Design of High precision Machines-analysis, principles and techniques

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(Most slides by

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精密機械設計準則

The Eleven Principles and Techniques for the Design of High Precision Machines (McKeown, 1986)

1. Structure: **symmetry; dynamic stiff; high damping; secular stability; thermal stability; independent of foundation; seismic isolation**
2. Kinematic/Semi-Kinematic Design: **rigid body kinematics; three point support**
3. Abbé Principle (or options)
4. “Direct” Displacement Transducers: **scale or laser interferometer(s)**
5. Metrology Frames: **isolate measuring system from force paths and machine distortion**
6. Bearings: **high accuracy; high averaging/low rumble; low thermal effects; low limiting friction; high damping**

The Eleven Principles and Techniques for the Design of High Precision Machines (McKeown, 1986)

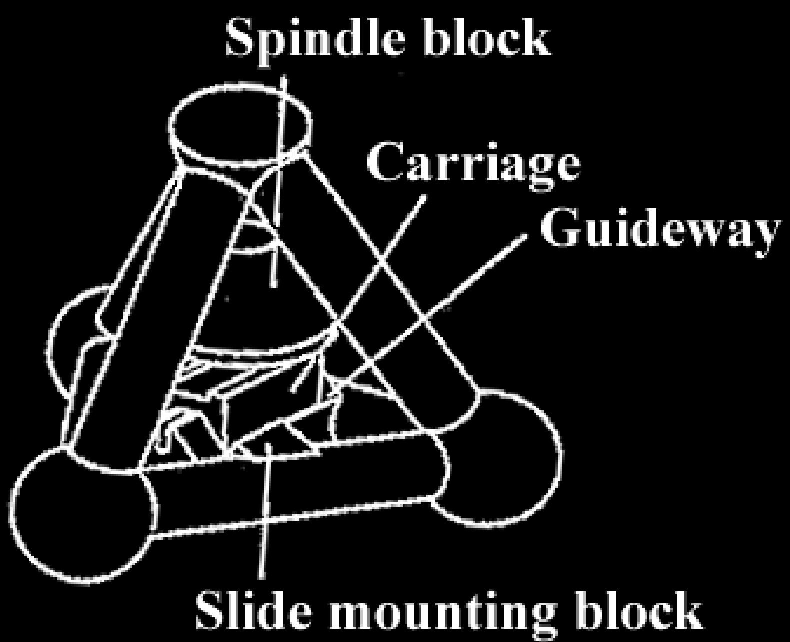
7. Drives/Carriages: **through axes of reaction; "non-influencing" couplings and clamps**
8. Thermal Effects: **eliminate/minimise thermal inputs and drift; stabilisation/compensation**
9. Servo-Drives and Control (CNC): **high stiffness/response/response/bandwidth; zero following errors; dynamic position-loop synchronisation**
10. Error Budgeting: **(i) geometrical-angular, straightness and orthogonal error motions (ii) thermal-loop expansions; deformations**
11. Error Compensation: **linear; planar; volumetric; quasi-static and dynamic**

Principle 1

Structure: **symmetry; dynamic stiff; high damping; secular stability; thermal stability; independent of foundation; seismic isolation.**

Structural Symmetry

- Highly stiff structure



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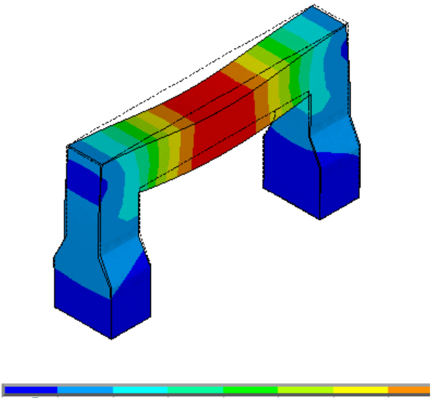
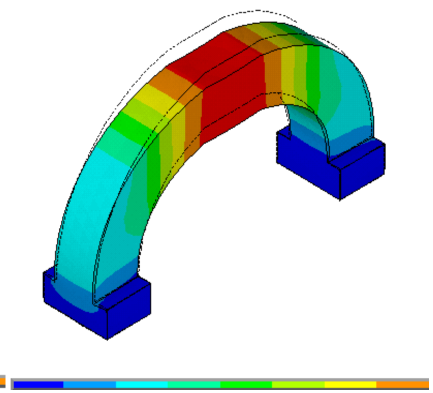
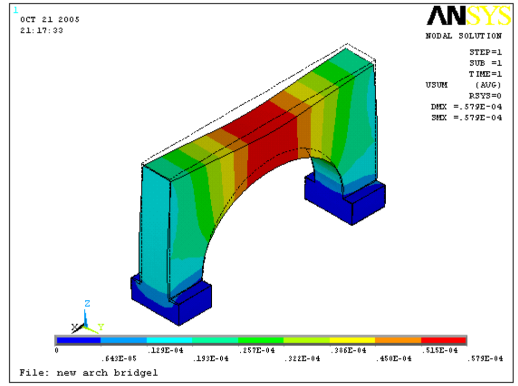
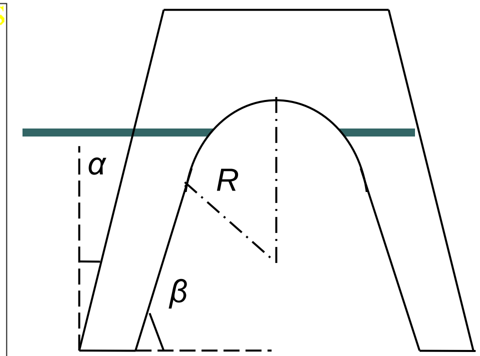
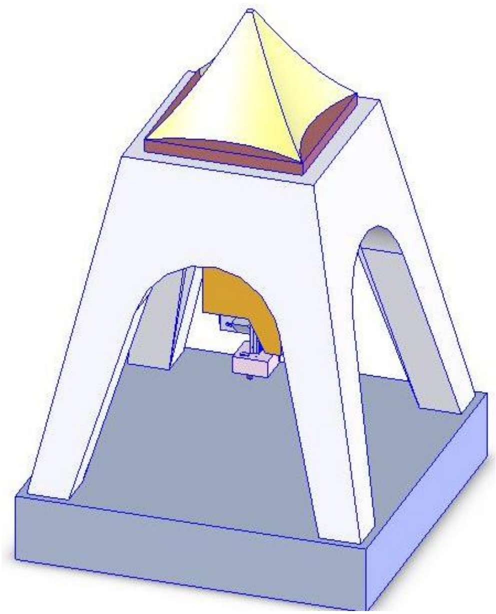
Comparison of Bridge Structures







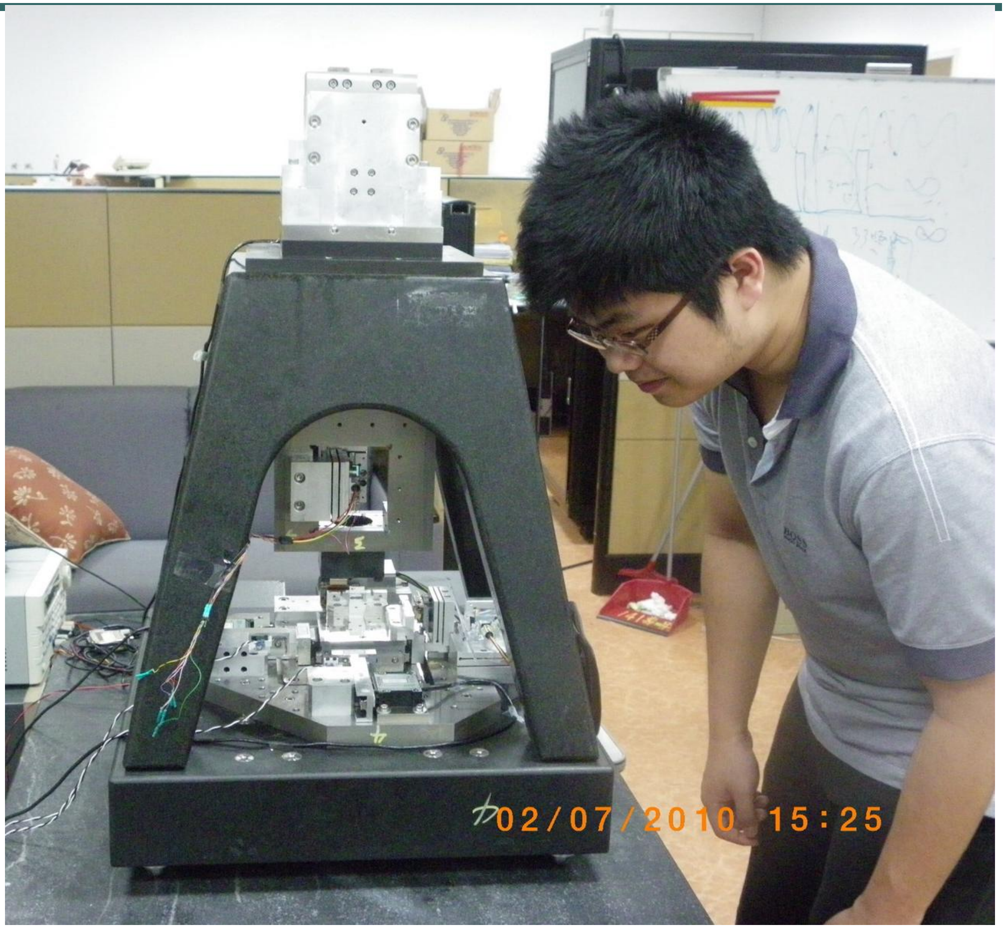




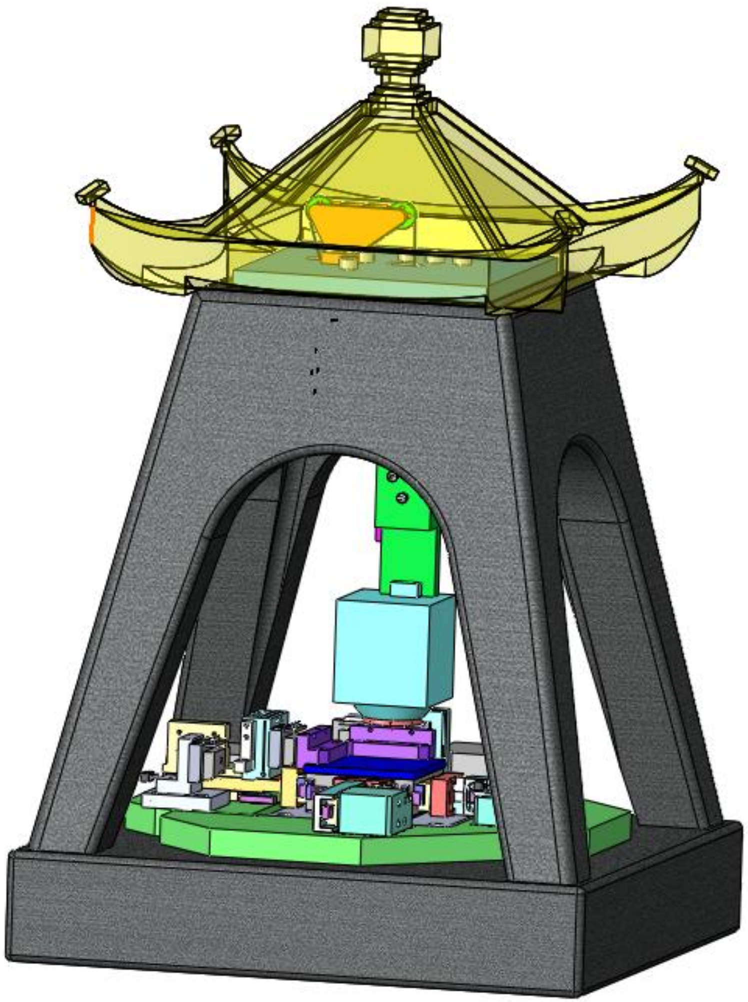
Type of Bridge	FEA	
	Spindle load	Self- weight
Rectangular	0.362um	0.156um
Arc	0.174um	0.102um
Arch	0.154μm	0.090μm
Optimized Arch	0.131μm	0.060μm
Pagoda	0.115μm	0.060μm

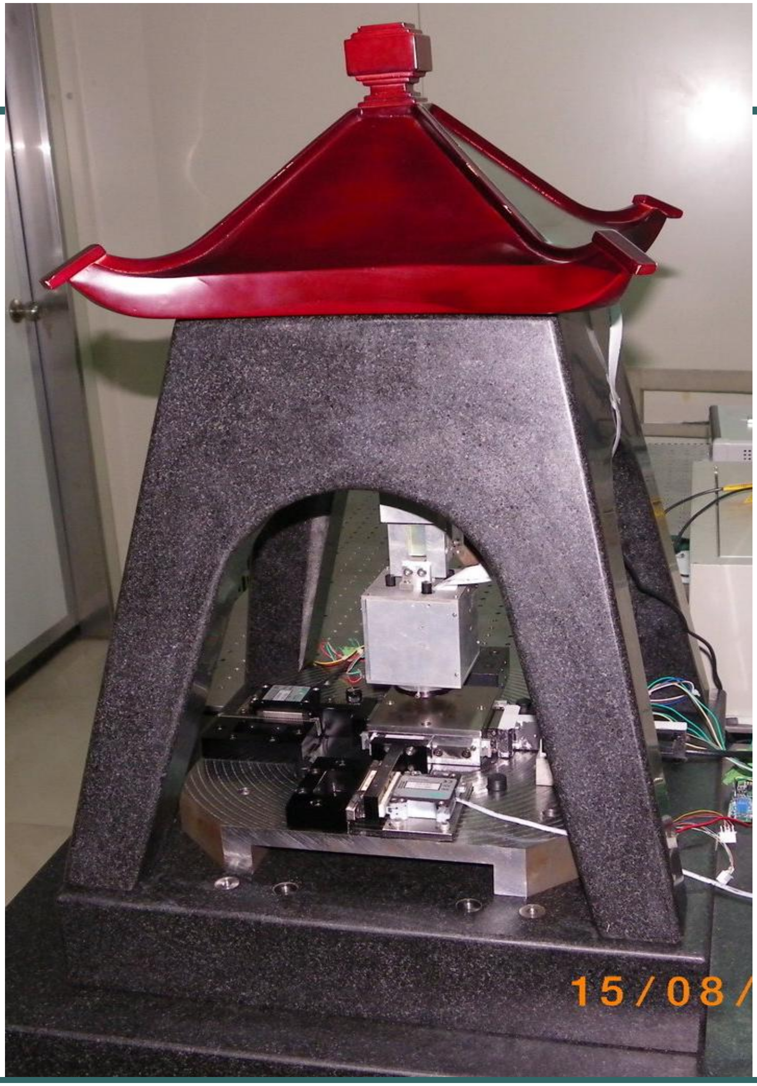
NTU Metrology Lab

Micro-CMM System at NTU Taiwan



Nano-CMM System at HFUT China





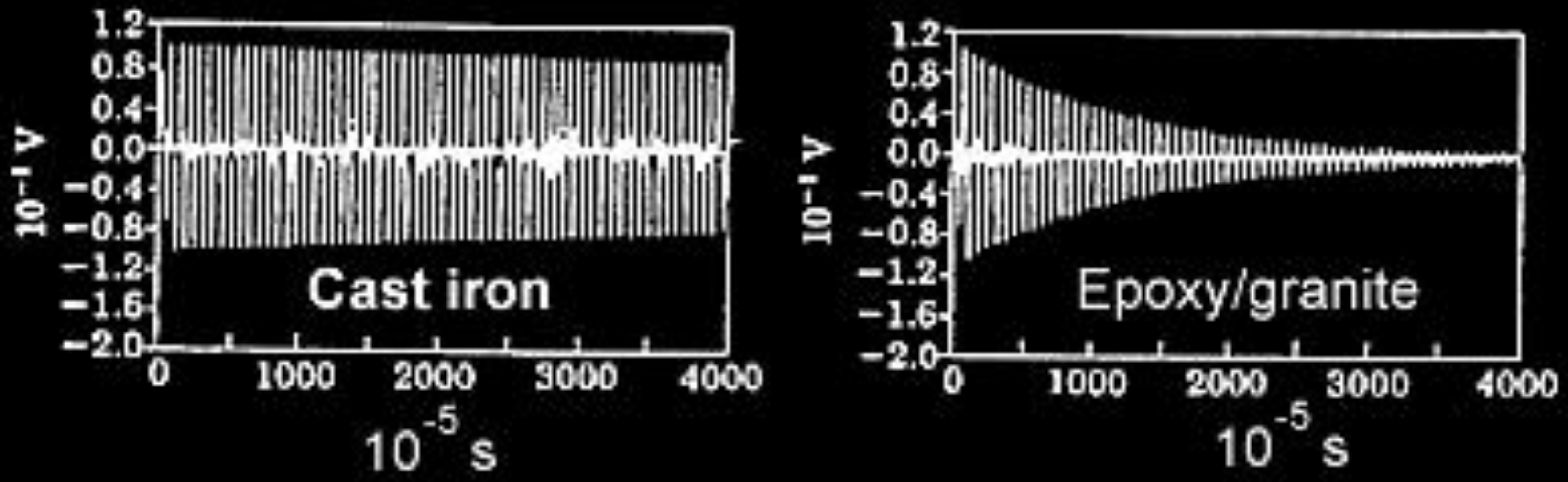
Damping

Dissipation of energy in typical structures is attributed to two basic factors：

- Material damping
- Damping at the joints

Material damping absorbs only a small part of the total dissipation –
the joints are, typically, responsible for most of the damping.

Material Damping
(Ref. Cincinnati Milacron)

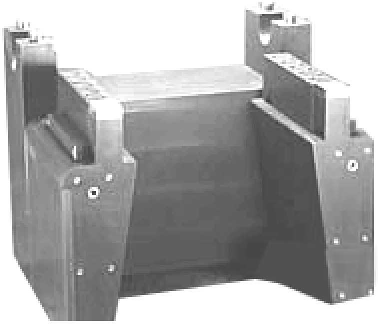


Relative damping capacity of grey cast iron and epoxy-granite composite material. Vertical scale is amplitude of vibration and horizontal scale is time.

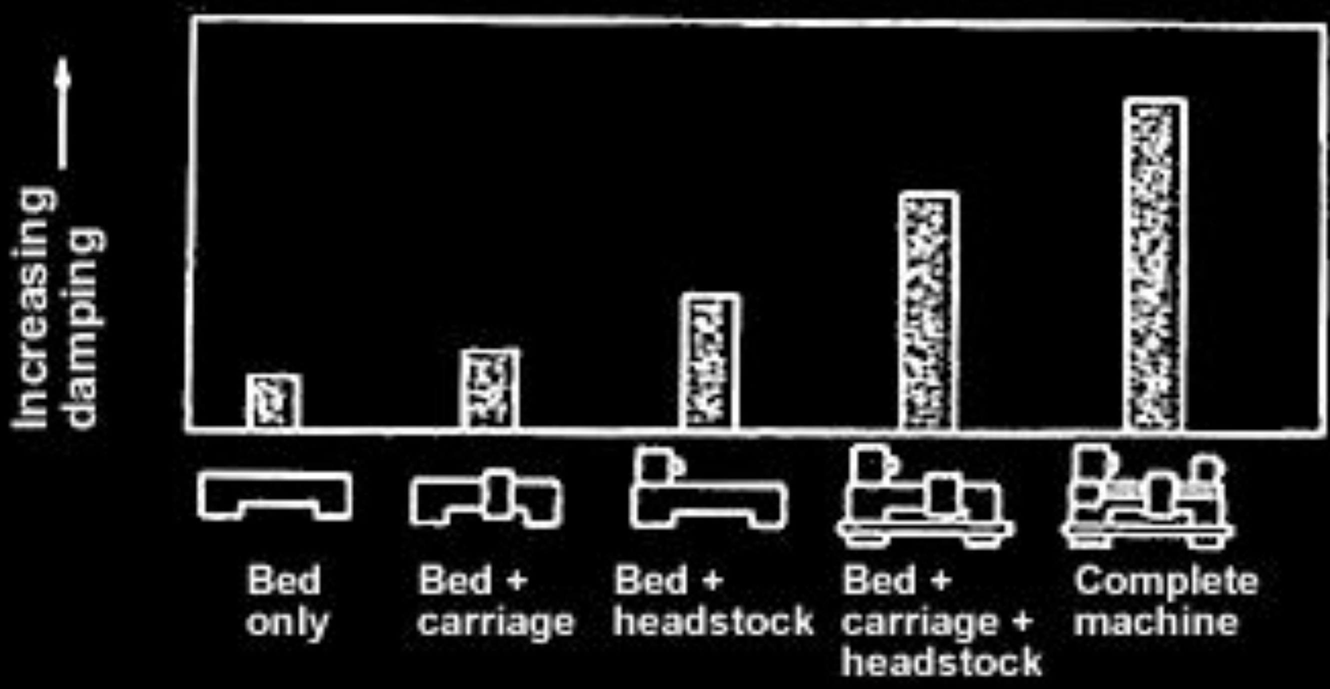
人造花崗岩 (Epoxy-Granite)

1. 振動阻尼良好，動態特性佳，改善加工件的表面光度。
2. 熱傳導係數低，受熱源及大環境的溫度變化影響小，故能維持機台的穩定度，提升加工件的精度穩定性。
3. 可埋入導軌、或螺絲孔或管線等嵌入件，外型比天然花崗岩更具變化彈性。
4. 簡化製程，節省加工、熱處理、搬運等作業。

財團法人精密機械研究中心
Precision Machine Research and Development Center, PMC



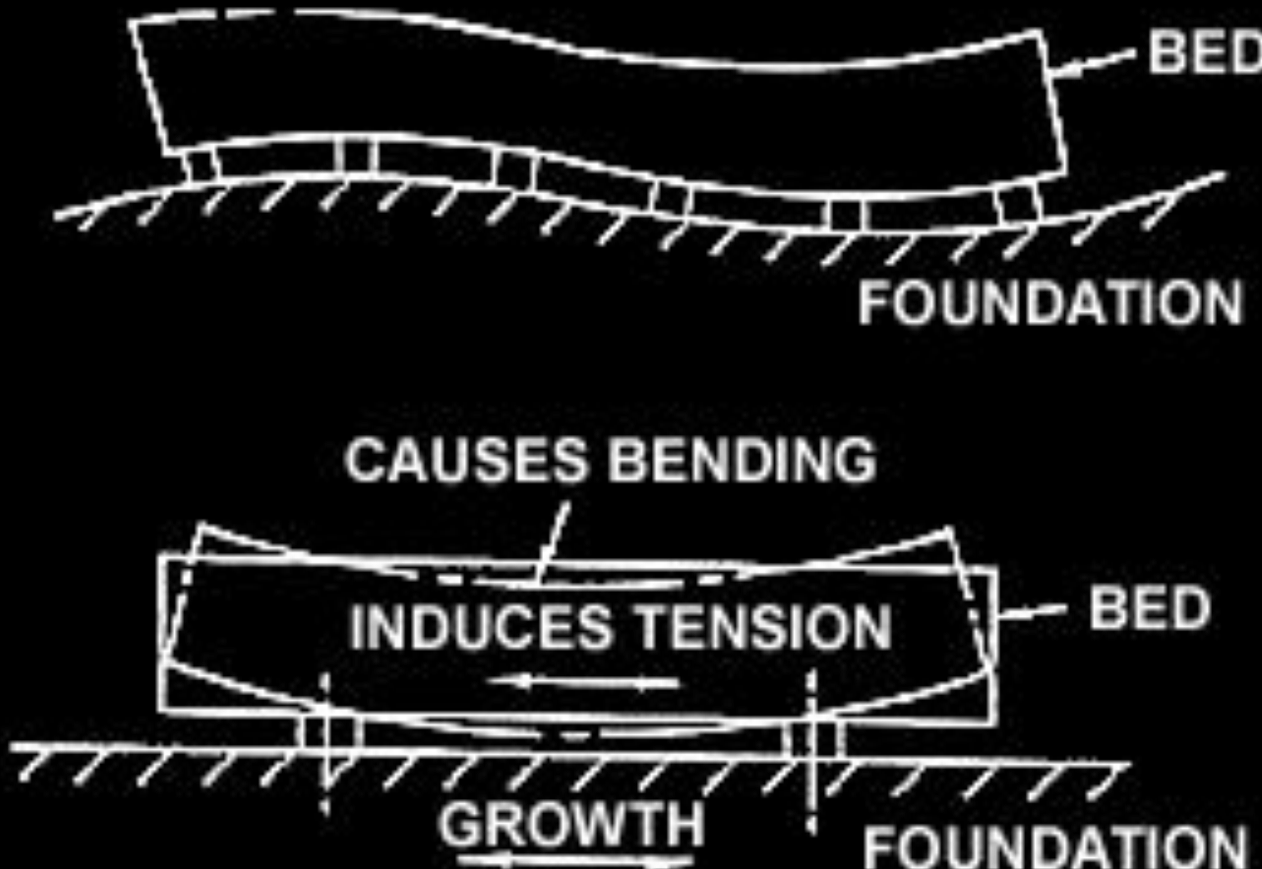
Damping of Vibrations vs Number of Components on a Lathe



Joints dissipate energy; thus the greater the number of joints, the higher the damping will be.

Direct clamping vs. Kinetic clamping

Direct clamping



Principle 2

Kinematic/Semi-Kinematic Design：

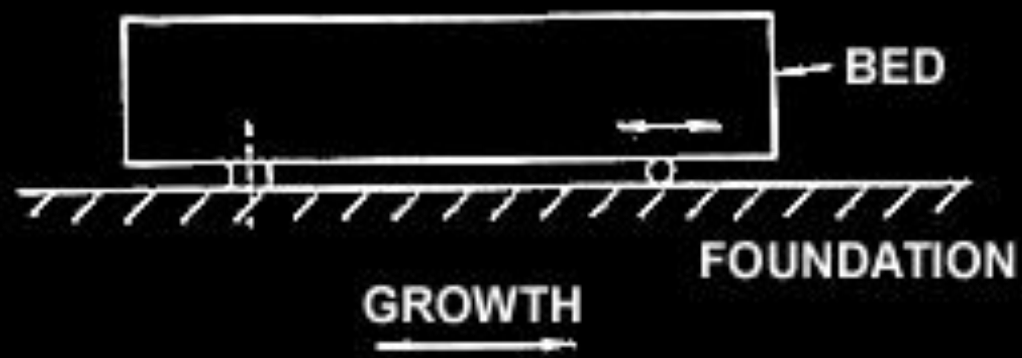
rigid body kinematics; three point support

支撐機構須防止拘束力產生

The principle of kinematic design

- Point contact should be established at the **minimum number of points** required to constrain a body in the desired position and orientation.
(This prevents over-constraint, and thus an "exact" mathematically continuous model of the system can be made.)
- Kinematic designs are subject to **high-contact stresses**, which often may require the uses of ceramic components.

Kinetic


BED
FOUNDATION
GROWTH

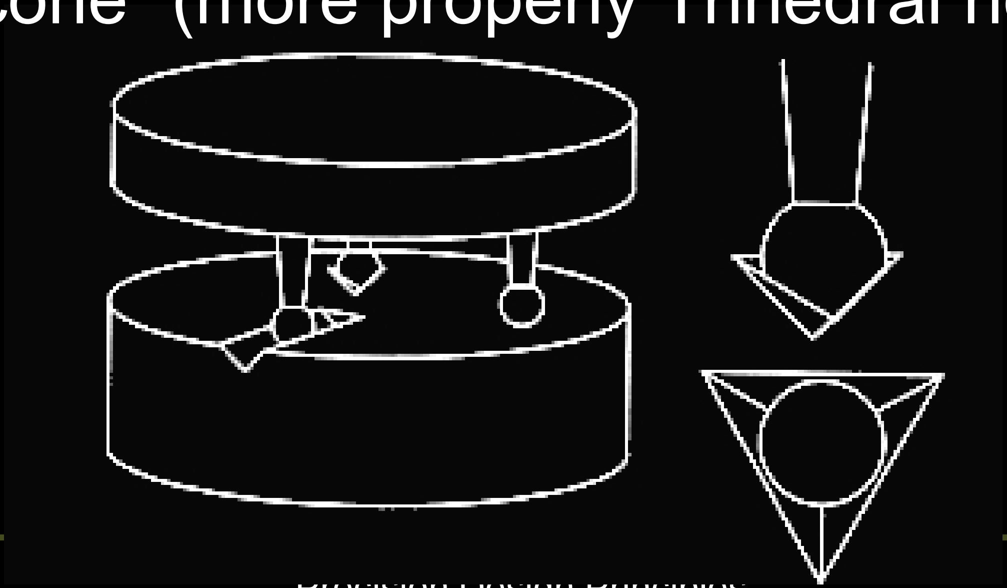

BED
ANTI-VIBRATION
MOUNTS
FOUNDATION

Kinematic Location (Clamps)

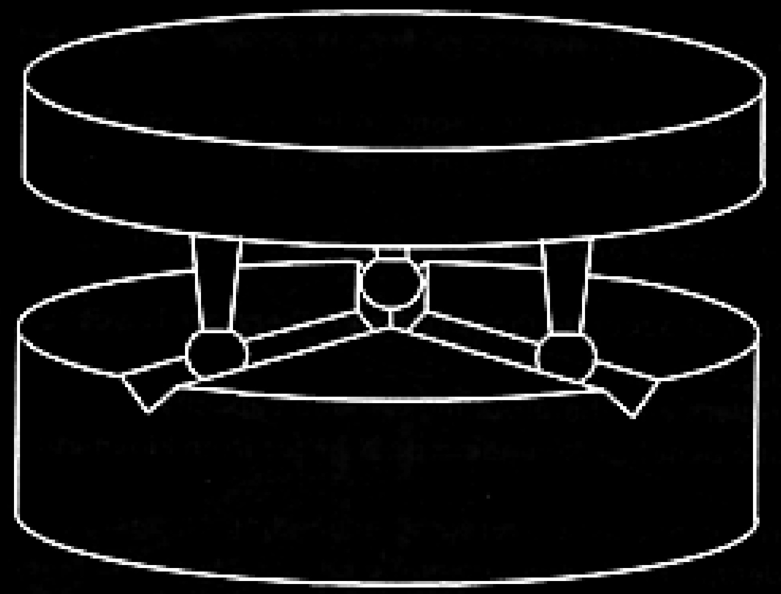
Based on constraint of the six degrees of freedom and the concept of rigid bodies for machine elements

Examples-

Vee-flat-“cone” (more properly Trihedral hollow)

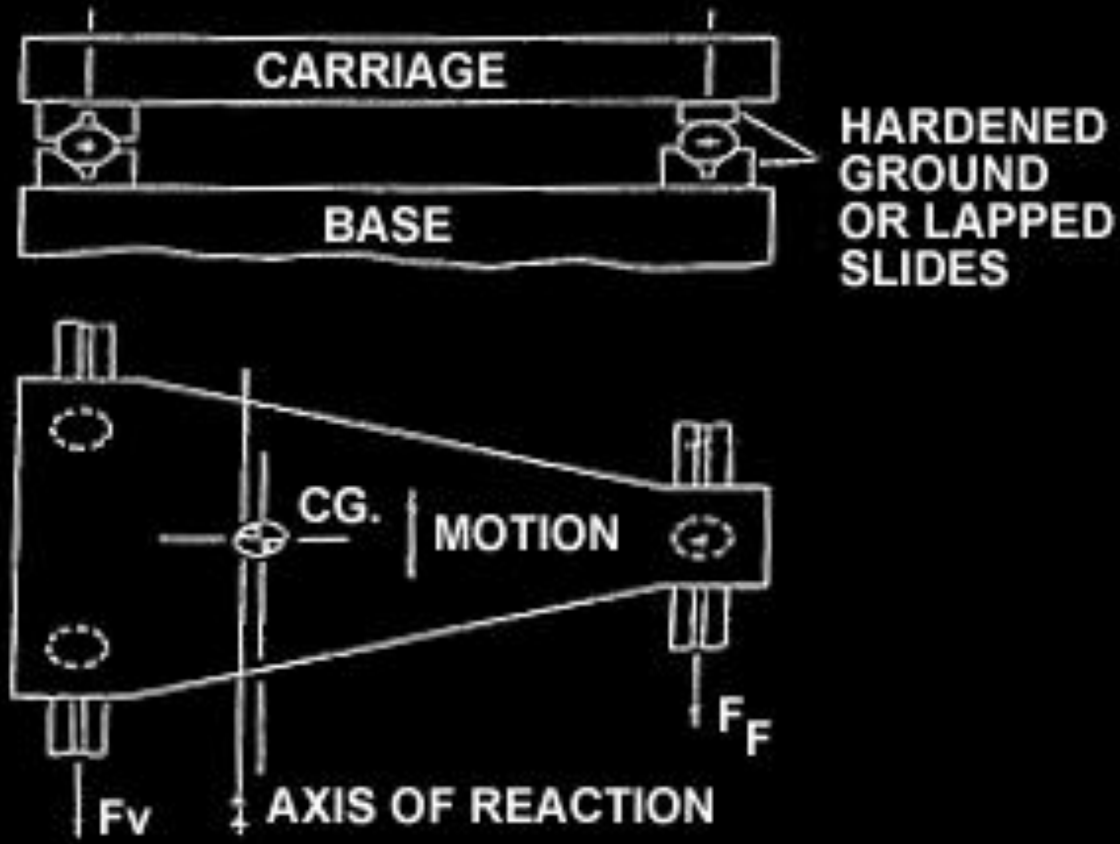


Alternative Kinematic Clamp



Three vees radiating from a centre point

- Accuracy of intersection not critical
- Accuracy of angle not critical



One Degree of Freedom-Linear Kinematic Ball Slide

Rolling element

Guideway Types

Kinematic vs. kinematic

- Kinematic-
  - Must use balls and be non-recirculating to be pure kinematic
- Therefore low load capacity and short stroke only
- Lowest friction
- Will faithfully reproduce accuracy of components but with no averaging
- Minimum number of accurate faces required therefore lowest cost
  Semi kinematic (Note 2)
- More balls or rollers and therefore higher load capacity
- Loss of kinematic benefits depending on how far from kinematic principles
- Can take advantage of elastic averaging depending on design

Note2- No strict definition of semi-kinematic design –here it is taken as design which uses some kinematic principles but departs to avoid disadvantages.

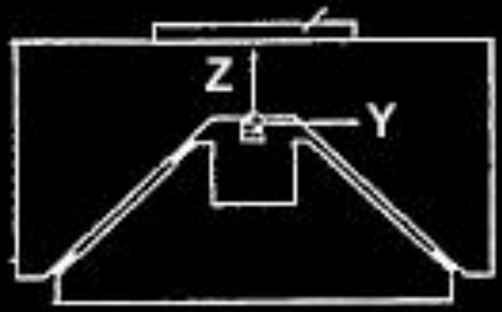
Kinematic Slideway Designs

硬軌:

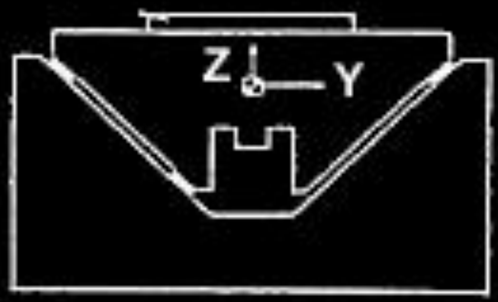
鳩尾槽

耐磨片(Turcite)

劏花 (油溝)

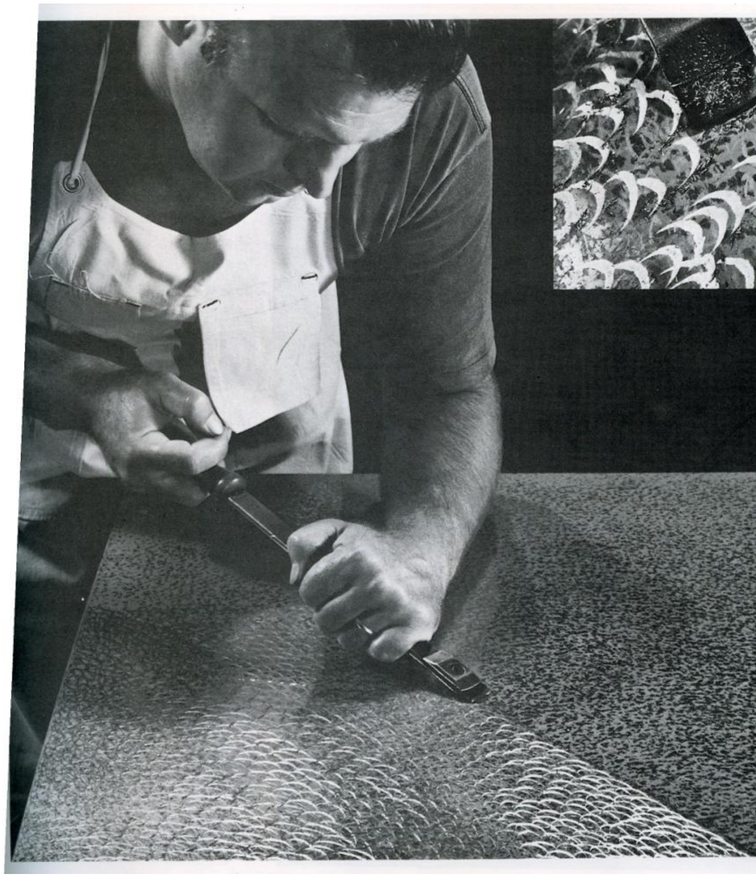


Single Vee

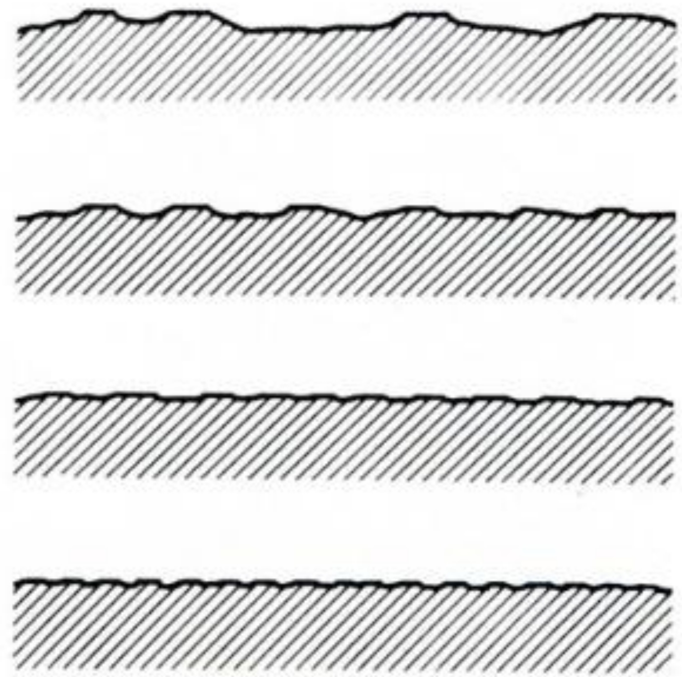


Inverted Vee

鏟花(括刀)技術: 真平度表面



"半月形" 爲所知最好的承斑

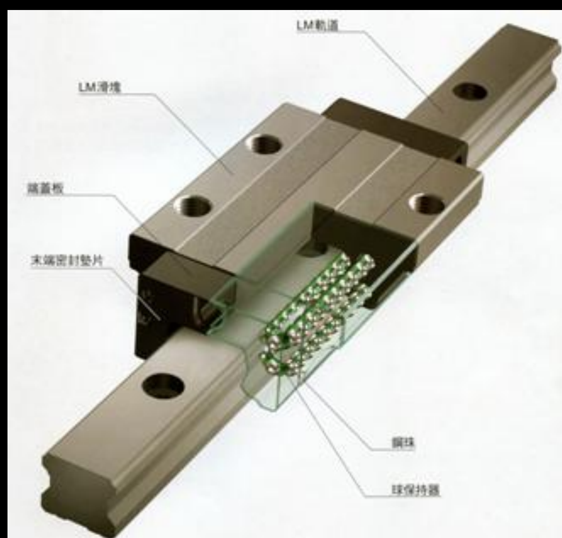


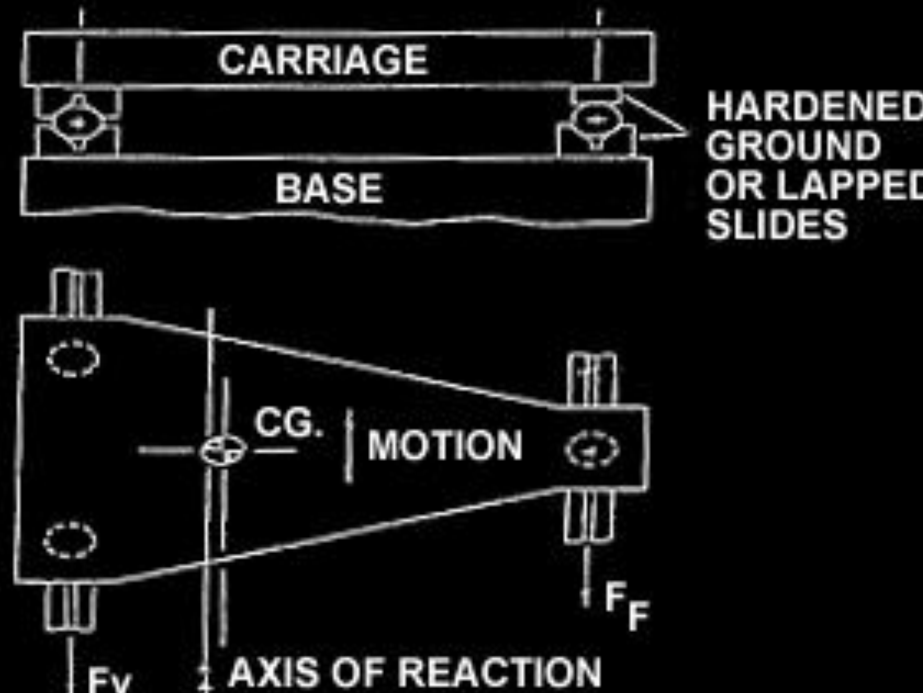
鏟花面的"承斑"爲一系列的均勻高原, 在鏟花開始時相距較寬, 經過重複的鏟花, 承斑變爲更爲接近及更爲密接

Examples of Kinematic Location

線軌:

置線性滑軌



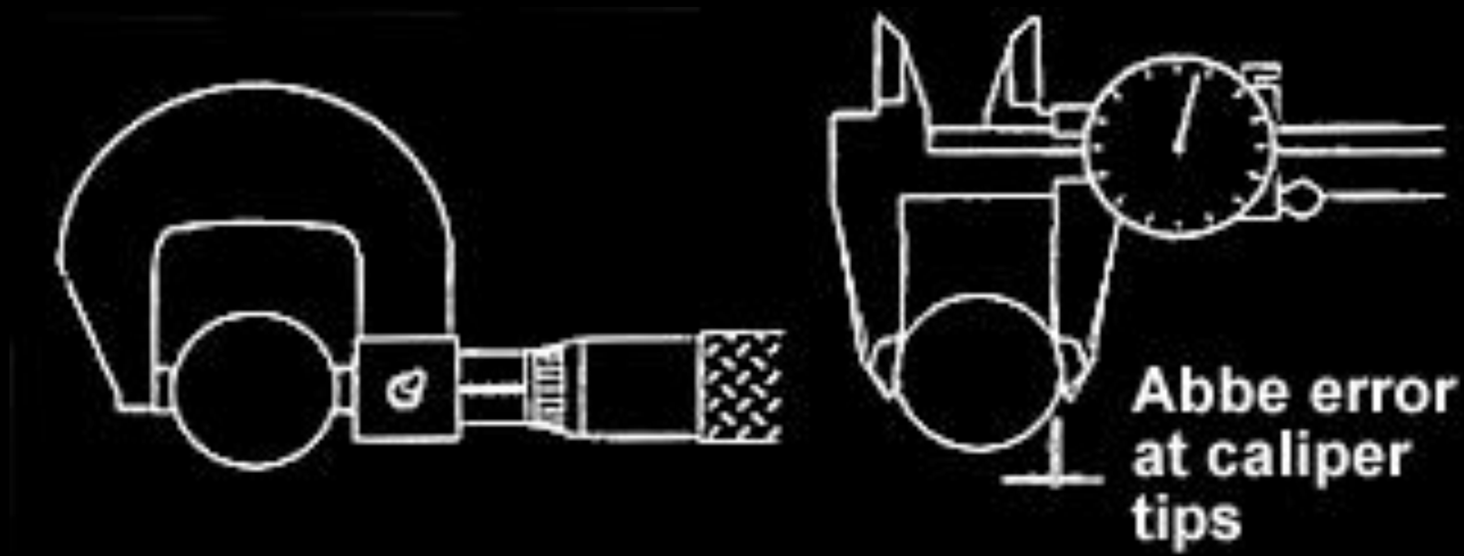


Principle 3

Abbé Principle (or options)

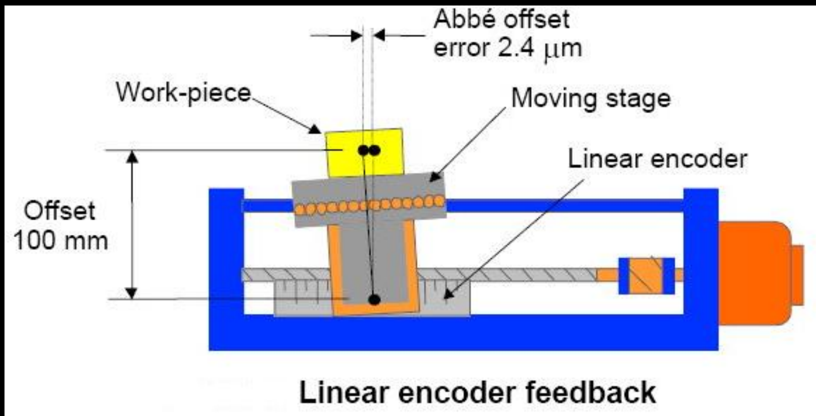
Abbé principle: Measuring Axis should be in line with the Moving Axis

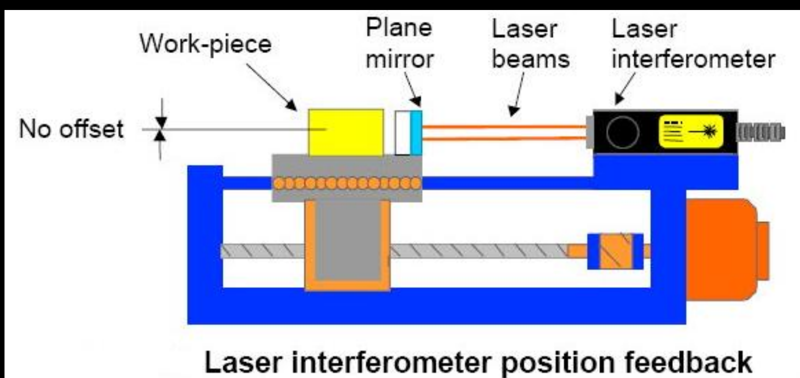
量測軸與運動軸產生偏位



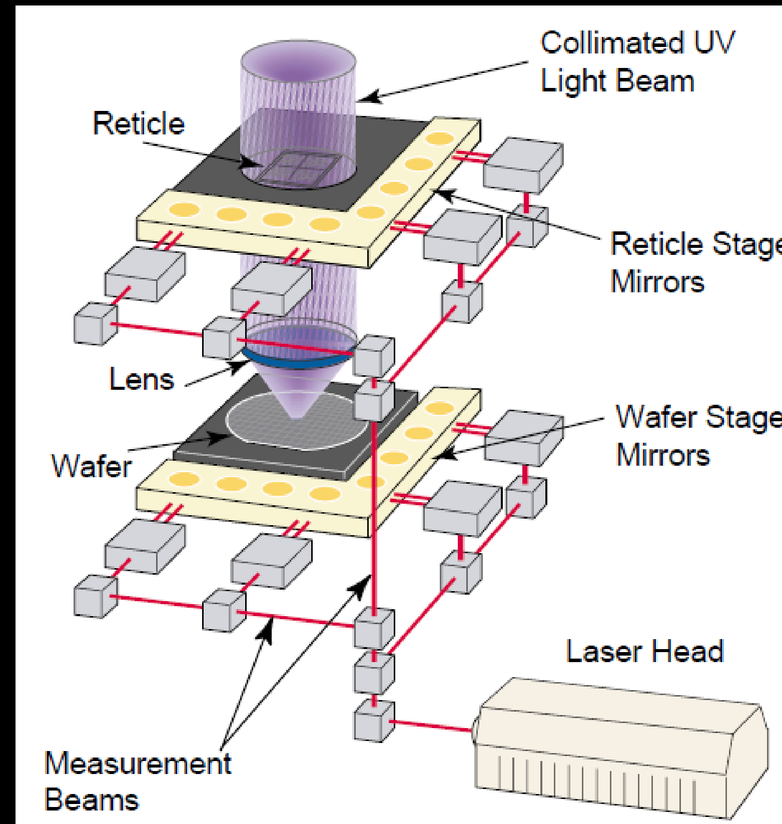
Abbé error illustrated through the use of a dial caliper and a micrometer

General linear stage





Scanning stepper

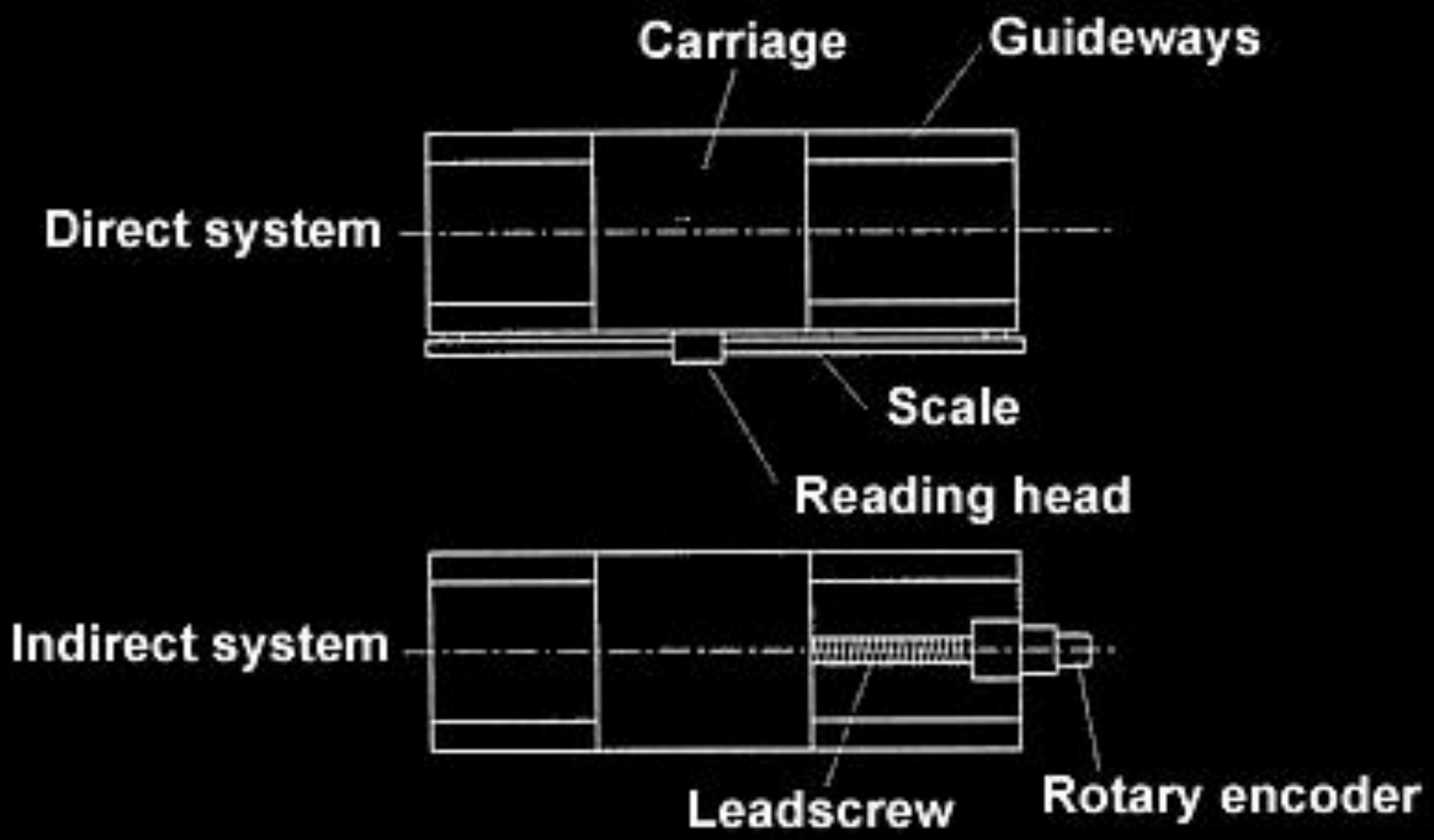


Compliance with Abbé Principle in Design of Ultra Precision CNC 7 Axis Grinding Machine

Principle 4

"Direct" Displacement Transducers：scale or laser interferometer(s)

Direct and indirect measuring systems



Indirect measuring systems

Not usually recommended for high precision

- Cyclic error due to misallignment (e.g. screw)
- Error due to angular deflection of screw (“windup”)
- Errors due to compression and extension of screw (e.g. process force, seal friction, preload of nut, etc.) Can be appropriate if above effects are within allowable limits

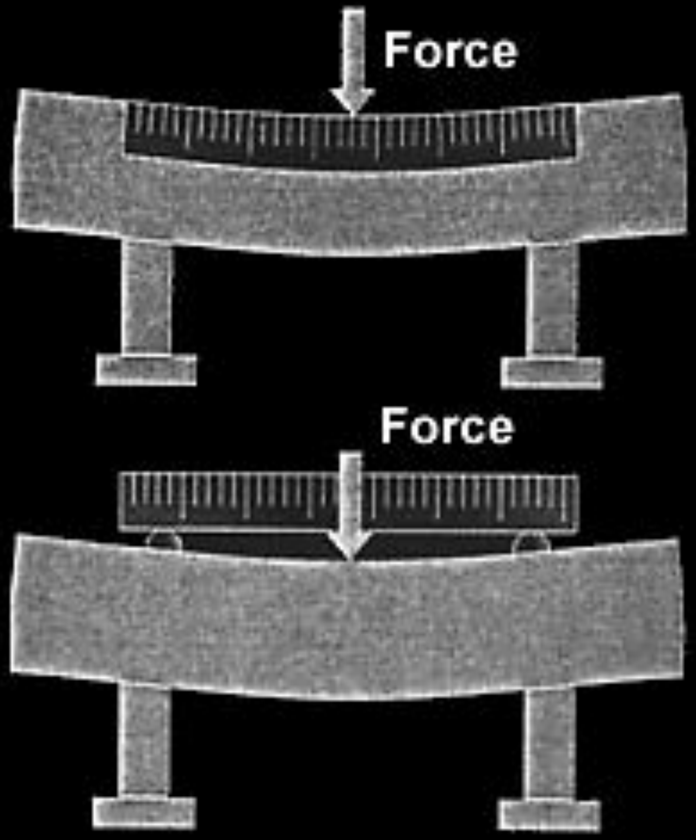
Potential advantages over direct system-

- Often easier to shield measuring system from adverse environmental effects
- May be lower cost

Principle 5

Metrology Frames：**isolate measuring system from force paths and machine distortion**

Metrology frame - Principle



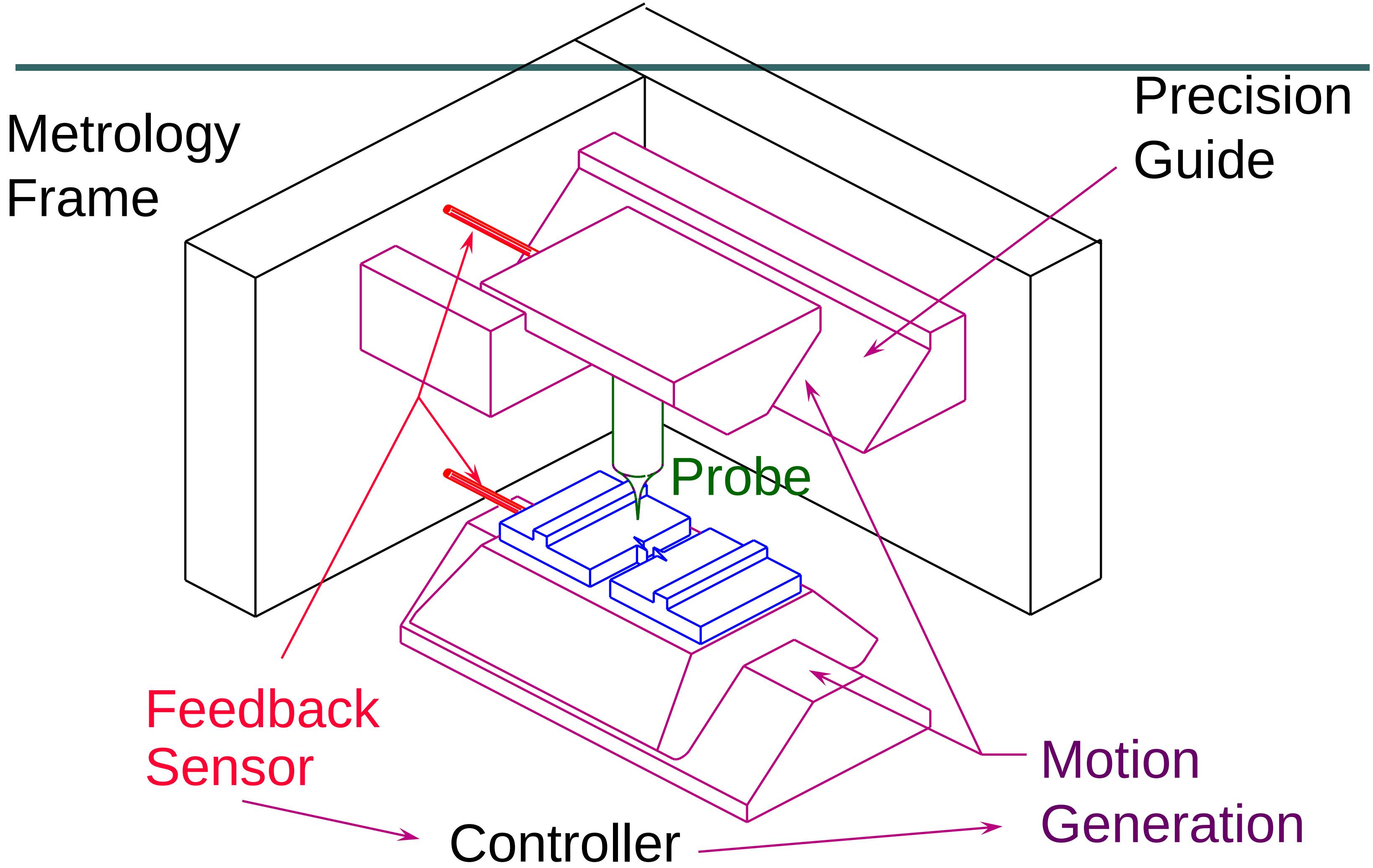
With out metrology frame.

Scale rigidly attached to load-carrying structure deforms, resulting in metrology errors.

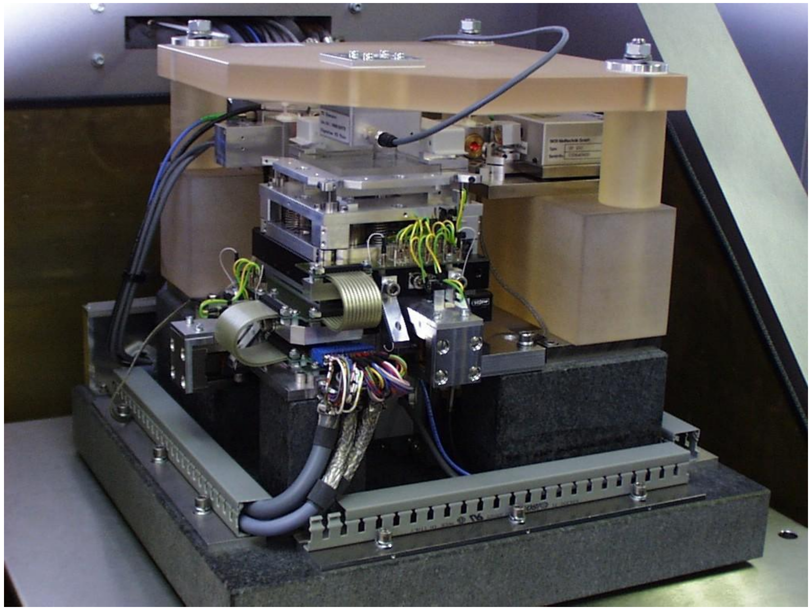
With metrology frame.

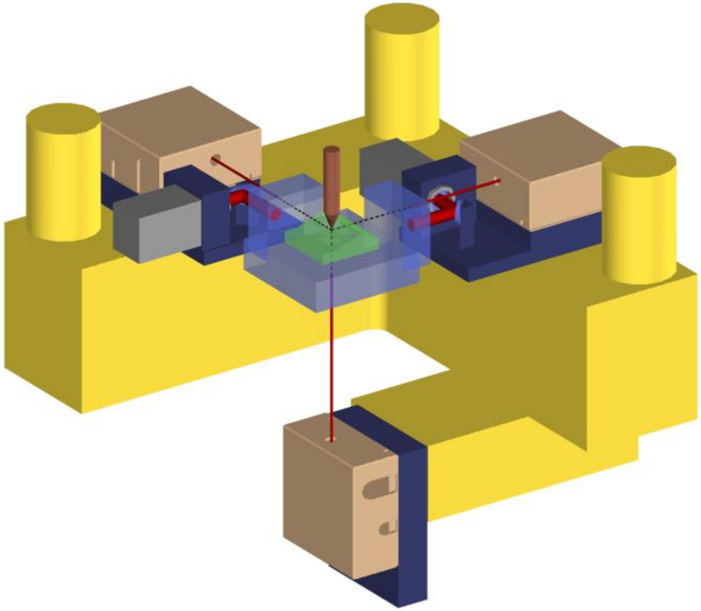
Self-stiff scale does not deform with loaded structure, reducing metrology errors.

Six components of a precision machine system



SIOS Nanopositioning Machine

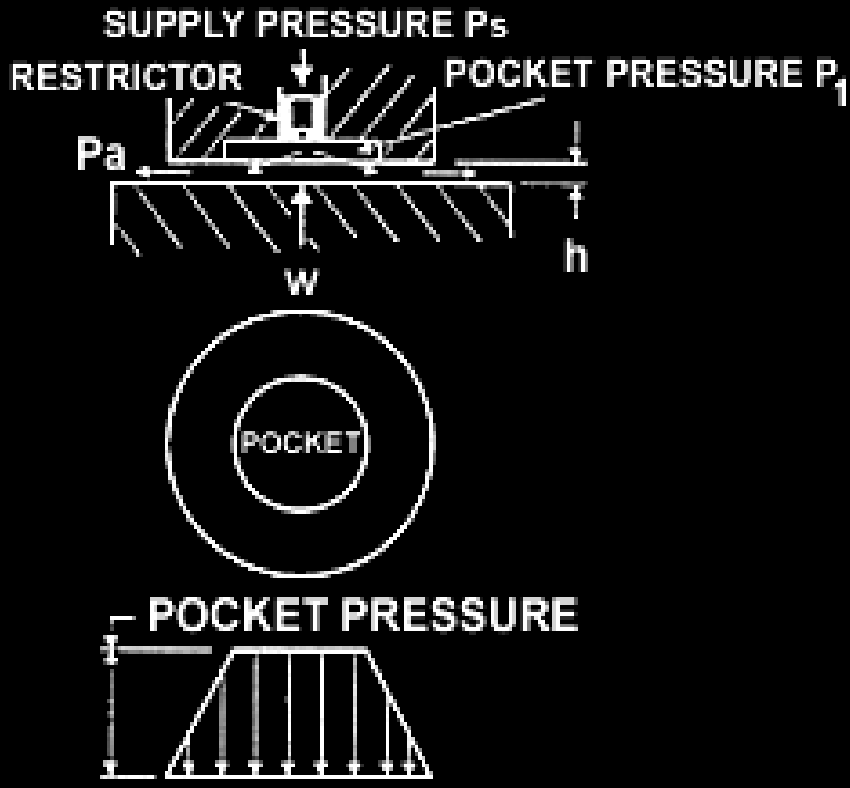




Principle 6

Bearings：**high accuracy; high averaging/low rumble; low thermal effects; low limiting friction; high damping**

Hydrostatic Bearing – Principle of Operation
(Constant Supply Pressure)



Two faces are separated by clearance ‘h’. Fluid enters the bearing via a restrictor which reduces the pressure to P_1. The fluid flows through the clearance ‘h’ dropping to atmospheric pressure P_a.

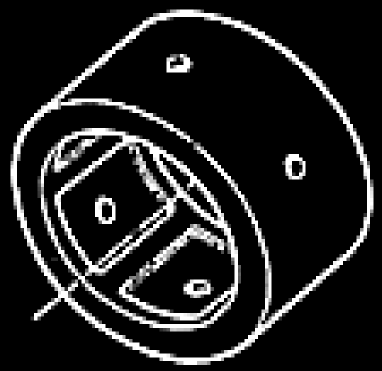
Changes in ‘h’ modify the restriction which affects the pressure in the bearing pocket. A reduction in ‘h’ increases the pocket pressure, and an increase in ‘h’ reduces the pocket pressure.

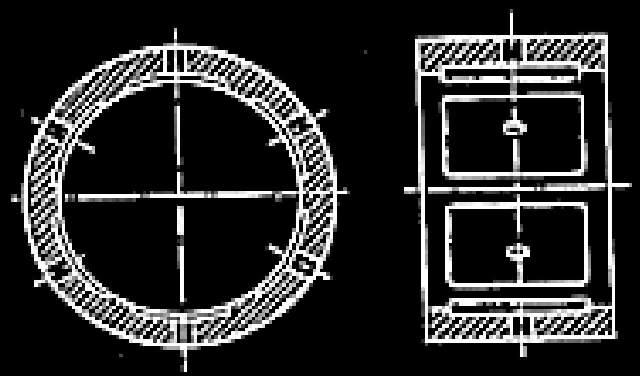
Fluid Film Bearings

- The machine tool and measuring instrument industries have made extensive use of hydrostatic and aerostatic bearings, where they have proved to be reliable and predictable and have often improved the performance of the machine beyond the capability of any other bearing.
- The exceptions have been where insufficient attention has been given to system design, including filtration and prevention of restrictor blockage.

Hydrostatic journal Bearings

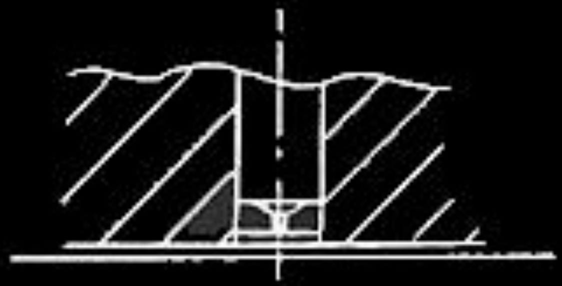
Hydrostatic bearings have the advantage of their ‘averaging’ effect. i.e. The load is spread over a large area by the layer of fluid, and the pocket pressure is dependent not on the minimum land clearance at any one point, but on the mean of the clearance all around the pocket; consequently, minor surface irregularities have very little disturbing effect.



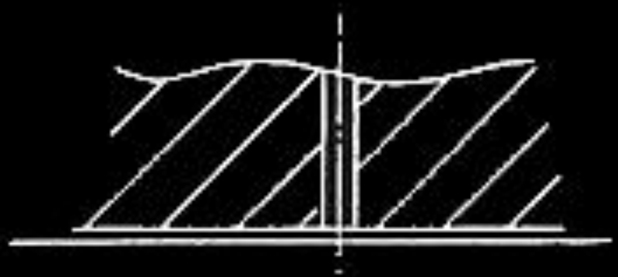


Air Bearing Design Considerations (2)

It is preferable to use pocketed orifices as these lead to greater stiffness. However when pocketed orifices are used the designer much give consideration to the avoidance of pneumatic hammer instability.



Pocked orifice



Inherently Compensated Orifice

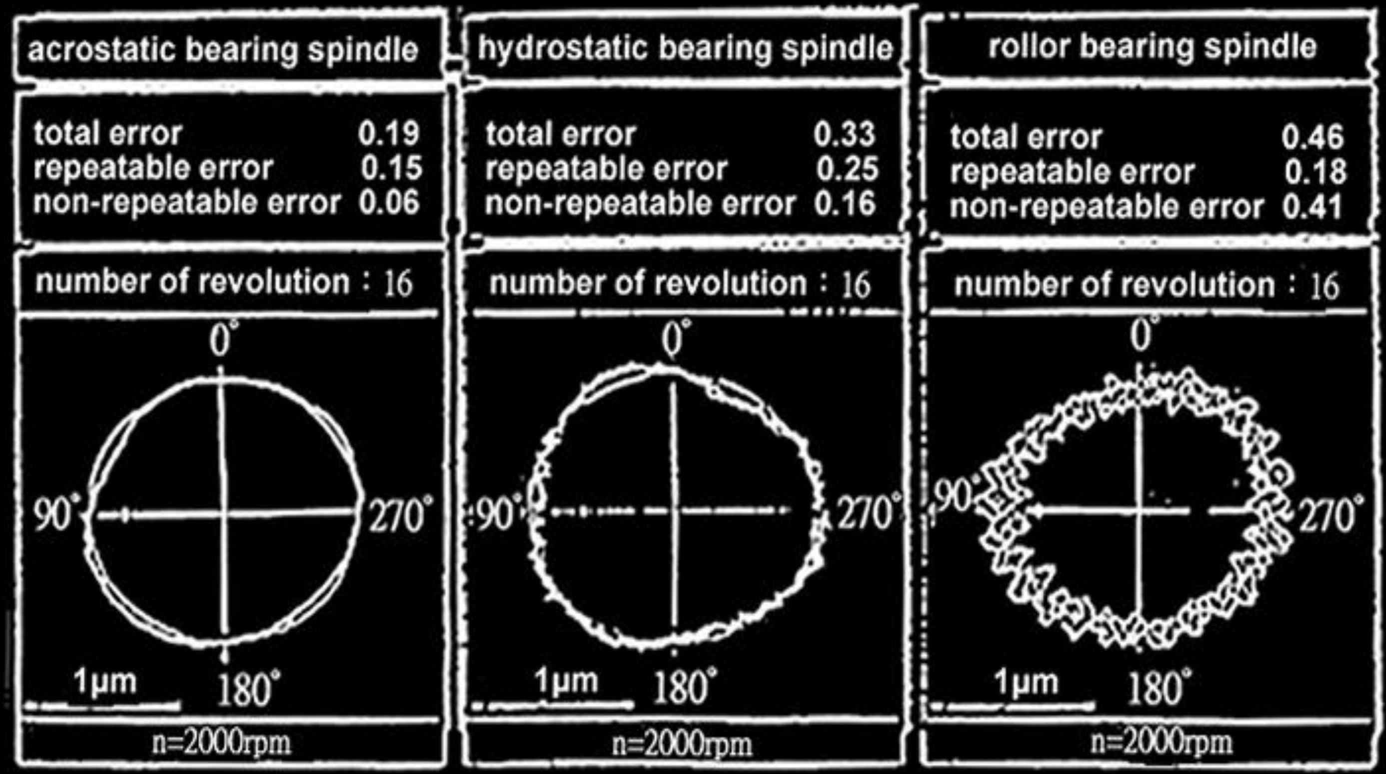
Aerostatic Instability (Pneumatic Hammer With Orifice Controlled Bearings)

1. Surfaces approach
2. Instantaneous difference between flow in and out.
3. There is a pocket pressure variation which lags relative to the relative movement of the surfaces (+ fluid compresses).
4. Approach equilibrium and surfaces separate.
5. Again there is a lag before pressure equalises therefore there is oscillation (minute)

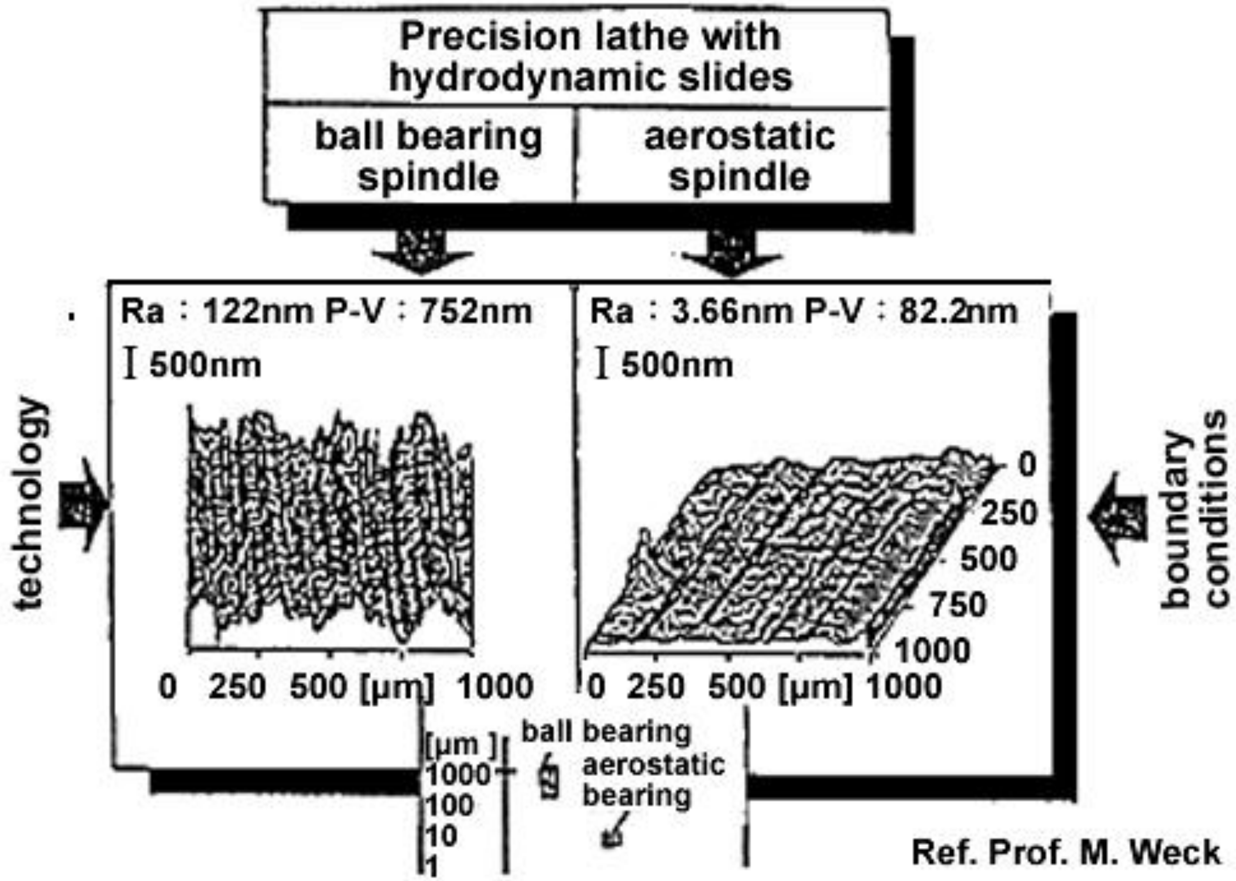
Cure by ： - minimise pocket depth
- minimise Ps to pocket
- maximise supply nozzle dia
- maximise ratio of land to pocket area

Error Motion of Different Spindle Bearings

Example



Influence on the Achievable Surface Quality

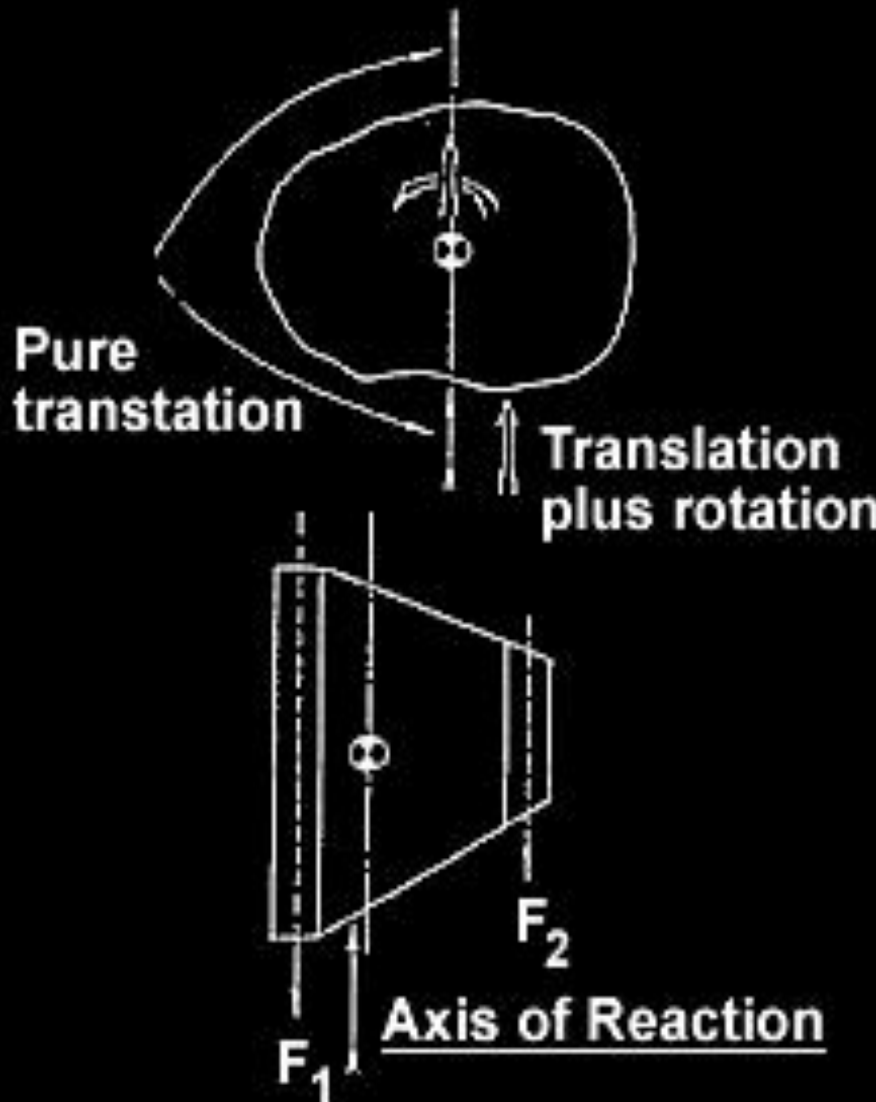


Bearing Systems used for Precision Machines

Machine Component		Machining Technology		
		Diamond Turning	Diamond Turning	Hard Turning
WORKHEAD SPINDLE	aerostatic	SOME	SOME	NONE
	hydrostatic	SOME	SOME	SOME
	rolling element	NONE	NONE	NONE
LINEAR GUIDEWAYS	aerostatic	SOME	FEW	FEW
	hydrostatic	SOME	SOME	SOME
	rolling element	FEW	FEW	FEW

Principle 7

Drives/Carriages：**through axed of reaction; “non-influencing” couplings and clamps**


Pure
transtation
Translation
plus rotation
F2
F1
Axis of Reaction

Positioning of Drive Axis on Carriage System

Ideal Position

Drive axis should be positioned on axis of reaction of-

- Friction forces and/or
- acceleration forces

to avoid influencing accuracy of carriage motion

Trade off frequently required

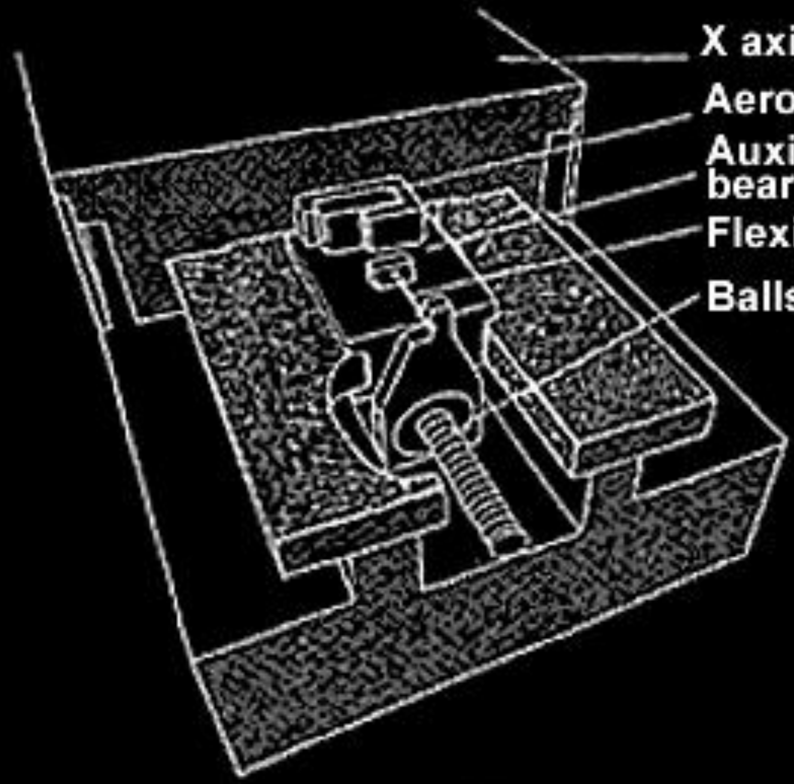
Guideway with high friction and low acceleration (e.g. plain type)-

- position on axis of reaction of friction forces

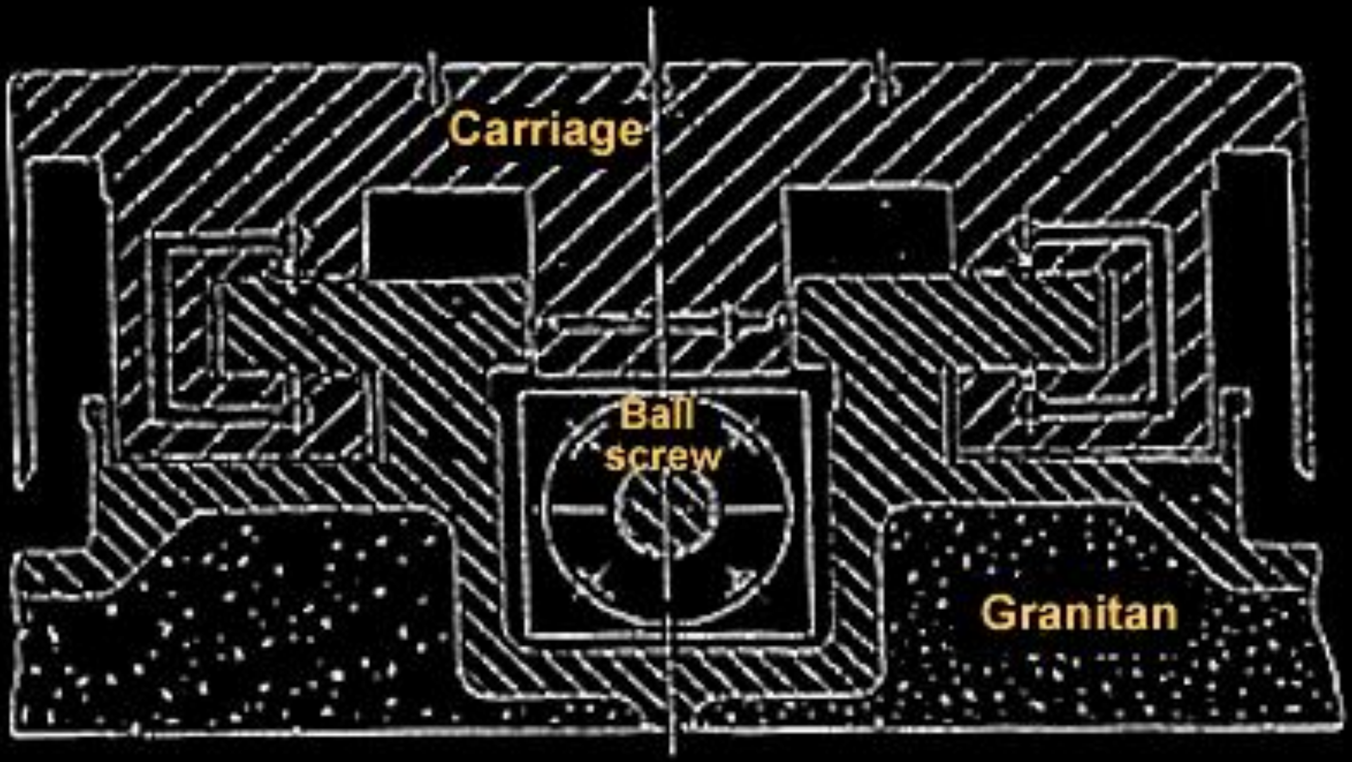
Guideway with low friction and high acceleration (e.g. rolling element)

- position on axis of reaction of acceleration forces - i.e. C of G

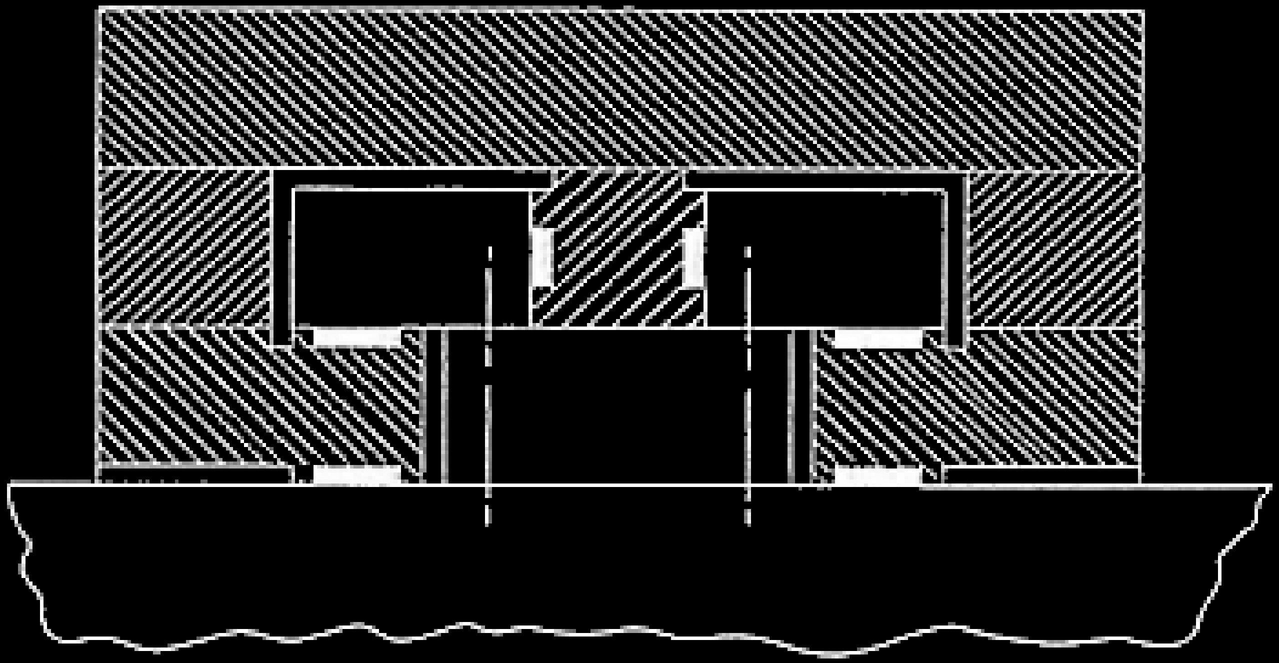
‘Non-influencing’ Drive System to Worktable



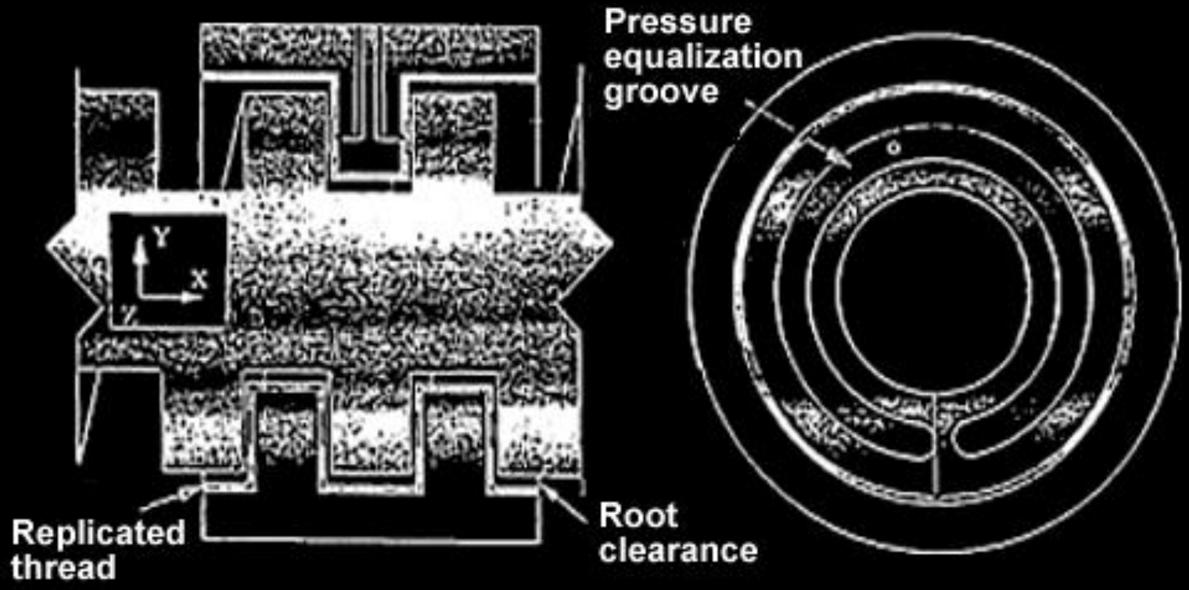
Schematic of an Air Bearing Work Table



Hydrostatic Guideway
(using 3 rectangular bars)



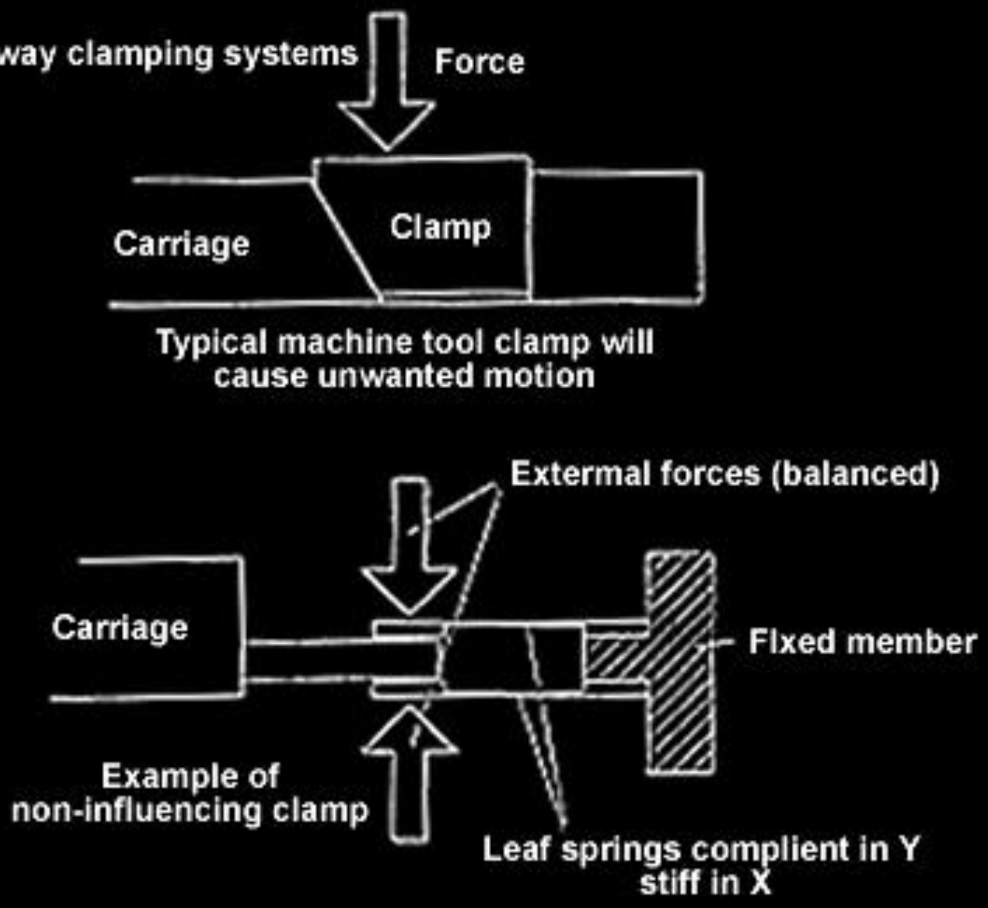
Self Coupling Hydrostatic Leadscrew



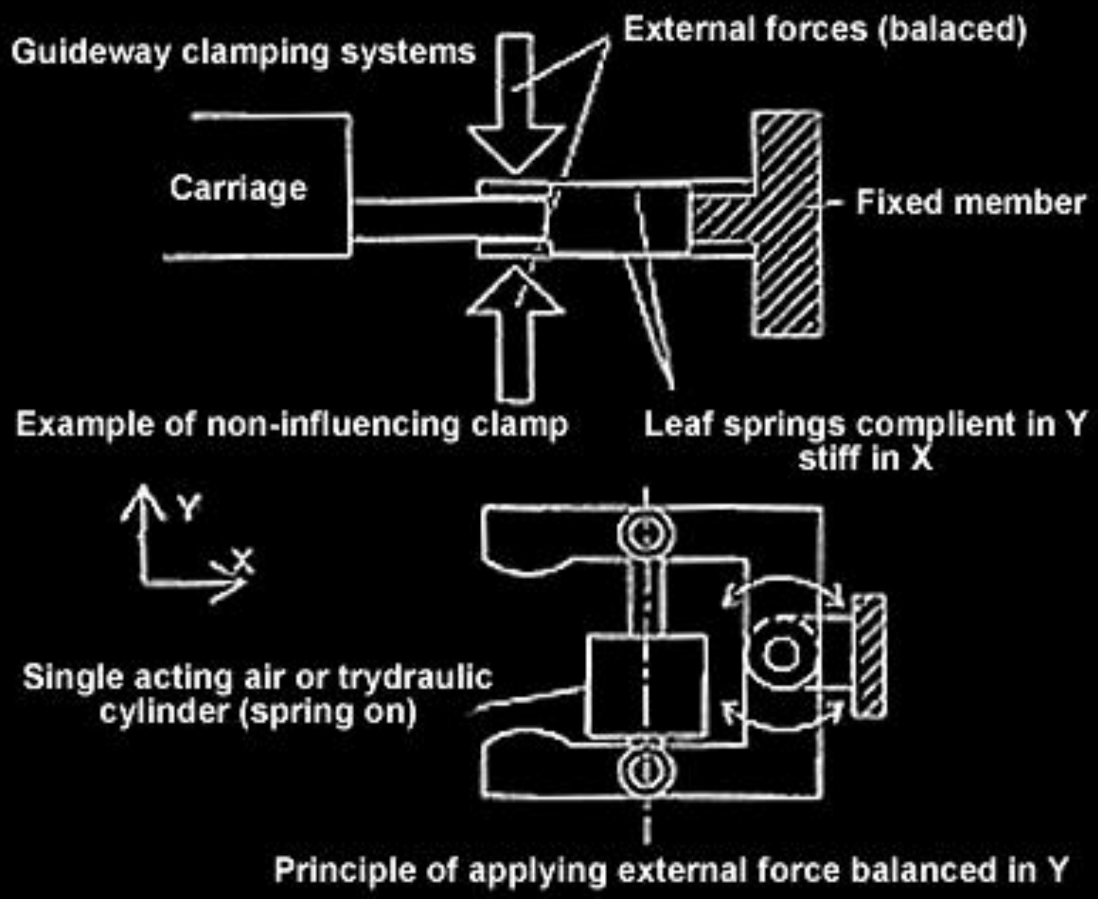
•Self-coupling: The nut is stiff only along the axis of motion and be free to move along and about all other axes.

•Note：The rectangular thread has a zero degree flank angle

Guideways for High Precision Machine Tools



Guideways for High Precision Machine Tools



Principle 8

Thermal Effects：**eliminate/ minimise thermal inputs and drift; stabilisation/compensation**

Effects of Temperature Rise

The main causes of inaccuracy in the machining process due to temperature rise in the machine tool are：

1. Thermal distortion
2. Variation in stiffness

Thermal distortion occurs through：

1. Expansion of the structure and uneven expansion of its components due to unequal temperature distribution
2. Bimetallic effect
3. Thermal inertia

External Influences
Factory floor climate
-horizontal / vertical
temperature distribution
-temperature variation
(day & night)

Direct radiation
-sun
-heating
-other machines
Others
-foundations
-open doors, windows

Internal Influences
machine sub-systems
-motors
-rotary bearings
-linear bearings
-hydraulic systems
-ballscrews
Machining process
-chips
-cooling lubricants

Thermal properties	**Structural shape**
thermal capacity	size of machine
thermal expansion	processing position
thermal conduction	

Unsteady temperature distribution in
the machine structure

Displacement at processing point

After Prof. M. Weck

Reference Temperature

Environmental Standard for Temperature

-Current international standards indicate that all pertinent components of a measuring system be at exactly 20 ◦ C

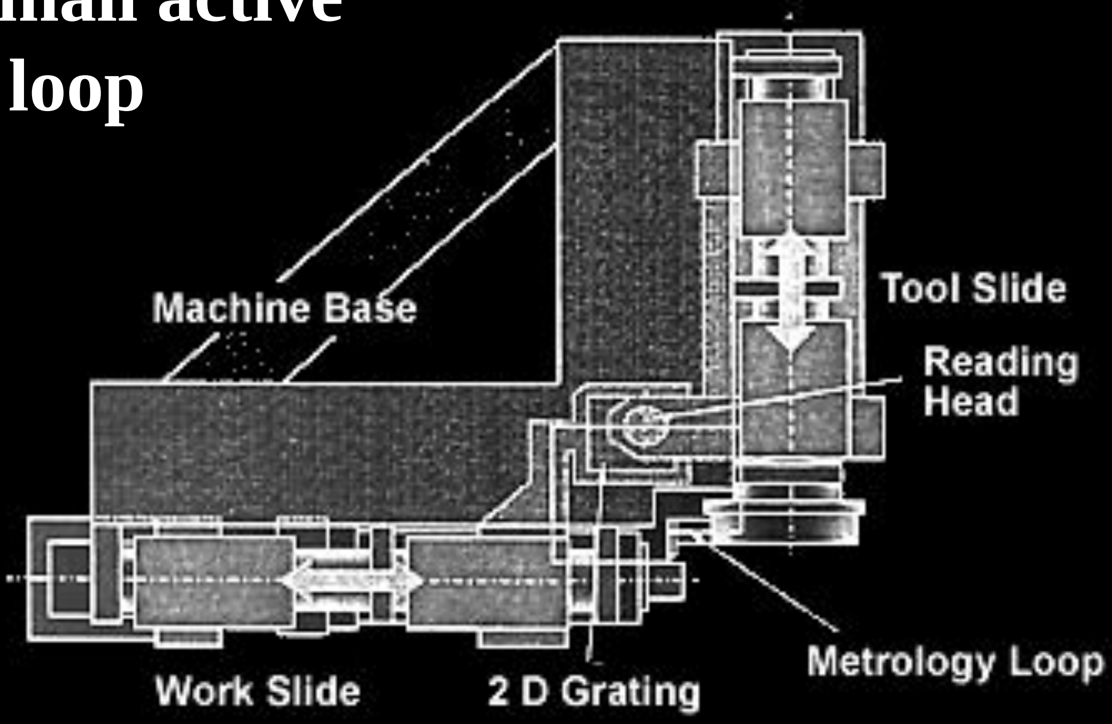
In practice this is most often not possible

-Acceptability of a thermal environment should therefore be specified in terms of its effect on the machine performance (http://www.zeiss.de)

-Temperature changes in terms of amplitude and frequency need to be defined

Thermal Design Considerations

Use of low expansion materials and a small active measuring loop



Thermal Design Considerations

- Thermal gradients

Thermal gradients are the most difficult of all non-ideal temperature conditions to assess for possible error effects

Machines with high vertical columns (vertical motions) are particularly affected.

Surface plates are affected in that a temperature difference between the top and bottom of the plate will cause the plate to bend.

Thermal Design Considerations

- Surface Plate Bending

For solid plates, the amount of bending or out of flatness (δ), caused by a vertical thermal gradient can be calculated from：

$$\delta \approx \frac{L^2 \cdot k \cdot T_d}{H\left(1-k\cdot\frac{T_d}{2}\right)}$$

Where

L = length of surface

H =thickness of surface plate

T_d =Temperature difference between top and bottom surfaces

K =co-efficient of thermal expansion

Machine guideways are similarly affected by both vertical and horizontal gradients which cause pitch, roll and yaw motions

Thermal Design Considerations

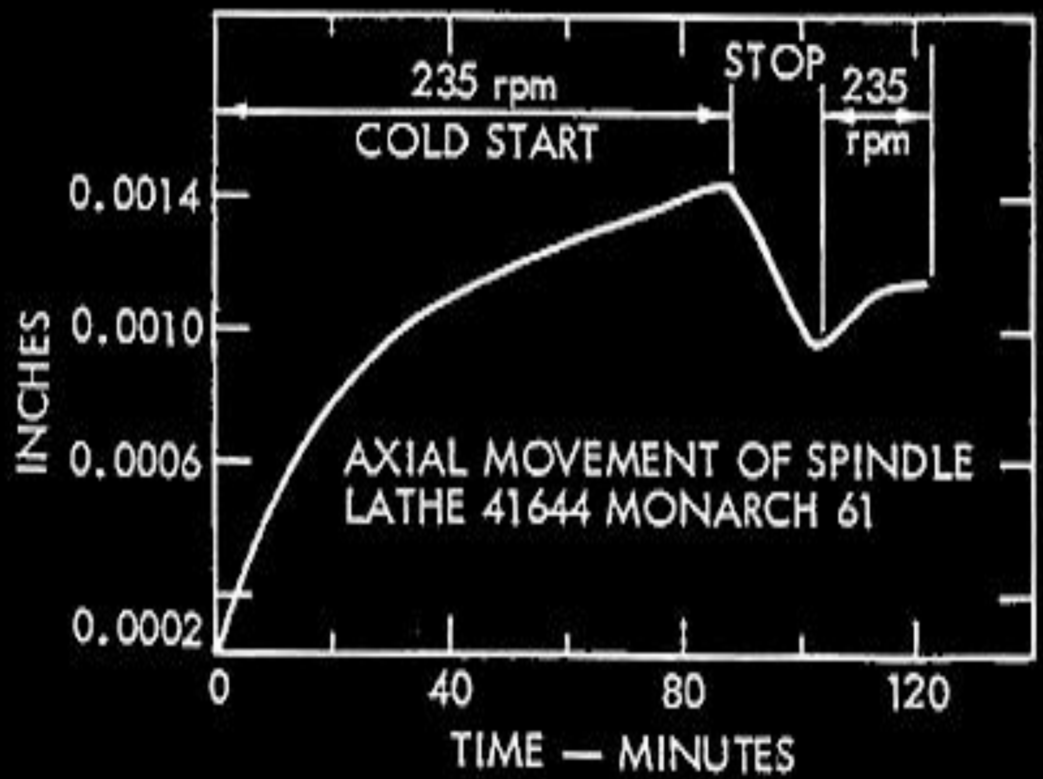
- Surface Plate Bending

(example)

A 2 metre long Granite surface plate of 330 mm thickness will have a flatness error of <u>10 μm p-p for each 1 ° C gradient</u>

Ref. US Std. GGG-P-463C

Axial Spindle Growth



4.Axial spindle growth, the result of bearing warmup, occurs when spindle is restarted, also when cold machine starts up in the morning

Principle 9

Servo-drives and Control (CNC)：high stiffness/response/bandwidth; zero following errors; dynamic position-loop synchronisation

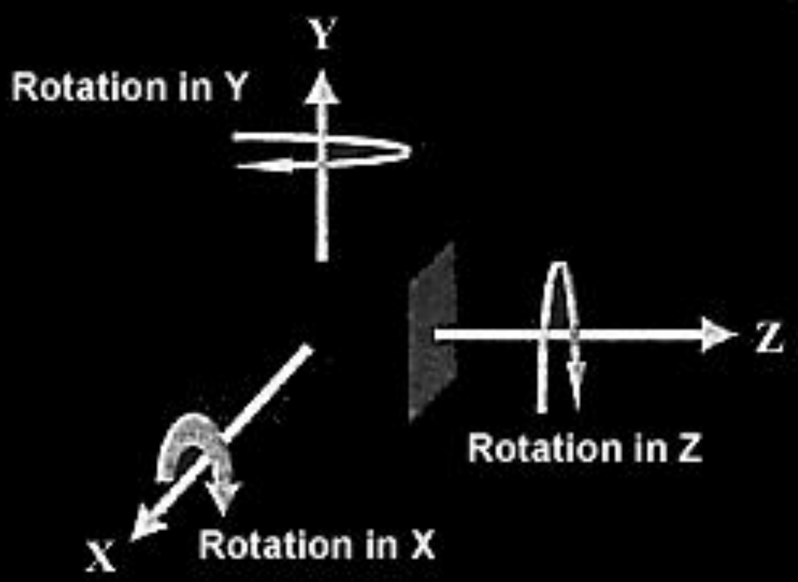
Principle 10

Error Budgeting :

(i) geometrical-angular, straightness and orthogonal error motions

(ii) Thermal-loop expansions; deformations

A body has 6 degrees of freedom



3 degrees of translation (linear movements)

- X
- Y
- Z

3 degrees of rotation (tilt or angular movement)

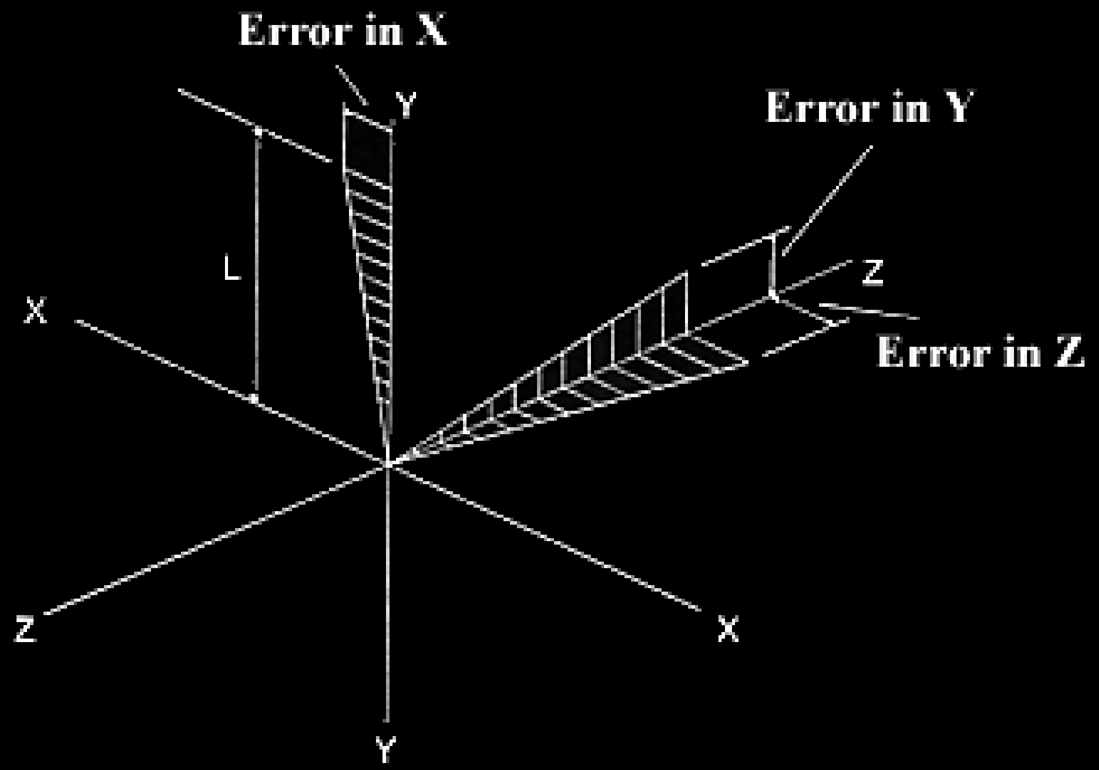
- Rotation in X
- Rotation in Y
- Rotation in Z

Geometric concepts

Summary of build up of errors in a single axis system (with required direction of motion in X)

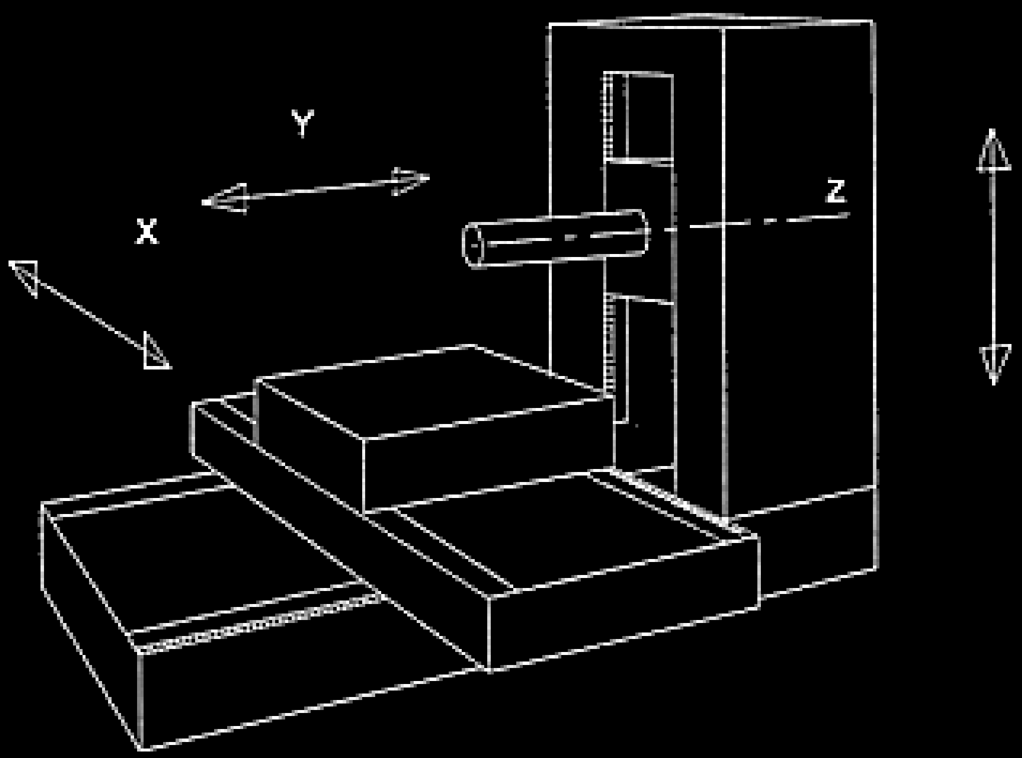
Error motion	Direction of error
Abbe errors due to pitch	X
Abbe errors due to yaw	X
Errors due to roll	Y and Z
Straightness-error in Y	Y
Straightness-error in Z	Z

Orthogonality errors between axes
X axis and XY plane taken as datums



Axis of motion	Element of error	Direction of error		
		X	Y	Z
X	Abbe error due to pitch	*		
	Abbe error due to yaw	*		
	Error due to roll		*	*
	Straightness-error error in Y		*	
	Straightness-error error in Z			*
Y	Abbe error due to pitch		*	
	Abbe error due to yaw		*	
	Errors due to roll	*		*
	Straightness-error error in X	*		
	Straightness-error error in Z			*
Z	Abbe error due to pitch			*
	Abbe error due to yaw			*
	Errors due to roll	*	*	
	Straightness-error error in X	*		
	Straightness-error error in Y		*	
	Orthogonality of X-Y	*		
	Orthogonality of X-Z	*		
	Orthogonality of Y-Z		*	

Hypothetical machining centre



Hypothetical Horizontal Machining Centre
Geometric Error Budget

Axis	Feature	Allowed Error		Max. Abbe Offset (mm)	Max. roll 'am'			Max. error		
		(arc sec)	(micro n)		X (mm)	Y (mm)	Z (mm)	X (micro n)	Y (micro n)	Z (micron)
X	Pitch	8		1000				40		
	Yaw	4		1000				20		
	Roll	4			--	1200	550		11	24
	S/ness-Y		12						12	
	S/ness-Z		12							12
Y	Pitch	4		250					5	
	Yaw	4		750					15	
	Roll	4			300		750	15		6
	S/ness-X		12					12		
	S/ness-Z		12							12
Z	Pitch	4		90						1.8
	Yaw	4		500						10
	Roll	4			0	1000		20	0	
	S/ness-X		12					12		
	S/ness-Y		12						12	
		Max. possible error per axis						119	55	65.8
		Root mean square (RMS)						14	7	8
		Root of the sum of the squares (RSS)						54	26	32

Error budgeting in precision machine design

Benefits of use at all stages of design and development：

- Concept design stage
- Detailed design stage
- Prototype build stage
- Development stage

Error budgeting in precision machine design

Concept design stage

- enables various concepts and configurations to be compared
- helps selection process

Detailed design stage

- highlights areas where redesign should be considered
- provides sound basis for machine acceptance procedures

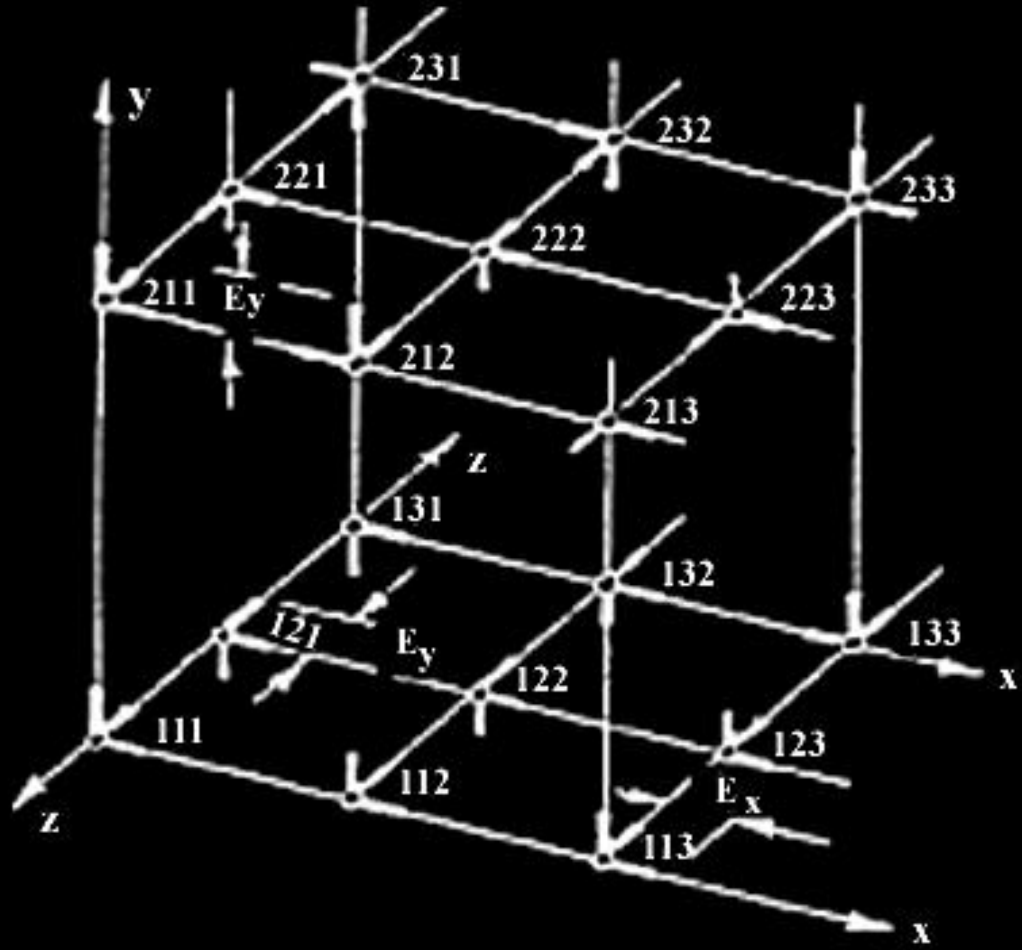
Error budgeting in precision machine design

Prototype build stage

- helps acceptance / rework decisions to be made

Development stage

- trade-offs in sub-system accuracy specification



A 3D error map for a precision machine showing the uncorrected systematic error in x, y, and z directions that can be reduced by software error compensation

Principle 11

Error Compensation： linear; planar; volumetric; quasi-static and dynamic

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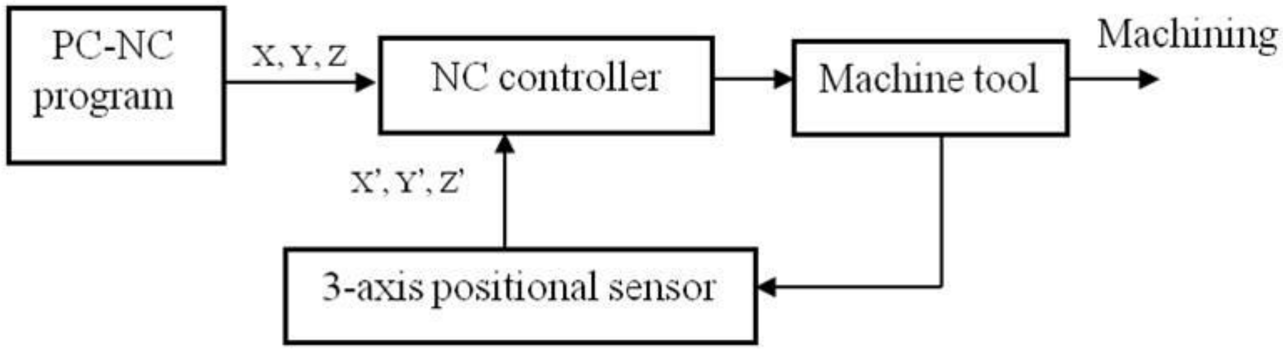
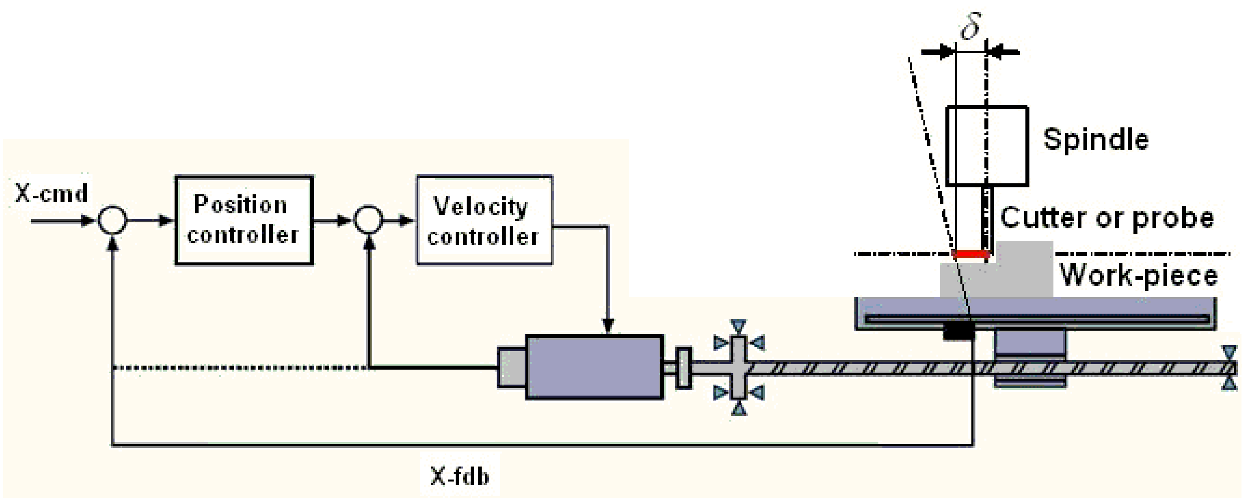


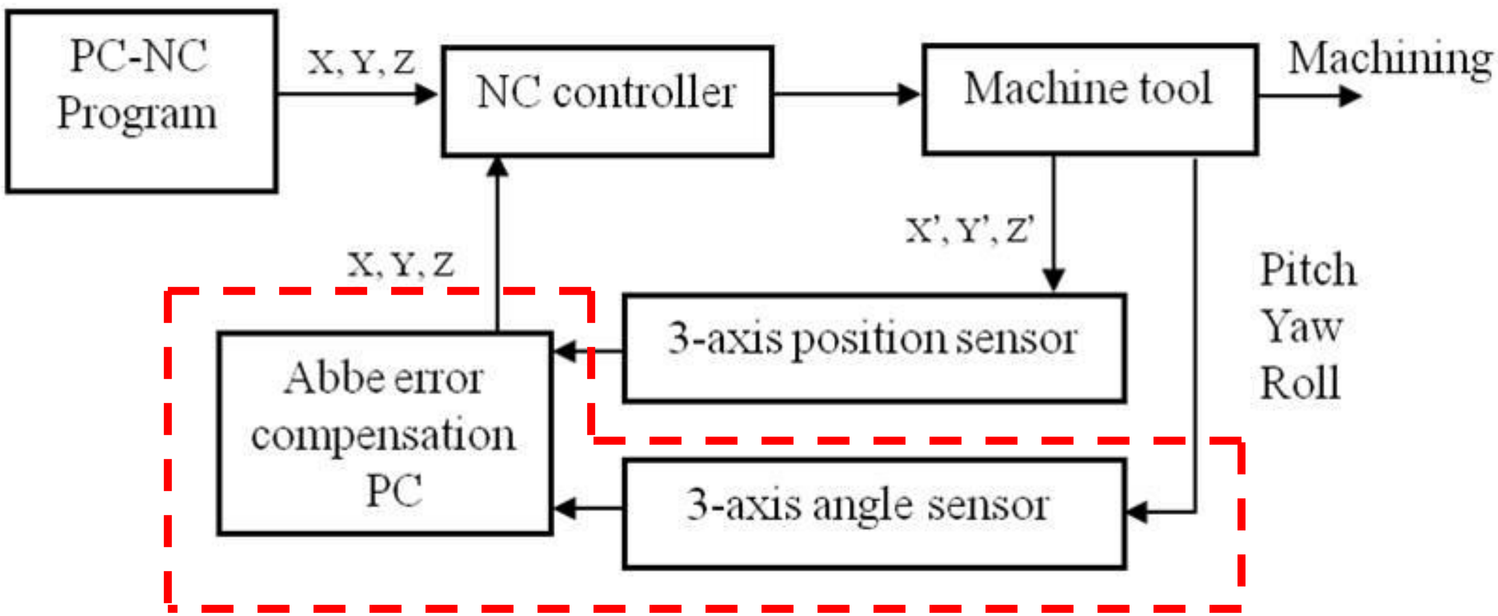


缺點：

工具機無可避免阿貝誤差

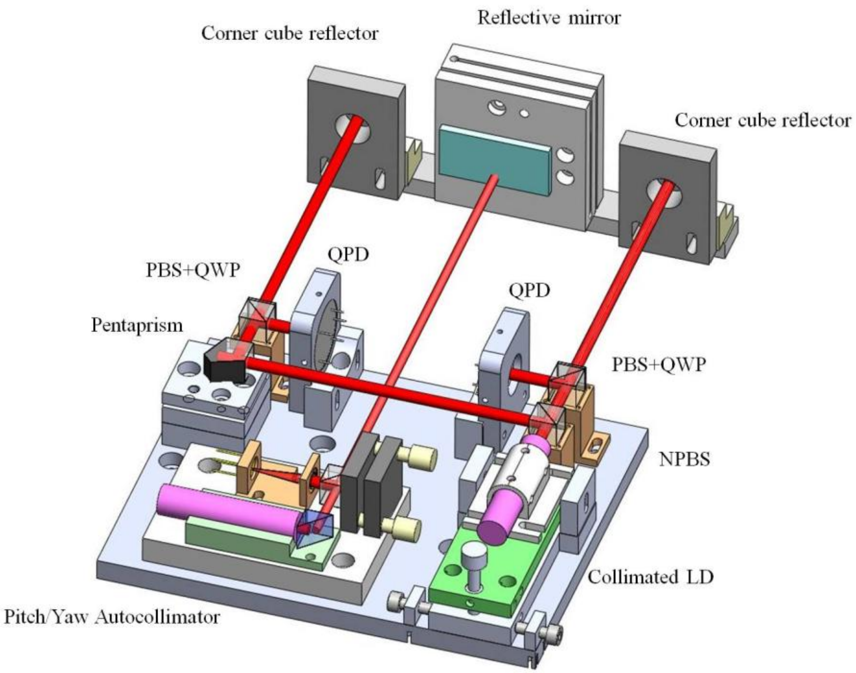
利用位移感測點來回饋加工點指令是不正確的

建議工具機位置控制迴路

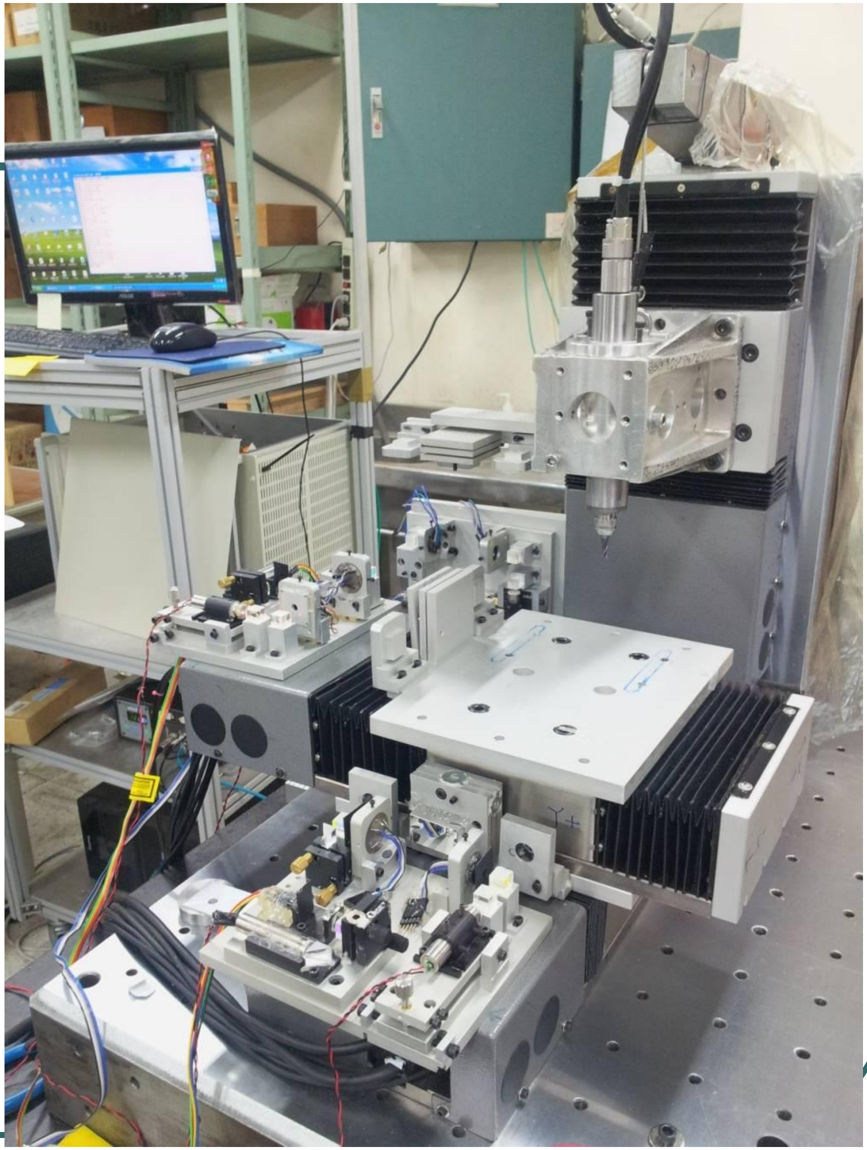


差異處：必須增加角度感測器、阿貝誤差補償器

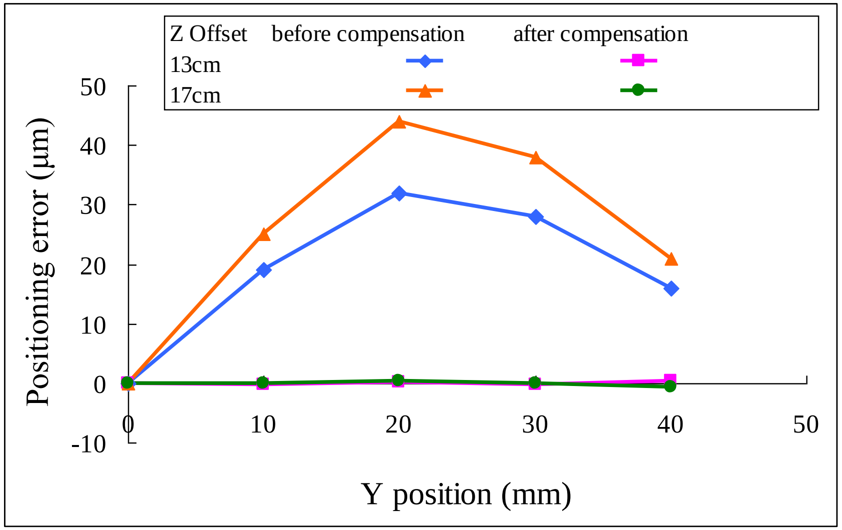
阿貝誤差補償器



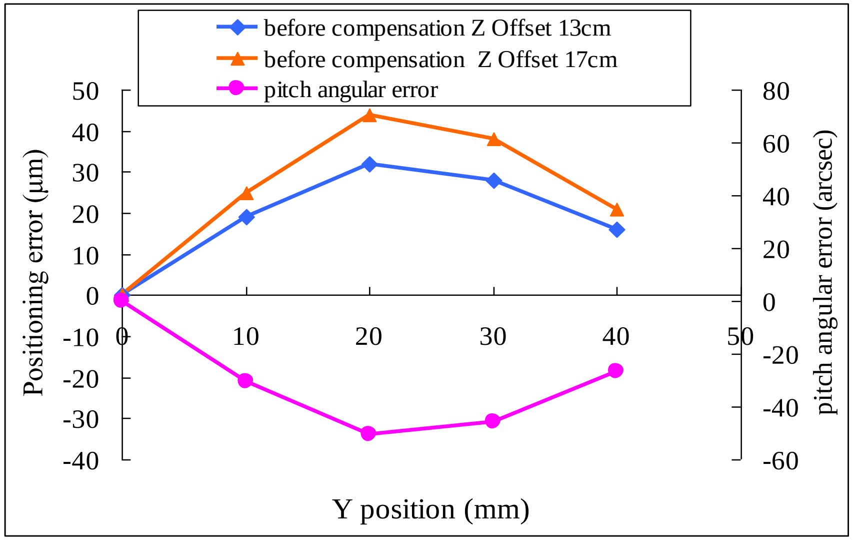
三角度感測器



Experiment of Z-Offset Effect on Y axis



定位誤差補償前後結果



定位誤差與pitch角度關係