed in the vertical transverse direction(Z) along the guideway. It can be due to the horizontal straightness error, $\delta x(y)$; or thermal deformation (thermal bending) of guideway.

Ey(y):Roll angular error observed in the direction of travel(Y) along the guideway. It can be due to the flatness, warping of the guideway.

Once the angular errors are observed, the Abbe errors are always induced. The Abbe error is defined as the product of angular error and the Abbe offset, where the Abbe offset is defined as the distance between the line of measurement(scale) and the line of dimension being measured.

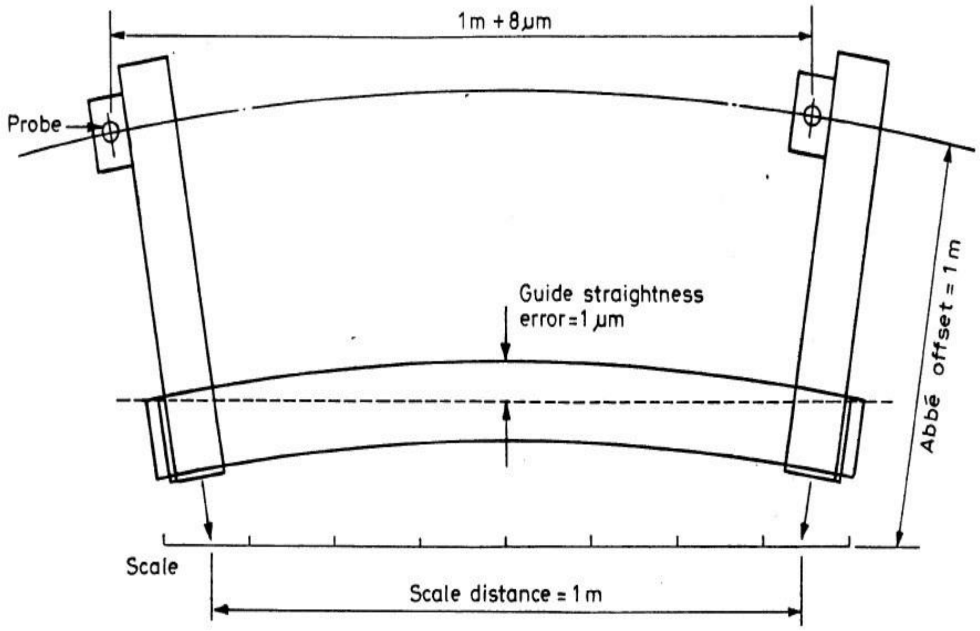
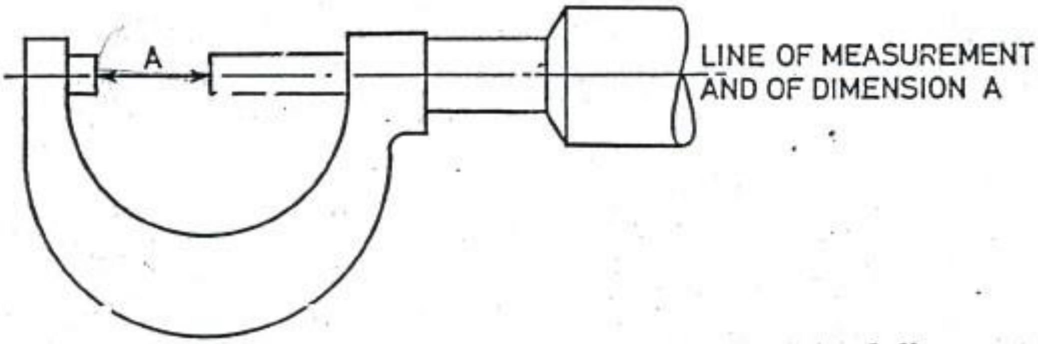


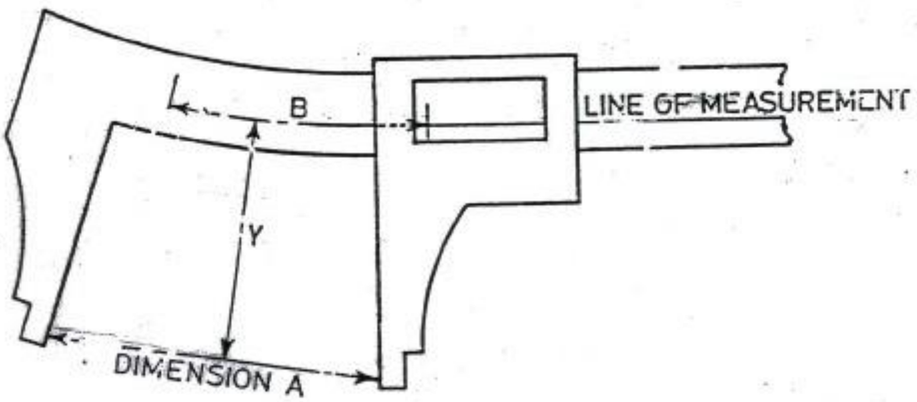
FIG.2.1 Influence of Abbé Offset and Guideway Straightness on Probe Position

14

	University of Manchester Institute of Science & Technology	M.Burdekin	0596 / A

*Source: Lecture Note of Dr. M.Burdekin, University of Manchester





*Source: 'Metrology for Engineers', 5th Ed. published by Cassel, and authored by J.F.W. Galyer and C.R. Shotbolt

The Abbe Principle or 'Principle of Alignment'

:The line of measurement(scale), and the line of the dimension being measured should be coincident. The Abbe offset is always to be removed or minimized for precision alignment, or sometimes called as 'principle of alignment'. This principle is very fundamental to precision metrology and design.

∴ Abbe Error induced[um]

= Angular Error[urad] X Abbe Offset[m]

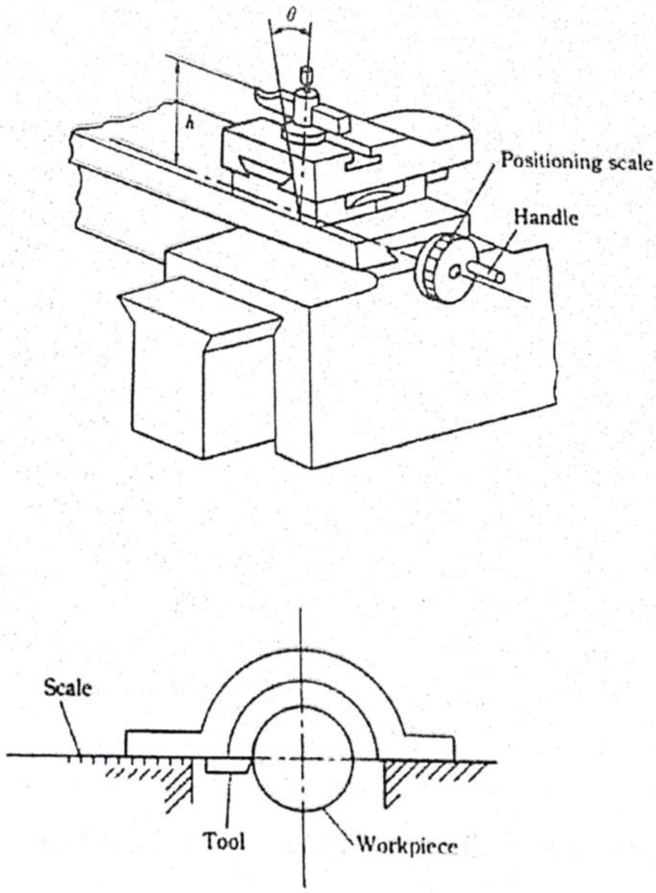
For the general 3D case;

The Abbe Error in 3D **=** [ΔX, ΔY, ΔZ]= **E** X **A** **=**

$$\begin{bmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ Ex & Ey & Ez \\ Ax & Ay & Az \end{bmatrix} = \mathbf{i}(Ey \cdot Az - Ez \cdot Ay) - \mathbf{j}(Ex \cdot Az - Ez \cdot Ax) + \mathbf{k}(Ex \cdot Ay - Ey \cdot Ax)$$

where **E** (Ex, Ey, Ez) is the angular error,

and **A** (Ax, Ay, Az) is the Abbe offset.



Lathe with tool post violating Abbe principle (upper), a tool post designed in accord with Abbe Principle, from Nakazawa

(Source:Dornfeld, Precision Manufacturing, Springer)

HW2: Prove the Abbe error is 8um for 1um straightness error guide and 1m Abbe offset.

(1) Simulate the straightness profile with an approximate mathematical functions such as parabolic, or sinusoidal function

(2) Derive the induced angular error by differentiating the straightness profile.

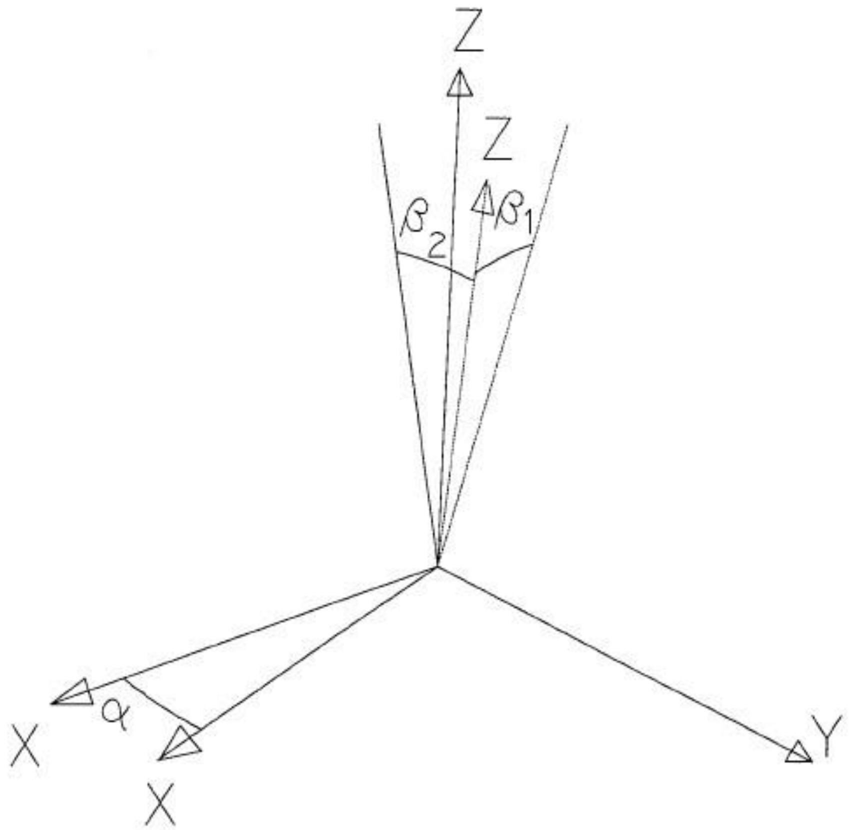
(3) Calculate the Abbe error accordingly

Squareness errors, out of squareness [urad]

:Due to the non-squareness of the nominal perpendicular axis, or non-orthogonality.

Q) Real, or Genuine 90 deg between Axis?

No way with exact 90 deg. Errors in Squareness, perpendicularity, or orthogonality exist between the motions of axis during the multi-axis movement. This is mainly due to the mis-assembly or mis-alignment between the machine axis. Typically, few 10 urad exists between precision machine axis movements.



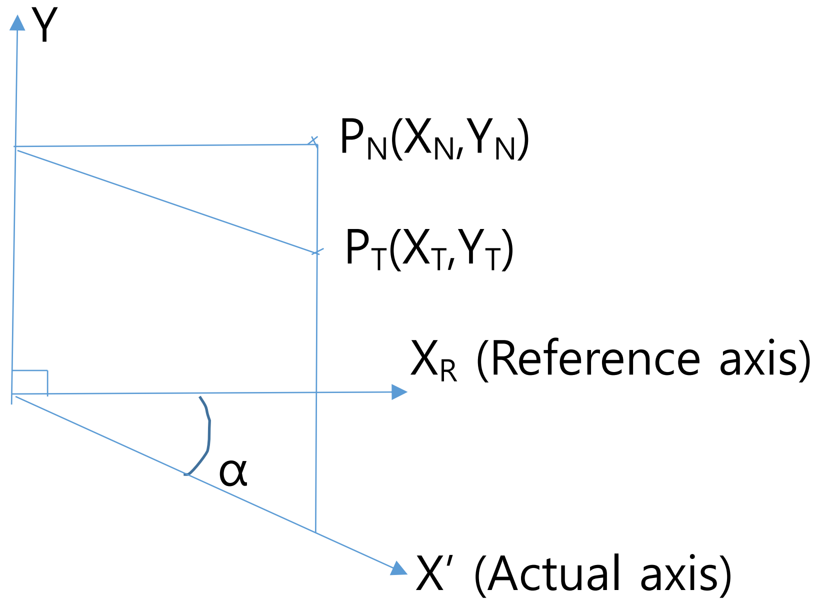
Three Squareness error compenents in 3D

(Source: PhD Thesis, Dr.H.J.Pahk, Univ. of Manchester)

When the geometric errors are existing, the true position is always different from the nominal position.

For the squareness errors;

(1) Squareness error, α, between X and Y axis



When machine moves nominally to $P_N(X_N,Y_N)$, true position would be $P_T(X_T,Y_T)$;

$X_T=X_N \cdot \cos\alpha \fallingdotseq X_N$

$Y_T=Y_N-X_N \cdot \sin\alpha \fallingdotseq Y_N - X_N \cdot \alpha$

where α=squareness error=out of squareness [urad]

and α is assumed as typically 10 urad=10^{-5} rad. Then,

$\cos\alpha = 1 - \alpha^2/2! + \ldots \fallingdotseq 1 \quad (\because \alpha^2 \fallingdotseq (10^{-5})^2 = 10^{-10})$

$\sin\alpha = \alpha - \alpha^3/3! + \ldots \fallingdotseq \alpha$

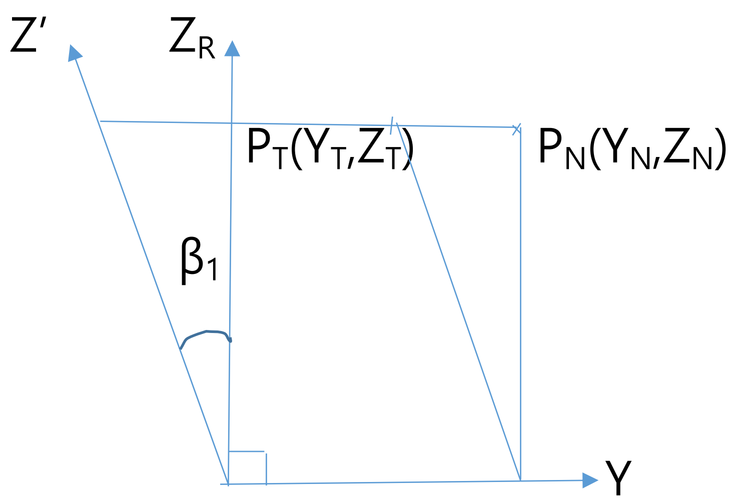
Thus, the squareness error contributes to the positioning errors;

Error in X, $\Delta X = X_T - X_N = 0$

Error in Y, $\Delta Y = Y_T - Y_N = -\alpha \cdot X_N = -\alpha X$

Similarly,

(2) Squareness error, β_1, between Y and Z axis



$Z_T = Z_N \cdot \cos\beta_1 \fallingdotseq Z_N \quad (\because \beta_1 \fallingdotseq 0)$

$Y_T = Y_N - Z_N \cdot \sin\beta_1 \fallingdotseq Y_N - Z_N \cdot \beta_1 \quad (\because \beta_1 \fallingdotseq 0)$

where β_1 is the out of squareness, and typically assumed as few 10 urad

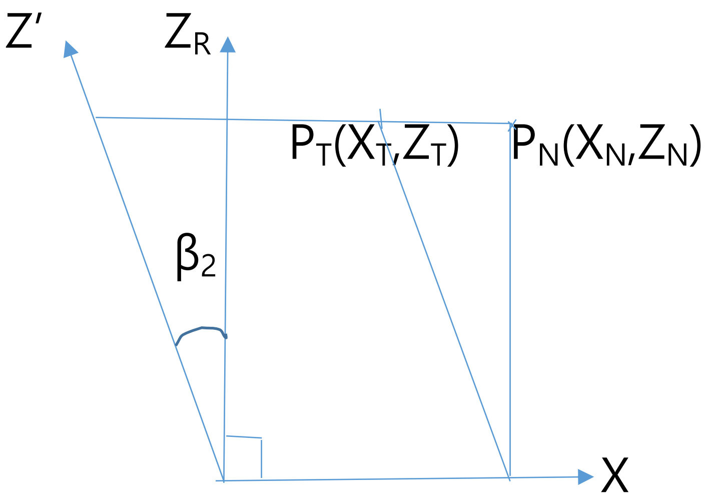
Thus, the squareness error contributes to the errors;

Error in Y, $\Delta Y= Y_T - Y_N= - \beta_1 \cdot Z_N=-\beta_1 \cdot Z$

Error in Z, $\Delta Z= Z_T - Z_N = 0$

Similarly,

Squareness error, β_2, between X and Z axis



$Z_T=Z_N \cdot \cos\beta_2 \fallingdotseq Z_N \quad (\because \beta_2 \fallingdotseq 0)$

$X_T=X_N - Z_N \cdot \sin\beta_2 \fallingdotseq X_N - Z_N \cdot \beta_2 \ (\because \beta_2 \fallingdotseq 0)$

where β_2 is the out of squareness, and typically few 10 urad

Thus, the squareness error contributes to the errors;

Error in X, $\Delta X = X_T - X_N = -\beta_2 \cdot Z_N = -\beta_2 \cdot Z$

Error in Z, $\Delta Z = Z_T - Z_N = 0$

Three squareness errors, α, β_1, β_2 are defined in the 3D space, and they are all independent.

For a 3 axis machine, having 3 slide axis,

Geometric errors for each axis

X axis (or X slide):

$\delta x(x)$, $\delta y(x)$, $\delta z(x)$; $Ex(x)$, $Ey(x)$, $Ez(x)$: 6 components

Y axis (or Y slide):

$\delta x(y)$, $\delta y(y)$, $\delta z(y)$; $Ex(y)$, $Ey(y)$, $Ez(y)$: 6 components

Z axis (or Z slide):

$\delta x(z)$, $\delta y(z)$, $\delta z(z)$; $Ex(z)$, $Ey(z)$, $Ez(z)$: 6 components

Kinematic Errors between each axis

α (or α_{xy}) in XY plane

β_1 (or α_{yz}) in YZ plane

β_2 (or α_{xz}) in XZ plane

In total, 21 geometric/kinematic error components are independently existing, and they contribute to the accuracy and repeatability of the 3 axis machine in the 3D space.