ナノメートル計測学
システム創成学科BISコース

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東京大学工学系研究科精密機械工学専攻
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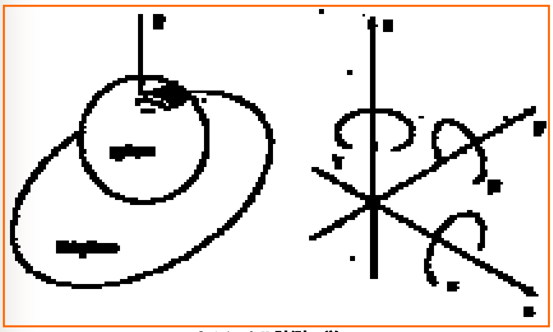
精密設計の基本概念

Fundamental Concepts in Precision Design

- Does it contain the correct number of kinematic constraints?
- Where are the metrology and force loops and how are they shared?
- Are there any heat sources and, if so, what are their likely effects?
- Is the design symmetrical and are the alignment principles obeyed?
- What other source of error are likely to be encountered and can they be reduced by using compensation or nulling?

Basic point constraints

- A single degree of freedom constraint provided by a sphere on a flat. The freedoms of the Cartesian coordinate system are also shown.

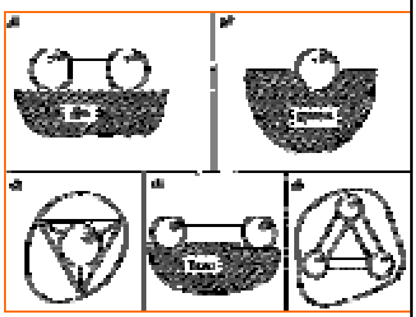


Two lemmas

- Any unconstrained rigid body has six degrees of freedom.
- The number of contact points between any two perfectly rigid bodies is equal to the number of their mutual constraints.
- 制約されていない剛体は6自由度を持つ．
X, Y, Z方向の平行移動．X軸，Y軸，Z軸周りの回転．
- 2つの剛体間の接触点の数が制約の数と等しい．
自由度は，6－制約の数

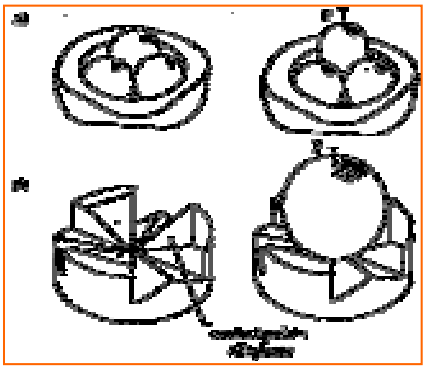
Number of contact points

- Idealized kinematic constraints
  - two balls rigidly connected and resting on a flat
  - a ball in a vee grove
  - a single ball in a trihedral hole
  - two balls rigid by attached with one resting in a groove and the other on a flat
  - three rigidly attached balls on a flat



Trihedral contacts

- Methods for achieving trihedral contacts



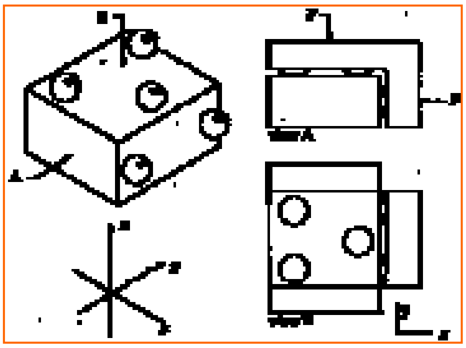
Idealized constraint geometries

- Idealized constraint geometries for the contact of rigidly connected spheres on a combination of flats, grooves and trihedral holes

Const-raints	Configuration
1	Ball on flat
2	Link on flat Ball in groove
3	Ball in trihedral hole Link with one ball in groove and other on flat Three links of balls suitably distributed on a flat
4	Link with one ball in trihedral hole and the other on a flat Link with two balls both in a vee groove Link of three balls with two on a flat and one in a groove Link of four balls suitably distributed on two inclined flats
5	Link of two balls with one in a trihedral hole and the other in a vee groove Link of three balls with two in vee grooves and one on a flat Link of four balls with one in a vee grooves and three on a flat Link of five balls suitably distributed on two inclined flats

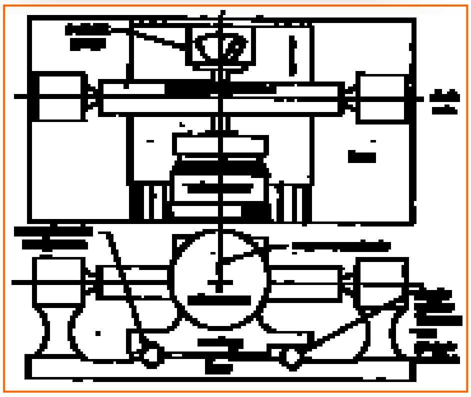
Single degree of freedom movement

- A single degree of freedom movement consisting of five point contacts on a straight prismatic vee slide

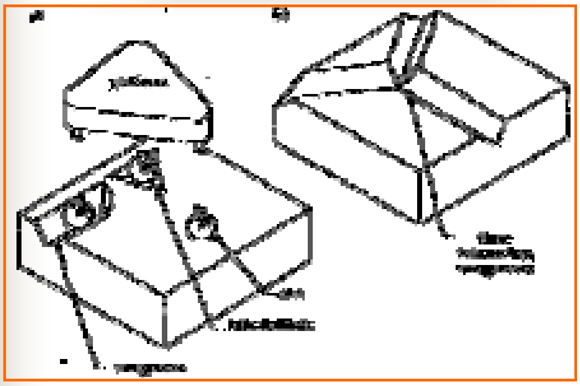


Screw and diameter measuring instrument

- schematic diagram representing two orthogonal views of a screw and diameter measuring instrument

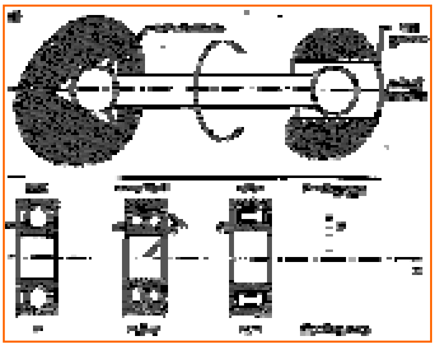


Kinematic clamps



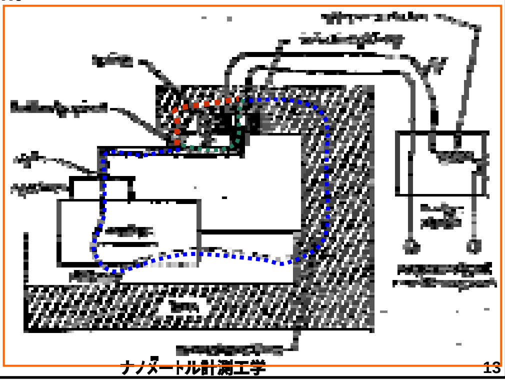
Rotary motion

- Kinematic representation of a system having five constraints
- A variety of rolling element bearings and their respective freedom axes



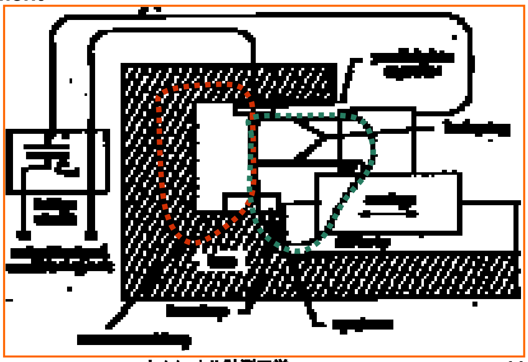
Measurement and force loop

- Schematic diagram of a simple surface measuring instrument



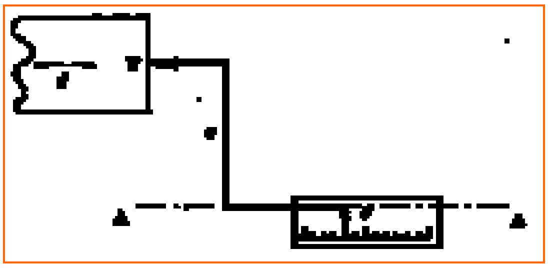
Simple surface measuring instrument

- An alternative design for the simple surface measuring instrument



Abbe offset

- Measuring displacement with an Abbe offset



$$S_\theta = \frac{d_0(1-\cos\theta)}{\cos\theta} - a\sin\theta$$

アッベ式測長機

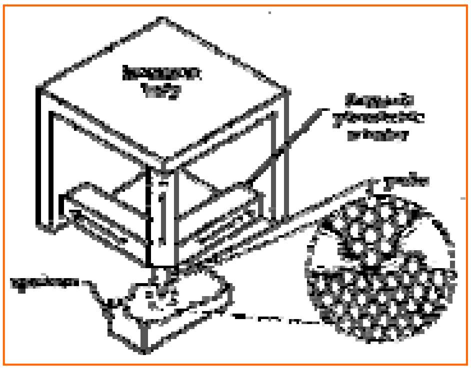
- ULM600 (ドイツ ツァイス社)
  - 測定範囲:外側測定 0 ～ 600 mm
  - 内側測定 1 ～ 460 mm
  - 測定システム:分解能 0.05 μm
  - 測定精度:比較測定 0.15 μm
  - 直接測定 (0.2 + L mm / 1000) μm

Abbe's Principle

- When measuring the displacement of a specified point, it is not sufficient to have the axis of the probe parallel to the direction of motion, the axis should also be aligned with (pass through) the point.
- Ernst Abbe, 1840ー1905
  founder of the Carl Zeiss

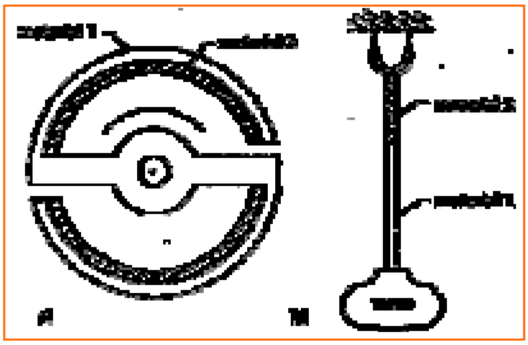
Nulling

- Scanning tunneling microscope



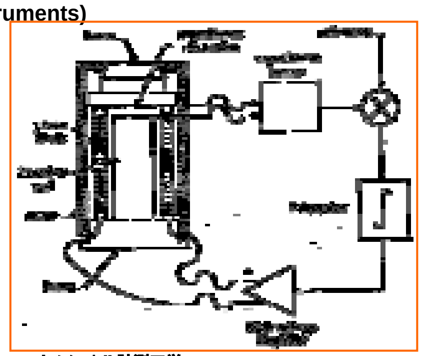
Mechanical compensation

- Examples of constant frequency oscillators for clocks and watches; a) constant inertia, b) constant length



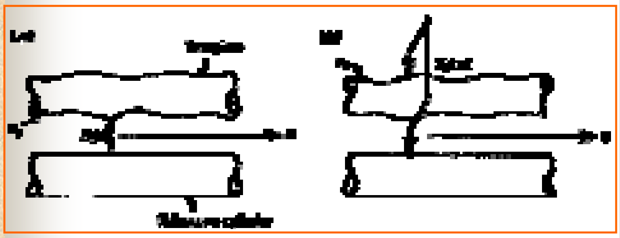
Piezoelectric actuator

- Piezoelectric actuator with inbuilt capacitance position sensing (reproduced with kind permission of Queensgate Instruments)



Reversal Method（反転法）

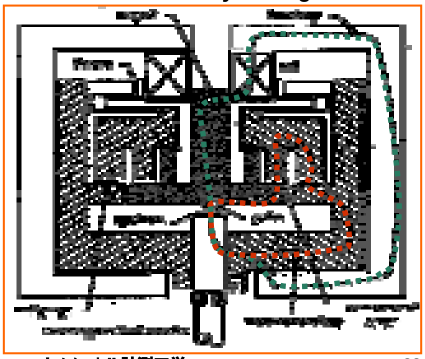
- Error inversion method



$$S_1(x) = R(x) + t(x)$$
$$S_2(x) = R(x) - t(x)$$

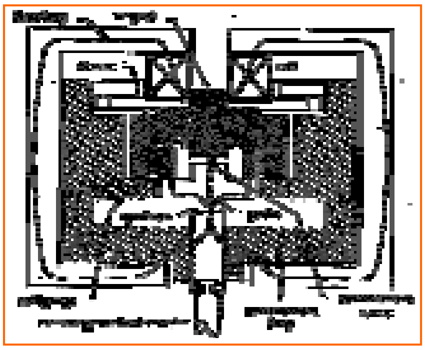
Nanohardness instrument

- Schematic representation of proposed nanohardness instrument. The hatched sections carry the high stability



Abbe Principle

- An alternative layout for the instrument, better complying with the Abbe principle

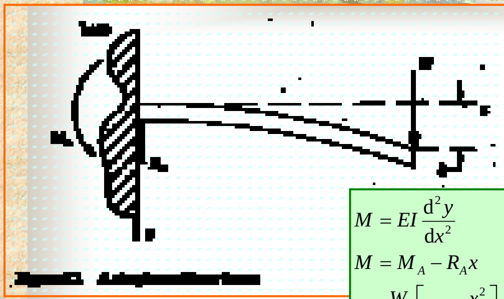


弾性ヒンジ

Flexure Design for Positioning and Control

- A simple flexure design
- The pros and cons of flexure design
  - The advantages of flexures
  - The disadvantages of flexures
- Linear spring mechanisms
  - Simple and compound leaf spring mechanisms
  - Notch type spring mechanisms
  - Kinematic analysis of linear spring mechanisms
  - Additional considerations with compound spring designs
- Angular motion flexures
- Dynamic characteristics of flexure mechanisms
- Case studies
  - X-ray interferometry
  - The measurement of friction between a diamond stylus and specimen

A Simple Cantilever Beam



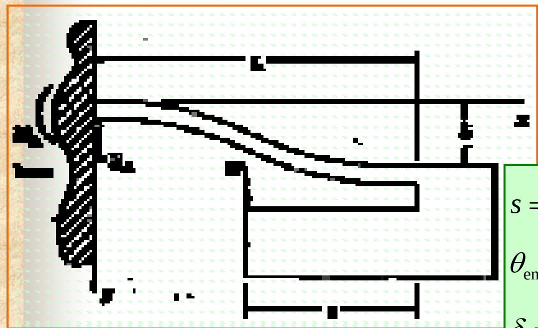
$$M = EI\frac{d^2y}{dx^2}$$

$$M = M_A - R_A x$$

$$\theta = \frac{W}{EI}\left[Lx - \frac{x^2}{2}\right] \; ; \quad \theta_{end} = \frac{WL^2}{2EI}$$

$$y = \frac{W}{EI}\left[\frac{Lx^2}{2} - \frac{x^3}{6}\right] \; ; \quad \delta = \frac{WL^3}{3EI}$$

Deflection of a cantilever beam



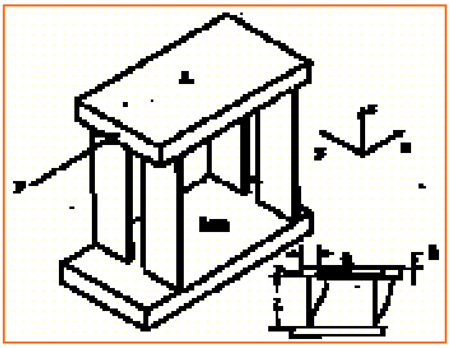
$$s = \frac{L}{2}$$

$$\theta_{end} = 0$$

$$\delta = \frac{WL^3}{12EI}$$

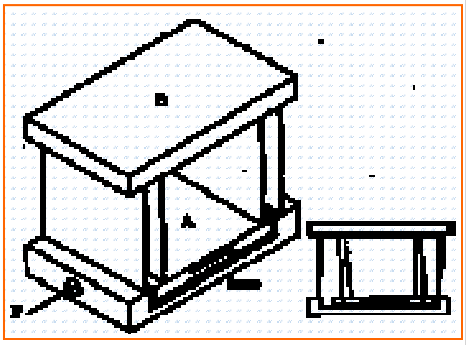
Simple leaf type linear spring

- Simple leaf type linear spring; schematic representation of flexure distortion shown in side view

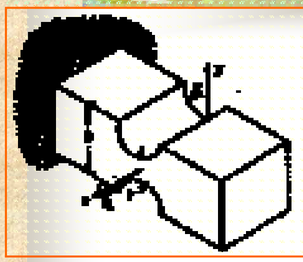


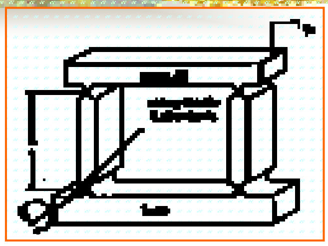
Compound linear spring

- Compound linear spring; schematic representation of the mode of distortion



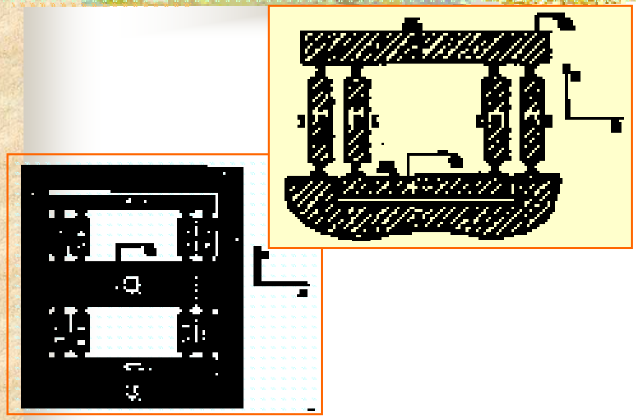
Notch hinge



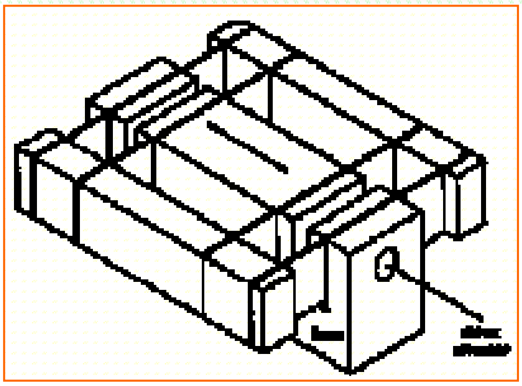


$$\theta_z = \frac{9\pi R^{1/2} M}{2Ebt^{5/2}} \approx \frac{9KRM}{EI} \approx \frac{24KRM}{Ebt^3}$$

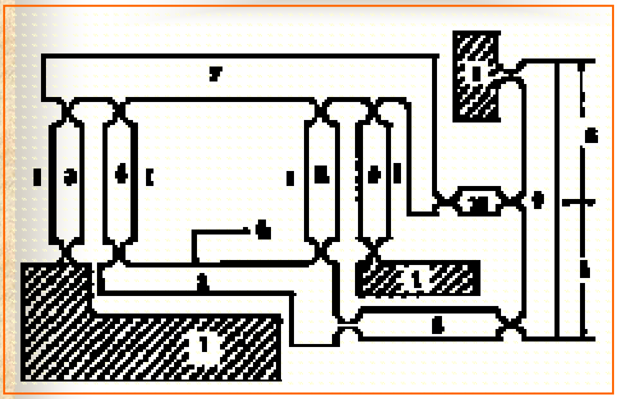
Notch type compound linear spring



Leaf type double compound rectilinear spring



Slaved compound rectilinear spring



Advantages of flexures

- They are wear free.
- Flexures can be manufactured from a single piece of material.
- Displacements are smooth and continuous at all levels.
- Insensitive to bulk temperature changes and to temperature gradients in some planes
- Displacements can be accurately predicted.
- Failure mechanisms due to fatigue or overloading can be easily detected.

Disadvantages of flexures

- The force for a given deflection is dependent upon the elastic modulus of the flexure.
- There will be hysteresis due to dislocation movement in most materials.
- Flexures are restricted to small displacements.
- Out of plane stiffness tends to be relatively low.
- They cannot tolerate large loads.
- Unless precautions are taken, accidental overloads can lead to fatigue.

ナノメートル計測のトレーサビリティ

Traceable Nanometrology

- Advances in traceable nanometrology at the National Physical Laboratory
- NPL (www.npl.co.uk) 1900年に設立
  - The National Physical Laboratory is the United Kingdom's national standards laboratory. From the supermarket to the hospital, from manufacturing to information technology, accurate measurement is essential to a civilised way of life. The work of the NPL as the UK authority for physical measurement standards and metrology (the science of measurement) is therefore vital to us all.

対応する計測機器

- 4種類の測定機
  - NanoSurf IV
  - Metrological AFM
  - Combined optical and x-ray interferometer (COXI)
  - Small-scale CMM

Figure 1. Range of the instruments used at NPL (the scale is in metres).

- 現実には多くのGapが存在する．
  - SXMとCMM
  - 2.5Dと3D

NanoSurf IV

- 表面測定機にレーザ測長を付加した
  - X軸，Z軸の不確かさ 1.3 nm

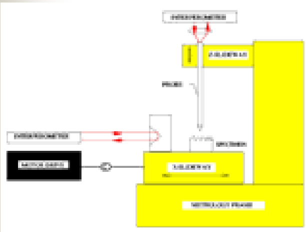


Figure 2. Schematic diagram of NanoSurf IV.

Metrological AMF

- AFMにレーザ測長を不可した
  - 6DOFの測長

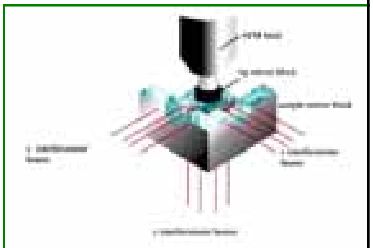


Figure 4. Head and target mirror configuration of the metrological AFM.

COXI

- X線干渉と光干渉を組合わせた．
  - X線：0.192 nm
  - 光：633 nm

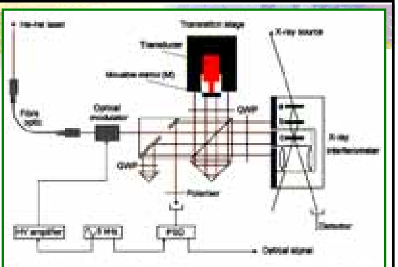
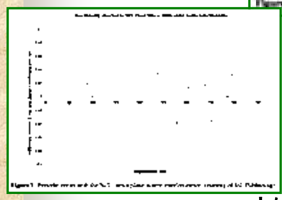


Figure 6. Schematic diagram of the COXI system (courtesy of Royal Society of London).



Small-scale CMM

- SCMM
  - CMMの上に組み込んでいる．
  - 50 mm x 50 mm の測定範囲で，不確かさ 50 nm
  - 6本のレーザを使い，3つの鏡の6DOFを測定する
  - 定接触力 (0.1 mN) のプローブ

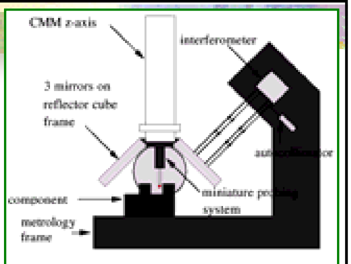


Figure 8. Schematic diagram of the SCMM.

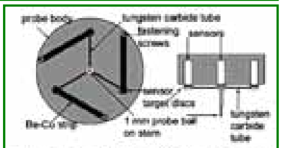


Figure 9. Probe assembly of the SCMM showing transducers and flexures.