5. Measurements of the mechanical quantity

5.1 Measure Surface

5.1.1 Measure Angle

In SI, unit of angle is $[rad]$. Right angel is defined by make equal angles next to each other making two intersecting straight lines. Right is $90°$, and $1°$ is $60'$, $1'$ is $60''$. This hexadecimal notation has been used since old time. It can also use in SI. A point on surface, and around angle of the point is $360° = 2\pi\ [rad]$. Degree, minute, second and $[rad]$ has relation can be expressed by

$$1[rad] = 57.2958° = 3437.75' = 206265''$$

a) Angle Gauge

Like Block Gauge used in length, there is angle gauge made by some angles. Tomlinson invented N.P.L angle gauge is shown in Fig.5.1. The size is $89 \times 16mm$, and accuracy is ± 2 [second]. There are 13 pairs, where are $1, 3, 9, 27, 41$ [deg], $1, 3, 9, 27$ [minute], and $3, 9, 27$ [second], can be combined until $81°$ with step $3'$.

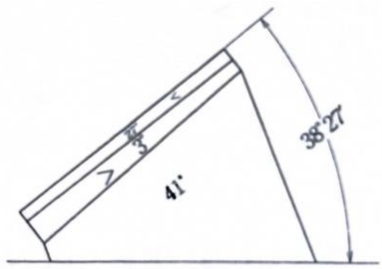


Fig.5.1 N.P.L Angle Gauge

b) Polygon

In Fig.5.2, is an angle ruler with polygonal columnar shape made by glass or metal. And each measurement surface is mirror. It is used to measure the dividing accuracy of the dividing circular table and other dividing devices. Usually, use with Auto Collimator, and accuracy is 1 second.

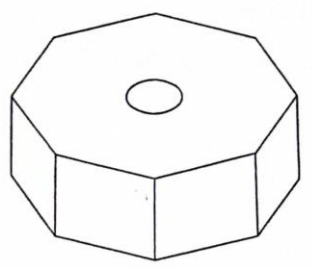


Fig.5.2 Polygon

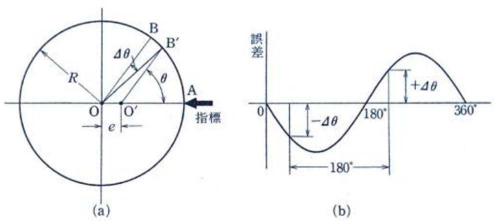


Fig.5.3 Eccentric

c) Scale Disk

Like ruler when measure length, there are evenly spaced in circumference of disk. Most angle measurement are settled inner of scale disk. Error of scale disk. 1) error position of scale. 2) decentering of disk. Fig.5.3 (a) show the decentering. If $\boldsymbol{O}$ is the center of scale, and $\boldsymbol{O}'$ is the rotation center. And $\boldsymbol{OO}' = e$ is decentering error. At first, match the point A to microscope's divide, read the scale when disk turned angle θ. Point $\boldsymbol{B}'$ is the right reading, but the scale shows point $\boldsymbol{B}$. Therefore, there is an error $-\Delta\theta$. The error in Fig.5.3 (a) is occurred by θ and shown in Fig.5.3 (b).

$$R sin\Delta\theta = e sin\theta$$

$$\therefore \Delta\theta \approx \frac{e}{R} sin\theta$$

In another word, this error is systematic error. At the scale positions 180° away from each other, the same signs of values are reversed. For remove this error, set reading in positions 180° away from each other, and take average of the readings. In practically, this method is settled in scale disk.

d) Dividing Head

Dividing head is settled in table of milling machine, not only used for dividing work of gear or jig, but also used for measurement. Main application is work, turn object by worm or worm gear, read turning angle of scale disk mostly, and for measurement is called optical dividing head, which is a device within glass scale disk, and read value by microscope or projection reading device. There is a example, a optical dividing head made by Leitz company, disk scale is $20'$, smallest reading scale is $1''$. The spindle of dividing head can be inclination or horizontal, use with tail stock to support two-side of object.

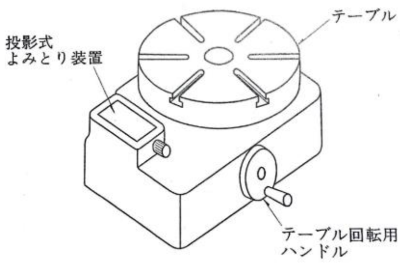


Fig.5.4 Circular Dividing Table

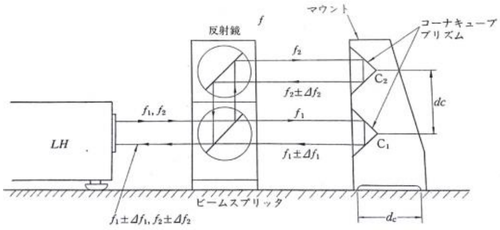


Fig.5.6 Lase Interference Angle Meter
(Hewlett-Packard Co.)

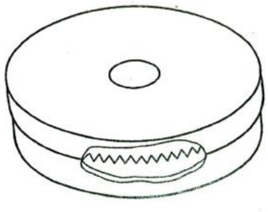


Fig.5.5 Serration Type Dividing Device

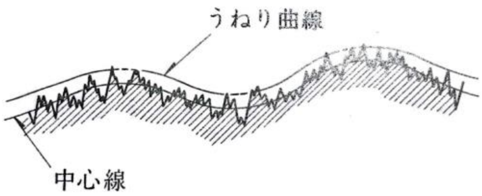


Fig.5.7 Section Curve

Circular dividing table is a device that dividing object with fixed angle by spindle, which is settled in vertical direction of turning table. (See Fig.5.4) Used on the table of UMM (universal measuring microscope) or jig boring machine.

As a dividing device, worm or worm gear, a cam to correct accumulation pitch error of worm gear by, read scale disk by optical reading, serration or ball dividing mechanism. (Fig.5.5)

Device with serration is dividing object by engaging a pair of grinding lap finished serrations. Which means it has a very high accuracy, Ultra dex (A.A. Gage) is $1/4$ [second] And because of accuracy improves by smaller abrasion. Dividing device made by arranged ball inside of serration.

e) Laser Interference Angle Meter

In Fig.5.6, an angle meter with two stable wavelength leaser sources.
Two sources' frequency are f_1, f_2, spitted f_1, f_2 by beam splitter, each direct to corner cube prism C_1, C_2. Frequency of reflection of C_1, C_2 will not change if the mount is stationary, but if the mount is dynamic, because of doppler effect, each variation is $f_1 \pm \Delta f_1$, $f_2 \pm \Delta f_2$. And these two encounters again, take difference that $\Delta f_2 - \Delta f_1$ and calculate. Because of Δf_1 is proportional with speed in the optical axis direction of C_1, Δf_2 is proportional with speed in the optical axis direction of C_2, result of the calculate is difference of amount of movement of C_1 and C_2, in another word, proportional with mount inclination. Measurement arrange is $\pm 10^{\circ}$, resolution is $0.1''$.

5.1.2 Measure Surface Roughness

If zoom in surface of finished surface of workpiece and will get a picture like Fig.5.7.
Section curve will be difference by cutting direction or processing method. The degree of unevenness is called surface roughness. There are many ways to express the roughness, in JIS 0601, maximum of height (R_{max}), average roughness of ten points (R_z), and average roughness of certain line (R_a).

1) Maximum of height (R_{max})

By section curve, the value calculates from Fig.5.8 expressed by μm is called maximum height of sampled part. In this situation, it is necessary to record reference length. For example, 8.5[μm], $R_{max}, L = 2.5$ [mm]. Reference length is selected from 0.08, 0.25, 0.8, 2.5, 8, 25 [mm].

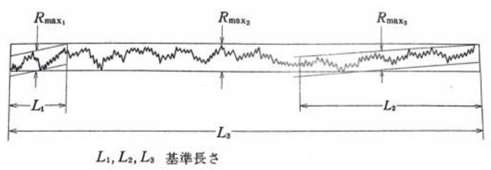


Fig.5.8 Find Maximum of Height (R_{max})

2) Average roughness of ten points (R_z)

Taking reference length from section curve only, make a pair of parallel lines through the third highest point and third deepest point, distance of the parallel lines expressed by μm and get average roughness of ten points by taking it. R_{max} and R_z are find some section curve from measurement surface, calculate average from each taking part of R_{max} and R_z.

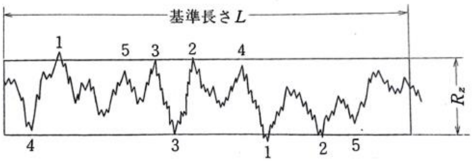


Fig.5.9 Average roughness of ten points (R_z)

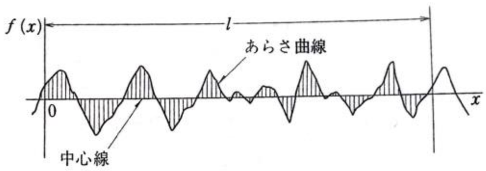


Fig.5.10 Average roughness of certain line

3) Average roughness of certain line (R_a)

In Fig.5.10, take l length part of roughness curve, $\int f(x)\,dx = 0$, and set parallel line against average line as center line (x axis).

$$R_a = \frac{1}{l}\int_0^1 |f(x)|\,dx$$

Use above equation, R_a expressed by μm is called average roughness of center line. Stylus electric type measurement device is use above principle by electric and shows R_a directly. Also, the curve got by movement of stylus, include not appropriate wavelength (low-frequency). Passed by high-pass filter to remove part of low-frequency, the result is called roughness curve. And amplitude ratio of wavelength correspond to frequency is 70[%] is called cut-off wavelength. When find R_a, the standard cut-off wavelength is 0.8 [mm].

Methods of measure surface roughness are, stylus type measuring method, light cutting type measuring method, light wave interference type measuring method, NF roughness measurement method, and so on. And here, introduce stylus type measuring method.

Stylus type measuring method is a method that, measure up-and-down movement of stylus when stylus touch surface of object and move on the surface. Electric type is record expansion

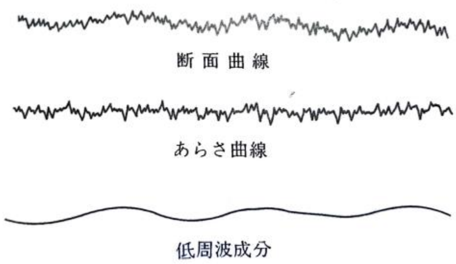


Fig.5.11 Section Curve and Roughness Curve

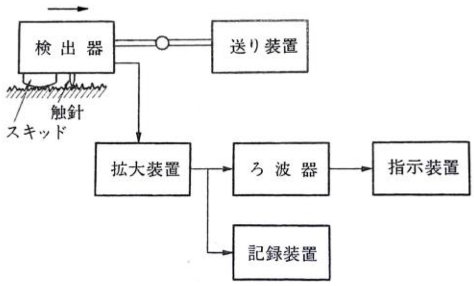


Fig.5.12 Stylus Type Measuring Method

of the up-and-down movement and show R_a on meter directly. Here is an example of Stylus electric type measurement device. Stylus is made from diamond mostly, and curvature radius of tip is around $2{\sim}15$ [μm]. Although the smaller curvature radius, the more accuracy will get, but if it is too small it scratches the material, so the measurement pressure has to be reduced. And there is mechanical restriction if measurement press has reduced.

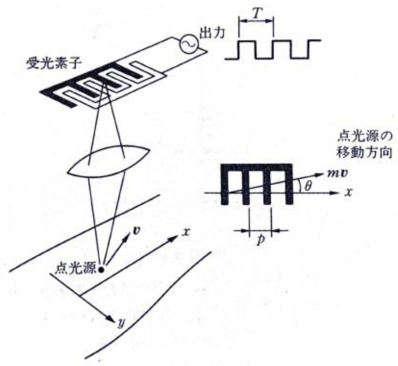


Fig.5.13 Spatial Filter

5.2 Measure Speed and Acceleration

5.2.1 Spatial filter

When observe human work in dark room, which have latticed door, the frequency of change in brightness is connect to speed of human. Speed measurement using this principle is called spatial filter (Fig.5.13).

Point light Source A is moving with speed v(m/s), when measure light receiving element, which is passed by lens with comb shape, output's period T[s] is same as time of movement that point light source through 1 pitch of comb shape receiving part, can be expressed by next equation.

$$T = \frac{p}{mv\cos\theta}$$

However, m is magnification of the optical system, θ is shift angle between movement direction of point light source and light receiving element. Therefore, speed $vcos\theta$ of light receiving element direction is,

$$vcos\theta = \frac{pf}{m}$$

However, $f(1/s, Hz)$ is frequency, speed can be calculated from frequency of output. In practical, point light source without irregular pattern move on light receiving element, but principle is same. This method is applicate in car speed sensor, in this situation, unevenness of the road surface is irregular pattern. This method even more correct than the methods that depend on engine rotation speed, diameter of tire. Also, this method can be applicated in measure speed of debris flow or river.

5.2.2 Correlation Method

Correlation method is a method that get speed by calculate movement time of irregular waveform. In Fig.5.14, an example that

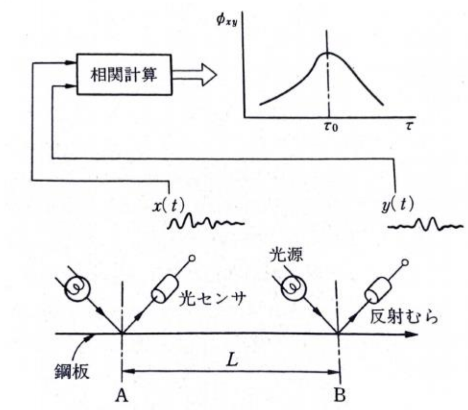


Fig.5.14 Principle of Correlation Method

measure feed speed of steel plate. Set light source and photo sensor at two points with distance L, measure uneven reflection from steel plate surface by each sensor. Because reflection includes irregular pattern, measurement signal is irregular time series waveform. But, measurement signal of point A can be measured at point B only have delay time $\tau_0(s)$, which is occur by move through A-B (length L). These two signals are $x(t)$, $y(t)$, cross-correlation function can be expressed by next equation.

$$\emptyset_{xy}(\tau) = \overline{x(t)y(t+\tau)}$$

$$= \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t)y(t+\tau)dt$$

If cross-correlation function $x(t)$ and $y(t+\tau)$ are similar, the bigger value will get. In Fig.5.14, the picture on upper right, when $\tau = \tau_0$ is the maximum, therefore, the feed speed of steel plate is,

$$v = \frac{L}{\tau_0}$$

Other application, measure car speed with image sensor, or correlation flowmeter to measure speed fluctuation of fluid and so on.

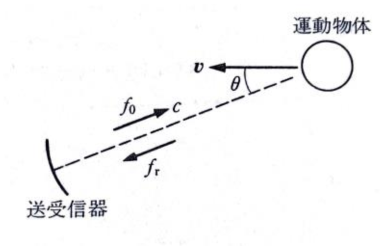


Fig.5.15 Doppler Velocimeter

5.2.3 Doppler Velocimeter

When police car or ambulance is closer to observer, the higher frequency of siren will be observed. Vice versa, the more far away, the lower frequency of siren will be observed. This phenomenon is called doppler effect. In Fig.5.15, Send radio wave or sound wave with frequency f_0 from source to moving object with speed v. And receive reflection at source (observer). Doppler frequency is

$$f_d = f_r - f_0 = 2f_0 \frac{v}{c} cos\theta$$

And speed of moving object can be expressed by next equation.

$$v = \frac{cf_d}{2f_0 cos\theta}$$

However, c is speed of sending signal, θ is angle between moving object direction and sending signal direction. Speed gun use this principle.

5.2.4 Acceleration Sensor (Seismic Pick Up)

Acceleration sensor is for measure acceleration, not only applicated in robot, but also applicated in vibration meter of seismograph, aircraft, vehicle. Construction of

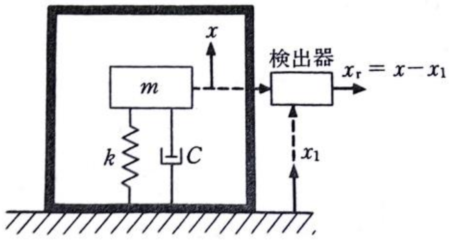


Fig.5.16 Seismic Pick Up

it shown in Fig.5.16. The mass is settled in box with spring and damper. This construction is called Seismic. Displacement of mass is x, object is x_1.

$$m\ddot{x} + c(\dot{x} - \dot{x}_1) + k(x - x_1) = 0$$

However, m(kg) is mass, k(N/m) is spring constant, c(N · s/m) is viscous damping coefficient.

Use relative displacement $x_r = (x - x_1)$.

$$m\ddot{x}_r + c\dot{x}_r + kx_r = -m\ddot{x}_1$$

Standardization of above equation.

$$\ddot{x}_r + 2\zeta\omega_n\dot{x}_r + \omega_n^2 x_r = -a_1$$

$$\omega_n = \sqrt{\frac{k}{m}}, \zeta = \frac{c}{2\sqrt{mk}}$$

However, $\omega_n(rad/s)$ is natural circular frequency, ζ is damping ratio, $a_1(m^2/s)$ is acceleration of x_1. Above equation, a_1 is input, and x_r is output, transfer function $G(s)$ can be expressed by next equation (s is Laplace operator).

$$G(s) = \frac{-1}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

And use $s = j\omega$,

$$G(j\omega) = \frac{-(1/\omega_n)^2}{1 - \lambda^2 + j2\zeta\lambda}$$

However, $\lambda(= \omega/\omega_n)$ is frequency ratio, therefore gain and phase can be expressed by next equation.

$$|G(j\omega)| = \left|\frac{x_r}{a_1}\right| = \frac{(1/\omega_n)^2}{\sqrt{(1-\lambda^2)^2 + (2\zeta\lambda)^2}}$$

$$\varphi = -tan^{-1}\frac{2\zeta\lambda}{1-\lambda^2} - 180°$$

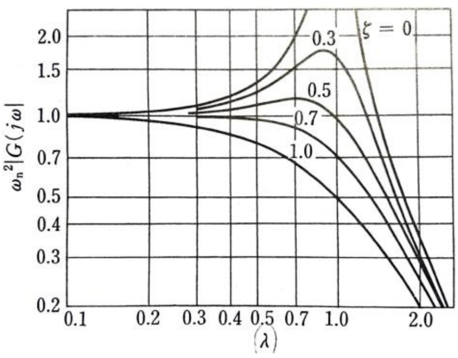


Fig.5.17 Frequency Characteristic

In Fig.5.17, $\omega_n^2|G(j\omega)|$ is shown, when $\zeta = 0.7$, $\lambda \ll 1$ (A frequency sufficiently smaller than the natural frequency), $\omega_n^2|G(j\omega)| \approx 1$, Phase difference is almost $180°$. In another word, acceleration can be measured if relative displacement x_r is $1/\omega_n^2$ times of acceleration amplitude of target object a_1. Strain gauge or piezoelectric element is used as an actual measurement device.

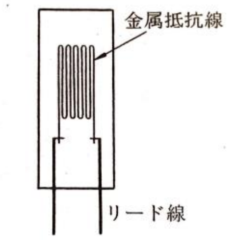


Fig.5.18 Strain Gauge

5.3 Measure Force and Torque

In our daily life, hit the nail with the hammer, grab eggs, open door and so on, force control can be used everywhere. Recently, to welding robot control position of hand is not enough, force control is needed too. Therefore, it is necessary to measure force and torque. This section introduces strain gauge mainly.

5.3.1 Strain Gauge

Strain gauge is a sensor that, when conductor get strain and resistance will change. In Fig.5.18, it is a usual type that metal resistance line settled on a paper or epoxy resin.

Resistance $R(\Omega)$ of conductor like metal resistance line, is direct proportion with length l, and inverse proportion with area A(m^2), can be expressed by next equation.

$$R = \frac{\rho l}{A}$$

However, ρ is resistivity, from above equation, variation ratio $\Delta R/R$ can be got.

$$\frac{\Delta R}{R} = \frac{\Delta\rho}{\rho} + \frac{\Delta l}{l} - \frac{\Delta A}{A}$$

$\Delta\rho$, Δl, ΔA is variation, strain is $\Delta l/l$ or can be written by ε. Resistance ratio to strain, in another word gauge ratio K is,

$$K = \frac{\Delta R/R}{\varepsilon} = 1 + 2\nu + \frac{\Delta\rho/\rho}{\varepsilon}$$

However, ν is Poisson's ratio, $\Delta A/A = -2\nu\varepsilon$. Gauge ratio K is depending on material of resistance line used in strain gauge, K is around 1.7=3.6 mainly. Use semi-conductor instead of metal, the gauge ratio is over 100 and sensitive is very high, temperature characteristic is worse than resistance wire.

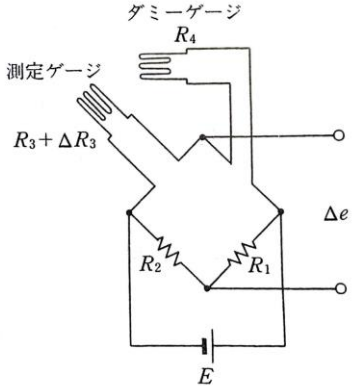


Fig.5.19 Bridge Measurement Circuit

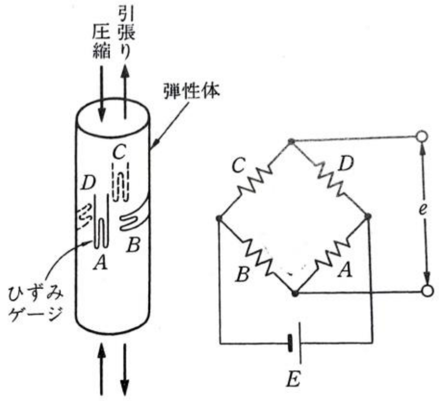


Fig.5.20 Load Cell

When measurement, use bridge circuit shown in Fig.5.19, tiny change of voltage Δe to tiny change of resistance is, (if $R_1 R_3 = R_2 R_4$)

$$\Delta e = \frac{a}{(1+a)^2}\left\{\left(\frac{\Delta R_1}{R_1}\right) - \left(\frac{\Delta R_2}{R_2}\right) + \left(\frac{\Delta R_3}{R_3}\right) - \left(\frac{\Delta R_4}{R_4}\right)\right\}E$$

$$a = \frac{R_2}{R_1} = \frac{R_3}{R_4}$$

Here, $R_1 = R_2 = R_3 = R_4 = R$, use R_3 as measurement gauge, we can get $\Delta R_3 = \Delta R$, $\Delta R_1 = \Delta R_2 = \Delta R_4 = 0$. Δe is,

$$\Delta e = \frac{1}{4}\left(\frac{\Delta R}{R}\right)E = \frac{1}{4}K\varepsilon E$$

Result is voltage, which is proportion with strain ε.

Introduce temperature compensation by dummy gauge. To strain gauge, resistance effected by temperature, so it is necessary that applicate temperature compensation. Change of resistance by strain use subscript ε, change of resistance by temperature use subscript T.

$$\Delta e = \frac{a}{(1+a)^2}\left\{\left(\frac{\Delta R_1}{R_1}\right)_T - \left(\frac{\Delta R_2}{R_2}\right)_T + \left(\frac{\Delta R_3}{R_3}\right)_T + \left(\frac{\Delta R_3}{R_3}\right)_\varepsilon - \left(\frac{\Delta R_4}{R_4}\right)_T\right\}E$$

However, $R_1 = R_2 = R$, since both resistors are in the same position, the rate of resistance change by temperature is canceled out.

$$\Delta e = \frac{a}{(1+a)^2}\left\{\left(\frac{\Delta R_3}{R_3}\right)_T + \left(\frac{\Delta R_3}{R_3}\right)_\varepsilon - \left(\frac{\Delta R_4}{R_4}\right)_T\right\}E$$

Since R_4 use as dummy gauge, close to measure gauge, $R_3 = R_4 = R$ means these two changes of resistance by temperature are same.

$$\Delta e = \frac{a}{(1+a)^2}\left\{\left(\frac{\Delta R_3}{R_3}\right)_\varepsilon\right\}E = \frac{1}{4}\left(\frac{\Delta R}{R}\right)E$$

5.3.2 Load Cell

For strain gauge used as force sensor, adhere strain gauge to surface of elastic body, get load on elastic body by measure strain.

There are four same resistance strain gauge *A*, *B*, *C*, *D*, pasting on elastic body in Fig.5.20, use Wheatstone bridge to measure. Change of *A*, *C* resistance change ratio to compression and pulling of elastic body is

$$\left(\frac{\Delta R_A}{R_A}\right)_\varepsilon = \left(\frac{\Delta R_C}{R_C}\right)_\varepsilon = \left(\frac{\Delta R}{R}\right)_\varepsilon$$

In lateral direction, *B*, *D* resistance change ratio is

$$\left(\frac{\Delta R_B}{R_B}\right)_\varepsilon = \left(\frac{\Delta R_D}{R_D}\right)_\varepsilon = -\nu_R\left(\frac{\Delta R}{R}\right)_\varepsilon$$

However, ν_R is Poisson's ratio of elastic body. Therefore, if $R_A = R_B = R_C = R_D = R$

$$\Delta e = \frac{1}{4}\left\{2\left(\frac{\Delta R}{R}\right)_\varepsilon + 2\nu_R\left(\frac{\Delta R}{R}\right)_\varepsilon\right\}E$$

$$= \frac{1}{2}(1+\nu_R)\left(\frac{\Delta R}{R}\right)_\varepsilon E$$

$$= \frac{1}{2}K\varepsilon(1+\nu_R)E$$

Therefore, force on elastic body, which can also use word load *W*(N) is

$$W = \sigma S = \varepsilon E_s S = \frac{2E_S S}{K(1+\nu_R)}\frac{\Delta e}{E}$$

However, $\sigma(Pa)$ is stress of elastic body, $E_S(Pa)$ is Young's modulus, $S(m^2)$ is sectional area. In this situation, four gauges are

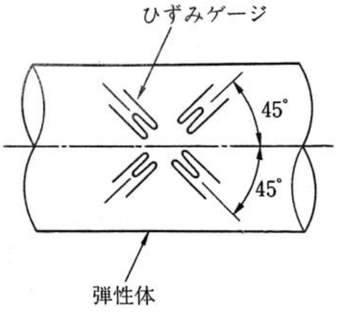


Fig.5.21 Measure Torque

installed on elastic body, not only for Temperature compensation, but also increase sensitivity. This construction of gauge is called 4 active gauge method.

5.3.3 Measure Torque

When measure torque by strain gauge, basically same as load cell. In Fig.5.21, Measure torsion of elastic rod by strain gauge. Because compression and tension occur in the direction of 45 ° to the axis when the rod twists, if four strain gauges are installed on rod, bending component will disappear, only measure torsional strain. There is relation between torsion angle θ and torque T(N·m), torque can be measured.

$$\theta = \frac{32L}{\pi d^4 G} T$$

However, L is length, d is diameter of rod, G(Pa) is modulus of transverse elasticity.

5.3.4 Piezoelectric Element

Polycrystalline like, crystal, barium titanite, rochelle salt, if add pressure on special direction on these polycrystalline, there will electric charge occur on surface. This phenomenon is called piezoelectric effect, and can be used in force sensor. In Fig.5.22, if add pressure on crystal or something else like it between two parallel plates, the electric charge Q(C) occur on surface is

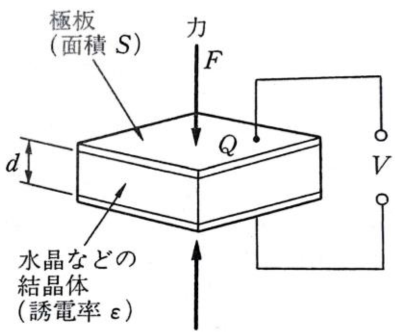


Fig.5.22 Piezoelectric Element

$$Q = \delta F$$

However, δ is piezoelectric modulus, and capacitor capacity C(F) is

$$C = \frac{\varepsilon S}{d}$$

However, ε is dielectric constant, S is effective area of plates, and d is distance between plates. Therefore, voltage of capacity is

$$V = \delta \frac{d}{\varepsilon S} F = gd \frac{F}{S}$$

Get V, which is proportion with force F. $g = \delta / \varepsilon$ is voltage sensitivity.

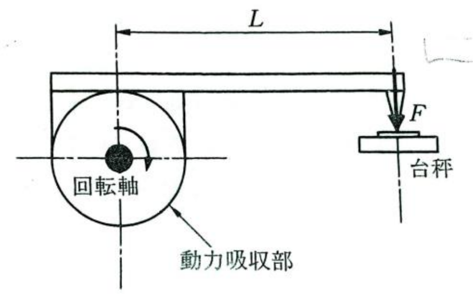


Fig.5.23 Absorption Dynamometer

5.3.5 Measure horsepower

Horsepower, in another word is power, is energy per unit time, there is W(watt) in SI unit. Conventional engineering unit PS (1PS = 735.5W) still used in automobile industry.

Generally, power of rotary machine is measure torque T(N·m) and rotation speed n(rpm), and calculate by next equation.

$$P = \frac{2\pi}{60} Tn$$

There are two types of dynamometer, absorption dynamometer and transmission dynamometer. Construction of absorption dynamometer shown in Fig.5.23. Absorb power of rotary machine by absorption part, measure reaction force by platform scale, which installed in extend arm from absorption part. The torque T(N·m) is

$$T = FL$$

However, F is measured force by platform scale, L is distance from axis of rotation to arm fulcrum. The way to absorb power are, friction by wooden brake, resistance of water by rotating disk rotating in water and so on.

Transmission dynamometer is measure torque from strain of transmission axis. Transmission axis is settled between prime mover and working machine.

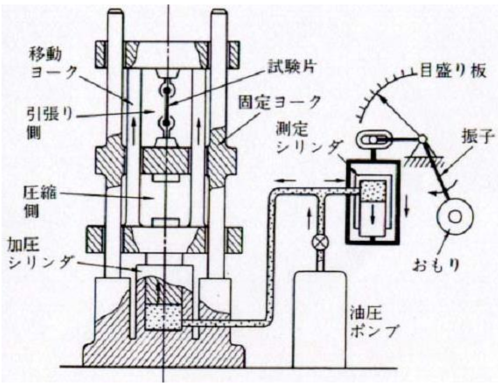


Fig.5.24 Universal Experimental Machine

5.4 Measure Strength and Hardness

5.4.1 Tensile and compression experiment

Tensile and compression experiment is basic knowledge, upon know the mechanical properties of materials. Only difference is direction of load, and compression experiments can also be extended to bending experiments by changing jigs, so tensile and compression experimental machines are usually said to be universal experimental machine.

In Fig.5.24, it is an example of construction of universal experimental machine from old time. Add pressure to pressure cylinder by movement of hydraulic pump, moving yoke move upward against standing yoke, make tensile or compression move. Hydraulic occurred by test pieces or cylinder in right side, load on piston measured by pendulum type gravity transducer. It is shaped to reduce the force according to the piston area ratio in the pressurizing cylinder and the measuring cylinder, and to balance with the small weight.

Fig.5.25 shows principle of gravity transducer. In the picture, load *F* to weight *W*.

$$F = \frac{Wr}{R}\frac{sin\theta}{cos(\alpha - \theta)}$$

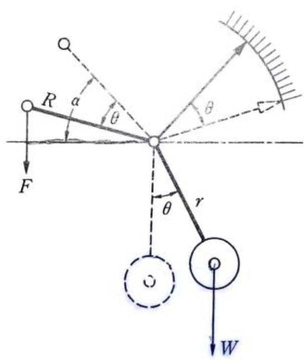
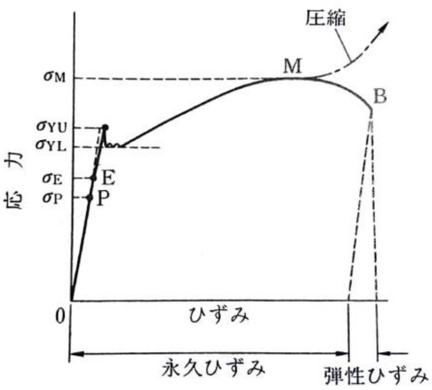
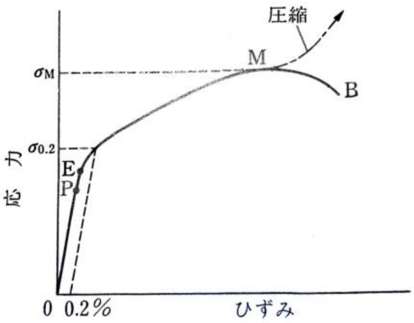


Fig.5.25 Gravity Transducer



(a) stress-strain curve of mild steel



(b) stress-strain curve of aluminum

Fig.5.26 stress-strain curve

This principle used from old time, equivalent to pendulum dish.

Fig.5.26 (a) shows tensile stress-strain curve of mild steel (C:0.12~0.25%) and aluminum. Area OE is elastic deformation region, E is called elastic limit. In elastic limit, if remove load, dimensions of the specimen return to the original state at all, and will not be a permanent strain. The point P is out of stress-strain curve, which is proportional limit. In the area OP, Hook's law is adopted. Generally, The P is lower than the E, if not, it is the difference between nonferrous metal like copper, aluminum and mild steel. Mild steel is a material that if shows pick, and keep load, the elongation will move on. In this area, material moves from elastic deformation to plastic deformation, which called yield. Pick σ_{YU} is called upper yield point, σ_{YL} is called lower yield point.

In Fig.5.26 (b), there is not a sharp yield. In practical, the limit of elastic deformation can be seen as yield point. 0.2% of permanent strain ($\sigma_{0.2}$) is called yield stress, or proof strength. The stress of point M σ_M is called tensile strength.

Compression experiment is usually used for

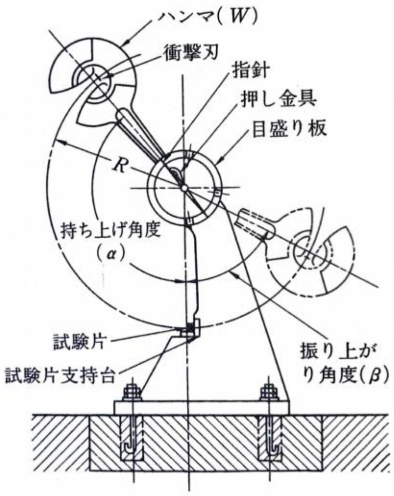


Fig.5.27 Charpy

nonferrous metal like concrete, metal like cast iron is rarely tested.

5.4.2 Impact test

Many parts of machine are got shocking load, and do not forget shocking force like earthquake is affect building. Even material has a very good preference during static force, it may very weak during shocking, especially for metal material like steel, it is very difference that material which been heat treatment or not. And, it becomes brittle when it gets colder, in another word, low temperature brittleness. Stickiness and fragility of material cannot be tested in static experiment. It is necessarily that do impact test.

The method of impact test, from common sense, measure energy that tear the test piece with a hammer needed.

The usually used one is called Charpy show in Fig.5.27. The Charpy uses pendulum hammer, drop hammer from lifting angle α and tear test piece, and then cause inertial force the hammer will lift an angle β, so energy can be calculated by next equation.

$$E = WR(cos\beta - cos\alpha) - L(J)$$

However, W(N) is mass of hammer, R(m) is distance between hit center (Centroid) and rotation center. L(J) is loss of energy.

The size of the hammer edge and test piece, test piece support are strictly specified by the standard.

5.4.3 Hardness test

A) Repulsive (Impact load type)

Shore is being used widely. Fig.5.28 shows construction of shore. A diamond hammer drop vertically from height $h_0(m)$, and measure jumping up height h(m) with visual.

Mass of hammer is $2.31 \times 10^{-2}N$, radius of diamond hammer is $10^{-3}m$, the height is 0.254m, hardness HS can be calculated by next equation.

$$\mathrm{HS} = \frac{10^4}{65}\frac{h}{h_0}$$

B) Push-in (Static load type)

Push rigid body in and measure resistance force, deformation amount. Measure area of indentation with constant load, measure height of indentation with constant load, measure force with constant area. There are many methods.

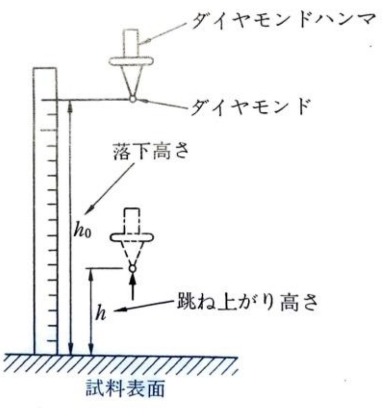
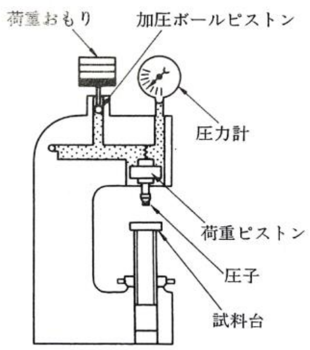
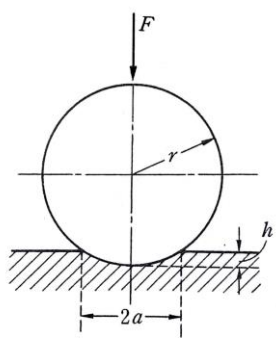


Fig.5.28 Shore



(a) Test Method



(b) Radius r ball

Fig.5.29 Brinell Machine

a. Brinell

Fig.5.29 shows construction of Brinell Machine. Fig.5.29 (b) shows radius *r* ball, which is made of steel or cemented carbide. Push test piece in with a load *F*(N), contact area of ball *S*(mm^2) is

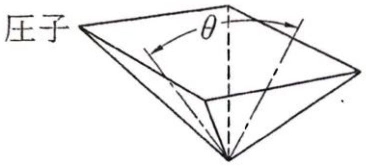
$$S = 2\pi rh$$

And *h* can be calculated by,

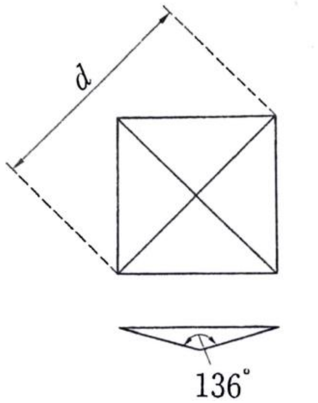
$$h = r - \sqrt{r^2 - a^2}$$

Therefore, average pressure of ball can be expressed by hardness, Conversion factor $(N) \rightarrow (kgf)$ of Brinell Hardness is 0.102

$$\mathrm{HB} = 0.102 \times \frac{F}{S} = \frac{0.102F}{2\pi r\left(r - \sqrt{r^2 - a^2}\right)}$$



(a) Vickers's Test Indenter



(b) Indentation Shape

Fig.5.30 diamond indenter

b. Vickers

Fig.5.30 shows diamond indenter with a regular square pyramid with angle θ is $136°$. Push test piece in with load *P*(N), remove load. Surface area *S*(mm^2) can be calculated from diagonal length *d*(mm). Hardness *HV* can be calculated from F/S.

$$\mathrm{HV} = 0.102 \times \frac{F}{S} = 0.102 \times \frac{2F sin\,\theta/2}{d^2}$$

This method could chose load freedom cause indentation shape has no relation to size of indenter. Usually load is $49.03\mathrm{N}(5kgf)$~$490.3\mathrm{N}(50kgf)$.