

Module 2 Mechanics of Machining

Lesson

10

Dynamometers for measuring cutting forces

Instructional objectives

At the end of this lesson, the students would be able to

- (i) show the general principle of measurement
- (ii) classify and apply different transducers for converting cutting forces into suitable signals
- (iii) state the design requirements of tool-force dynamometers
- (iv) develop and use strain gauge type dynamometer for
 - turning
 - drilling
 - milling
 - grinding

(i) General principle of measurement.

The existence of some physical variables like force, temperature etc and its magnitude or strength cannot be detected or quantified directly but can be so through their effect(s) only. For example, a force which can neither be seen nor be gripped but can be detected and also quantified respectively by its effect(s) and the amount of those effects (on some material) like elastic deflection, deformation, pressure, strain etc. These effects, called signals, often need proper conditioning for easy, accurate and reliable detection and measurement. The basic principle and general method of measurement is schematically shown in Fig. 10.1.

The measurement process is comprised of three stages:

Stage – 1 : The target physical variable (say force) is converted proportionally into another suitable variable (say voltage) called signal, by using appropriate sensor or transducer.

Stage – 2 : The feeble and noisy signal is amplified, filtered, rectified (if necessary) and stabilized for convenience and accuracy of measurement.

Stage – 3 : where the conditioned signal (say voltage) is quantitatively determined and recorded by using some read out unit like galvanometer, oscilloscope, recorder or computer.

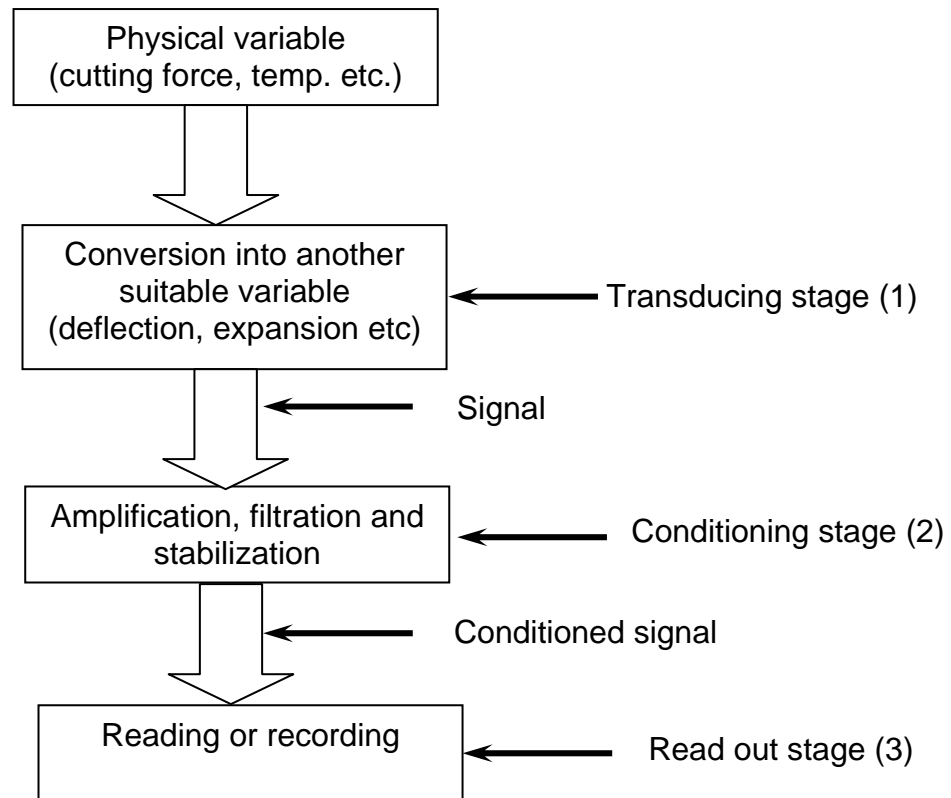


Fig. 10.1 General principle of measurement.

(ii) Different types of transducers used in dynamometers for measuring machining forces.

Measurement of cutting force(s) is based on three basic principles :

- (a) measurement of elastic deflection of a body subjected to the cutting force
- (b) measurement of elastic deformation, i.e. strain induced by the force
- (c) measurement of pressure developed in a medium by the force.

The type of the transducer depends upon how that deflection, strain or pressure is detected and quantified.

(a) Measuring deflection caused by the cutting force(s)

Under the action of the cutting force, say P_z in turning, the tool or tool holder elastically deflects as indicated in Fig. 10.2. Such tool deflection, δ is proportional to the magnitude of the cutting force, P_z , simply as,

$$\delta = P_z \left(\frac{L^3}{3EI} \right) \quad (10.1)$$

where,

L = overhang or equivalent projected length of the cantilever type tool (holder)

E = physical property (Young's modulus of elasticity of the

beam)
 I = size (plane moment of inertia) of the beam section.
 Since for a given cutting tool and its holder, E and I are fixed and the equation 10.1 becomes,

$$\delta \propto P_z \quad \text{or,} \quad \delta = kP_z \quad (10.2)$$

where, k is a constant of proportionality.

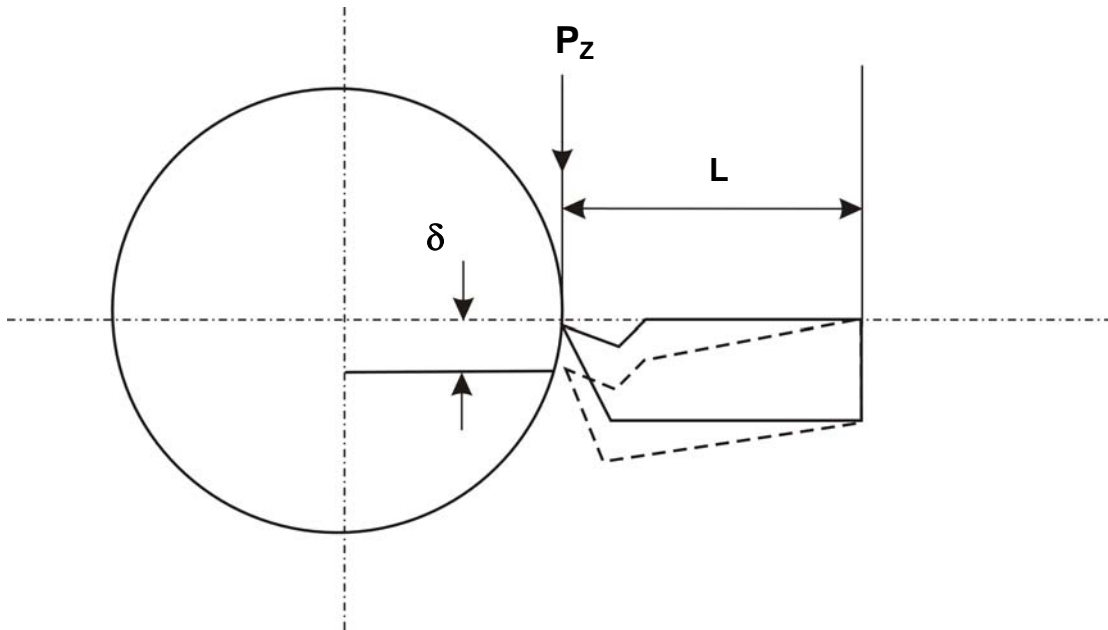


Fig. 10.2 Cutting tool undergoing deflection, δ due to cutting force, P_z

The deflection, δ , can be measured

- mechanically by dial gauge (mechanical transducer)
- electrically by using several transducers like;
 - potentiometer; linear or circular
 - capacitive pickup
 - inductive pickup
 - LVDT

as schematically shown in Fig. 10.3.

- opto-electronically by photocell where the length of the slit through which light passes to the photocell changes proportionally with the tool – deflection

All such transducers need proper calibration before use.

In case of mechanical measurement of the tool deflection by dial gauge, calibration is done by employing known loads, W and the corresponding tool deflections, δ are noted and then plotted as shown in Fig. 10.4. Here the slope of the curve represents the constant, k of the equation (10.2). Then while actual measurement of the cutting force, P_z , the δ^* is noted and the corresponding force is assessed from the plot as shown.

In capacitive pick up type dynamometer, the cutting force causes proportional tool deflection, δ , which causes change in the gap (d) and hence

capacitance, C as
$$C = \frac{\epsilon \cdot A}{3.6\pi d} \quad (10.3)$$

The change in C is then measured in terms of voltage, ΔV which becomes proportional to the force. The final relation between P_z and ΔV is established by calibration.

In case of LVDT, the linear movement of the core, (coupled with the tool), inside the fixed coil produces proportional voltage across the secondary coil.

Fig. 10.3 Electrical transducers working based on deflection measurement

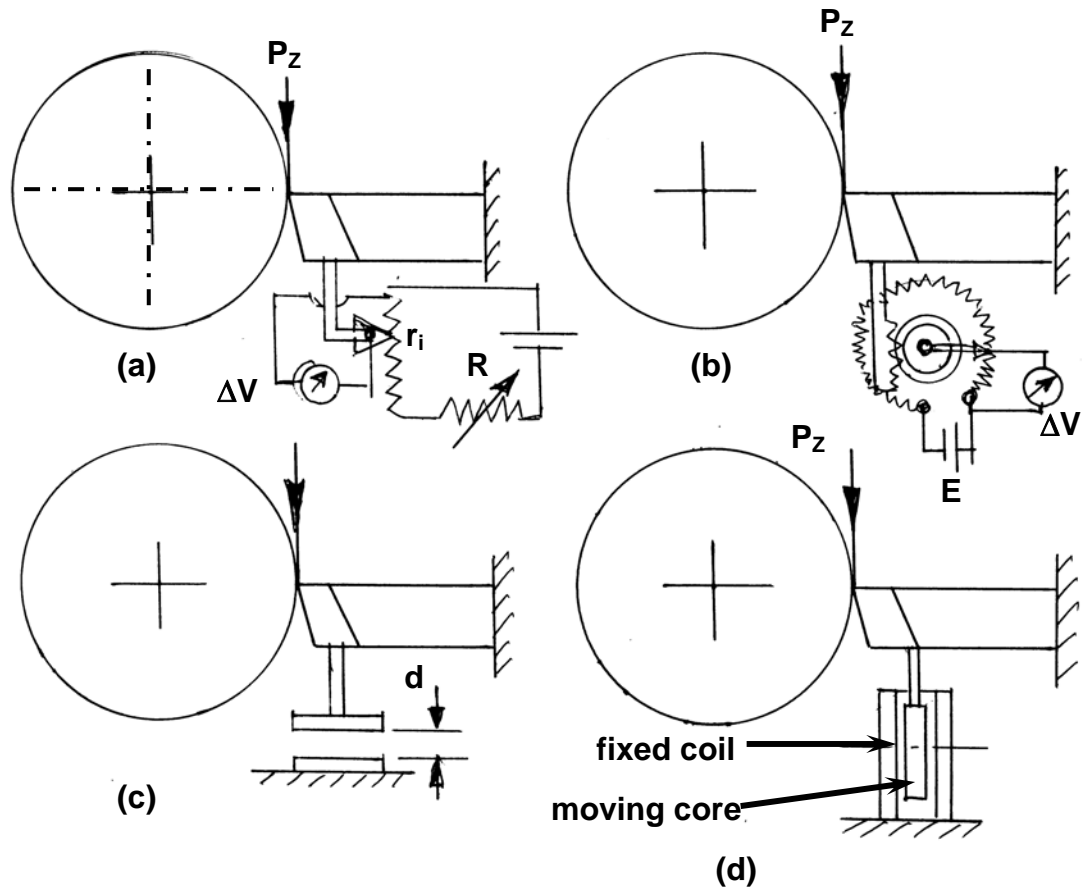


Fig. 10.3 Electrical transducers working based on deflection measurement
 (a) linear pot (b) circular pot (c) capacitive pick up (d) LVDT type

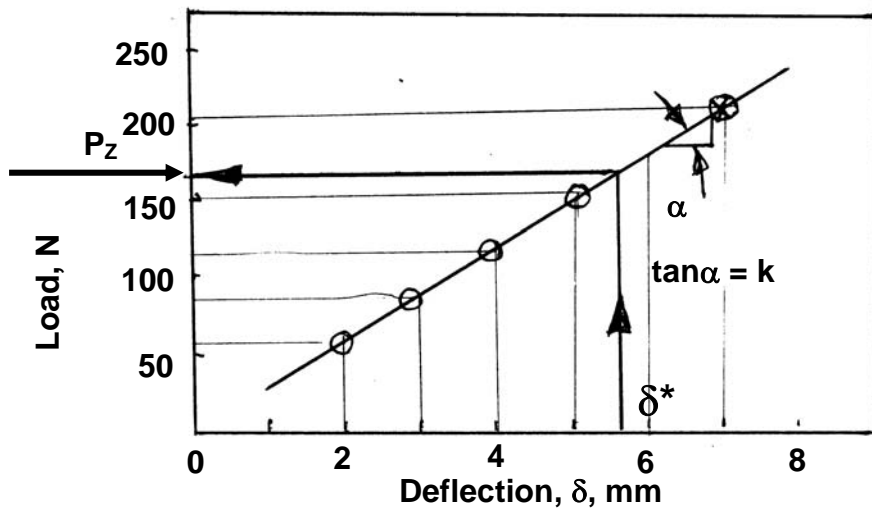


Fig. 10.4 Calibration of mechanical measurement system (dial gauge)

(b) Measuring cutting force by monitoring elastic strain caused by the force.

Increasing deflection, δ enhances sensitivity of the dynamometer but may affect machining accuracy where large value of δ is restricted, the cutting forces are suitably measured by using the change in strain caused by the force. Fig. 10.5 shows the principle of force measurement by measuring strain, ε , which would be proportional with the magnitude of the force, F (say P_z) as,

$$\varepsilon = \frac{\sigma}{E} = \frac{M/Z}{E} = \frac{P_z l}{Z.E} = k_1 P_z \quad (10.4)$$

where,

M = bending moment

Z = sectional modulus (I/y) of the tool section

I = plane moment of inertia of the plane section

y = distance of the straining surface from the neutral plane of the beam (tool)

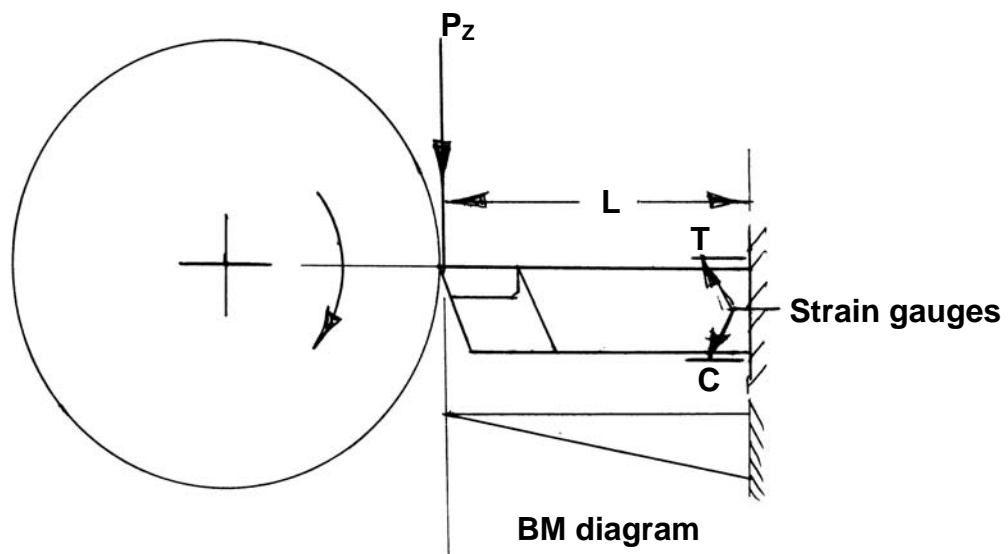


Fig. 10.5 Measuring cutting forces by strain gauges

The strain, ϵ induced by the force changes the electrical resistance, R , of the strain gauges which are firmly pasted on the surface of the tool-holding beam as

$$\frac{\Delta R}{R} = G\epsilon \quad (10.5)$$

where, G = gauge factor (around 2.0 for conductive gauges)
 The change in resistance of the gauges connected in a wheatstone bridge produces voltage output ΔV , through a strain measuring bridge (SMB) as indicated in Fig. 10.6.

Out of the four gauges, R_1 , R_2 , R_3 and R_4 , two are put in tension and two in compression as shown in Fig. 10.6. The output voltage, ΔV , depends upon the constant, G and the summation of strains as,

$$\Delta V = \frac{GE}{4} [\epsilon_1 - (-\epsilon_2) + \epsilon_3 - (-\epsilon_4)] \quad (10.6)$$

where, ϵ_1 and ϵ_2 are in tension and $-\epsilon_3$ and $-\epsilon_4$ are in compression
 The gauge connections may be

- full bridge (all 4 gauges alive) – giving full sensitivity
- half bridge (only 2 gauges alive) – half sensitive
- quarter bridge (only 1 gauge alive) – $\frac{1}{4}$ th sensitivity

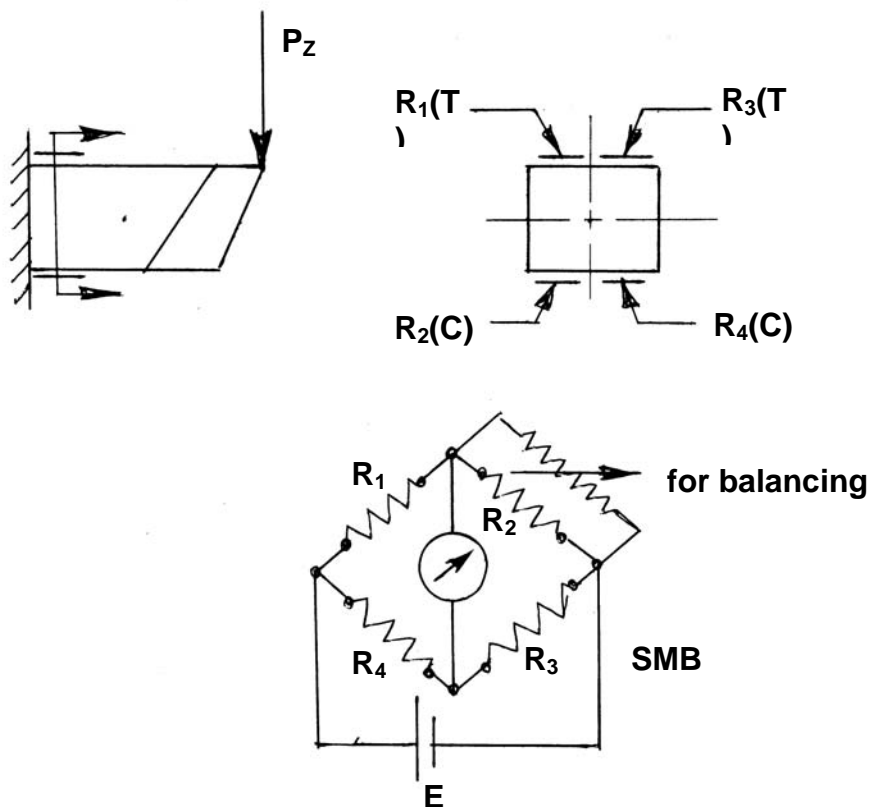


Fig. 10.6 Force measurement by strain gauge based transducer.

(c) Measuring cutting forces by pressure caused by the force

This type of transducer functions in two ways :

- the force creates hydraulic pressure (through a diaphragm or piston) which is monitored directly by pressure gauge
- the force causes pressure on a piezoelectric crystal and produces an emf proportional to the force or pressure as indicated in Fig. 10.7.

Here, $emf = \lambda tp$ (10.7)
where λ = voltage sensitivity of the crystal
 t = thickness of the crystal
 p = pressure

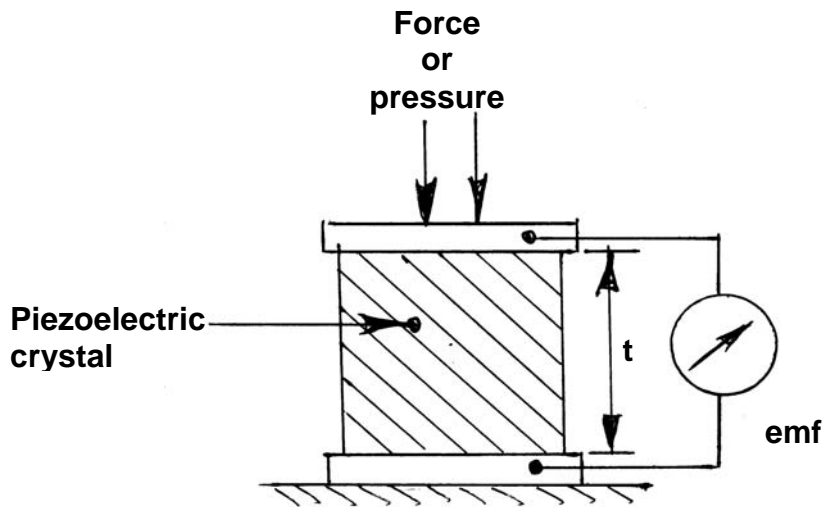


Fig. 10.7 Piezoelectric transducer for measuring force or pressure.

(iii) Design requirements for Tool – force Dynamometers

For consistently accurate and reliable measurement, the following requirements are considered during design and construction of any tool force dynamometers :

- **Sensitivity** : the dynamometer should be reasonably sensitive for precision measurement
- **Rigidity** : the dynamometer need to be quite rigid to withstand the forces without causing much deflection which may affect the machining condition
- **Cross sensitivity** : the dynamometer should be free from cross sensitivity such that one force (say P_z) does not affect measurement of the other forces (say P_x and P_y)
- Stability against humidity and temperature
- Quick time response
- High frequency response such that the readings are not affected by vibration within a reasonably high range of frequency
- Consistency, i.e. the dynamometer should work desirably over a long period.

(iv) Construction and working principle of some common tool – force dynamometers.

The dynamometers being commonly used now-a-days for measuring machining forces desirably accurately and precisely (both static and dynamic characteristics) are

- either • strain gauge type
- or • piezoelectric type

Strain gauge type dynamometers are inexpensive but less accurate and consistent, whereas, the piezoelectric type are highly accurate, reliable and consistent but very expensive for high material cost and stringent construction.

• Turning Dynamometer

Turning dynamometers may be strain gauge or piezoelectric type and may be of one, two or three dimensions capable to monitor all of P_x , P_y and P_z . For ease of manufacture and low cost, strain gauge type turning dynamometers are widely used and preferably of 2 – D (dimension) for simpler construction, lower cost and ability to provide almost all the desired force values.

Design and construction of a strain – gauge type 2 – D turning dynamometer are shown schematically in Fig. 10.8 and photographically in Fig. 10.9 Two full bridges comprising four live strain gauges are provided for P_z and P_x channels which are connected with the strain measuring bridge for detection and measurement of strain in terms of voltage which provides the magnitude of the cutting forces through calibration. Fig. 10.10 pictorially shows use of 3 – D turning dynamometer having piezoelectric transducers inside.

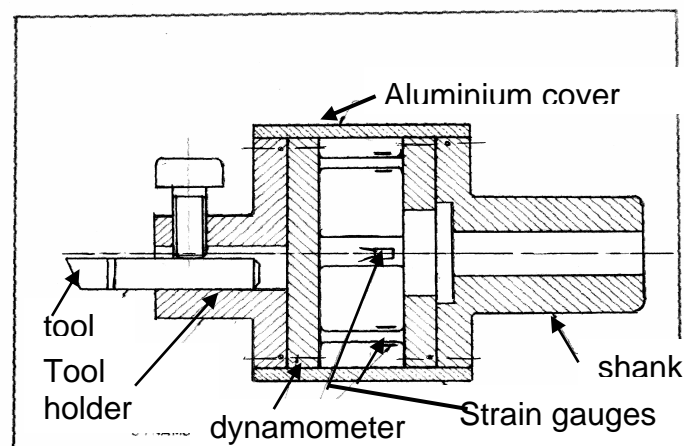


Fig. 10.8 Schematic view of a strain gauge type 2 – D turning dynamometer.

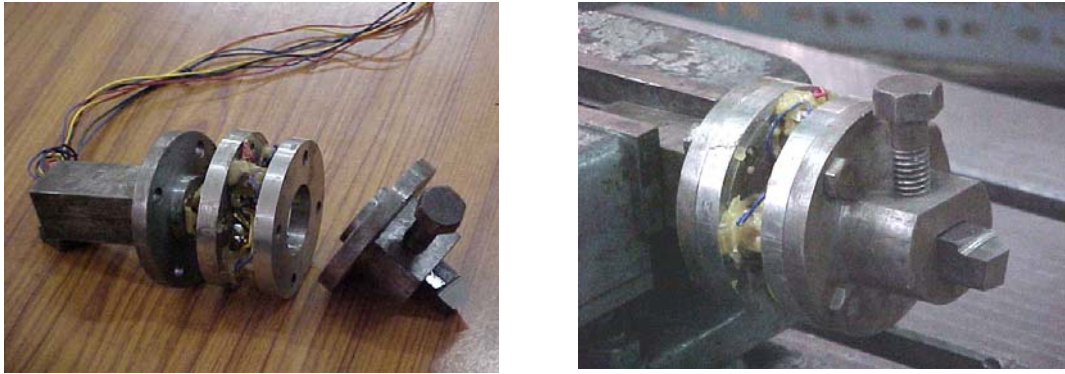


Fig. 10.9 Photographs of a strain gauge type 2 – D turning dynamometer and its major components.

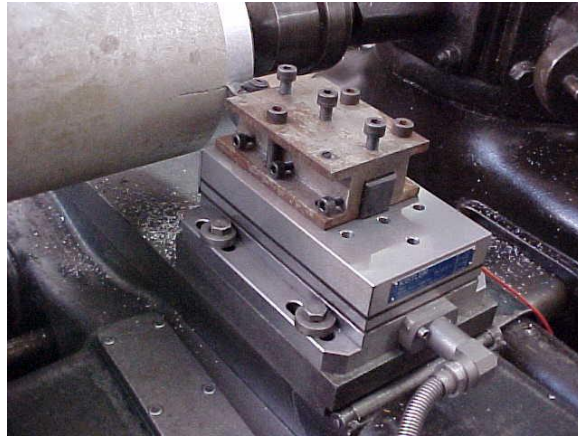


Fig. 10.10 Use of 3 – D piezoelectric type turning dynamometer.

- **Drilling dynamometer**

Physical construction of a strain gauge type 2 – D drilling dynamometer for measuring torque and thrust force is typically shown schematically in Fig. 10.11 and pictorially in Fig. 10.12. Four strain gauges are mounted on the upper and lower surfaces of the two opposite ribs for P_x – channel and four on the side surfaces of the other two ribs for the torque channel. Before use, the dynamometer must be calibrated to enable determination of the actual values of T and P_x from the voltage values or reading taken in SMB or PC.

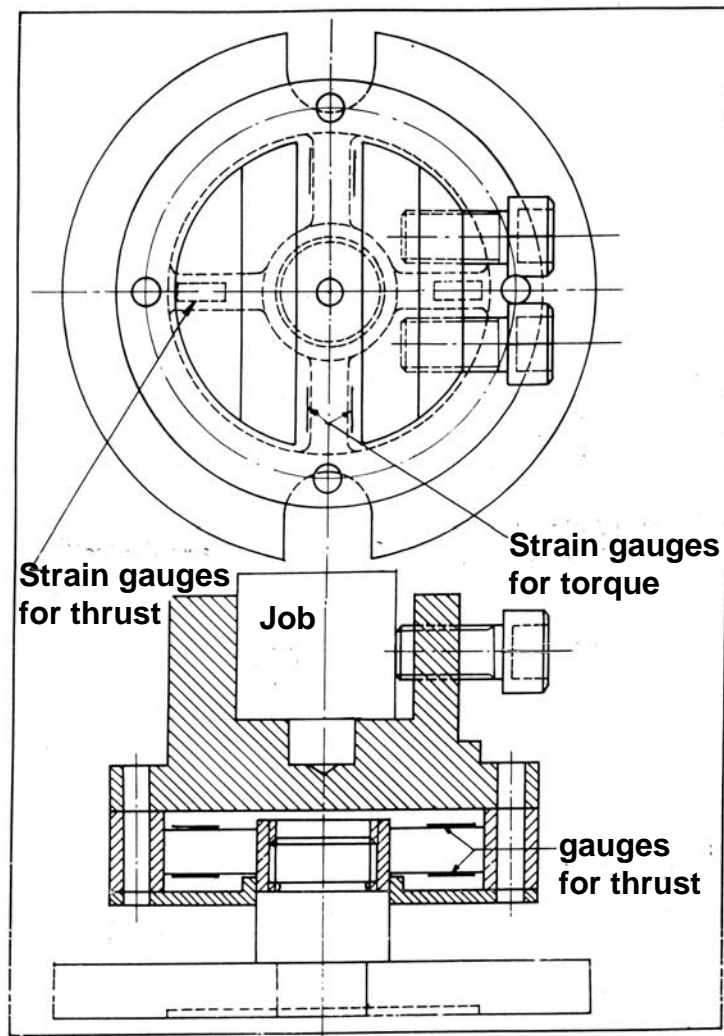


Fig. 10.11 Schematic view of construction of a strain gauge type drilling dynamometer.

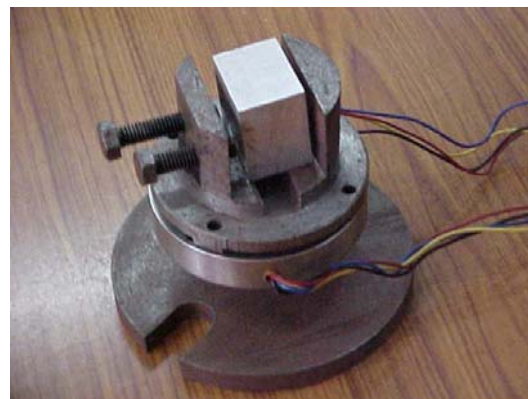
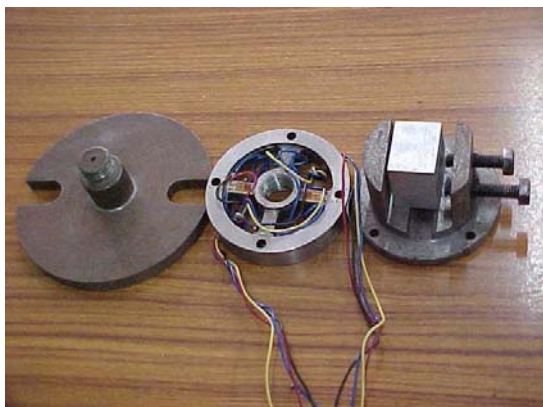


Fig. 10.12 A strain gauge type drilling dynamometer and its major components.

- **Milling dynamometer**

Since the cutting or loading point is not fixed w.r.t. the job and the dynamometer, the job platform rests on four symmetrically located supports in the form of four O-rings. The forces on each O-ring are monitored and summed up correspondingly for getting the total magnitude of all the three forces in X, Y and Z direction respectively.

Fig. 10.13 shows schematically the principle of using O-ring for measuring two forces by mounting strain gauges, 4 for radial force and 4 for transverse force.

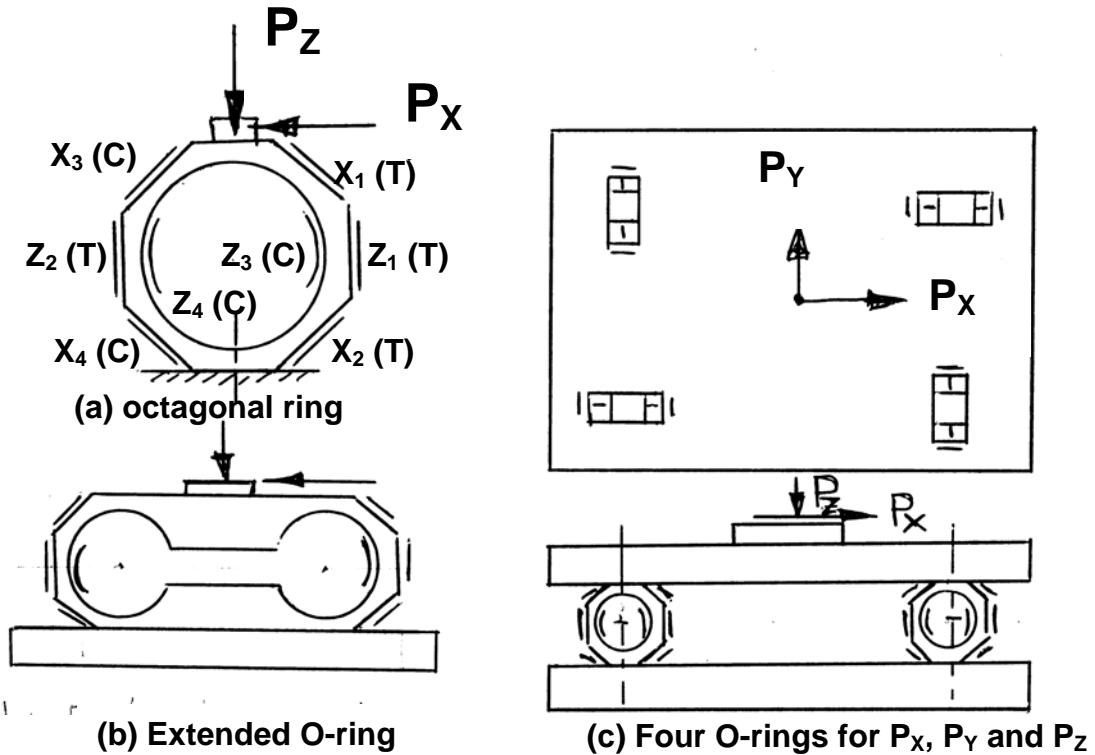


Fig. 10.13 Scheme of strain gauge type 3 – D milling dynamometer

Fig. 10.14 typically shows configuration of a strain gauge type 3 – D milling dynamometer having 4 octagonal rings. Piezoelectric type 3 – D dynamometers are also available and used for measuring the cutting forces in milling (plain, end and face)

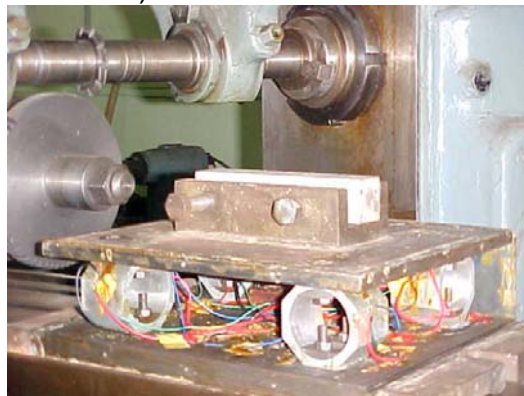


Fig. 10.14 A typical strain gauge type 3 – D milling dynamometer

- **Grinding dynamometer**

The construction and application of a strain gauge type (extended O-ring) grinding surface dynamometer and another piezoelectric type are typically shown in Fig. 10.15 and Fig. 10.16 respectively.

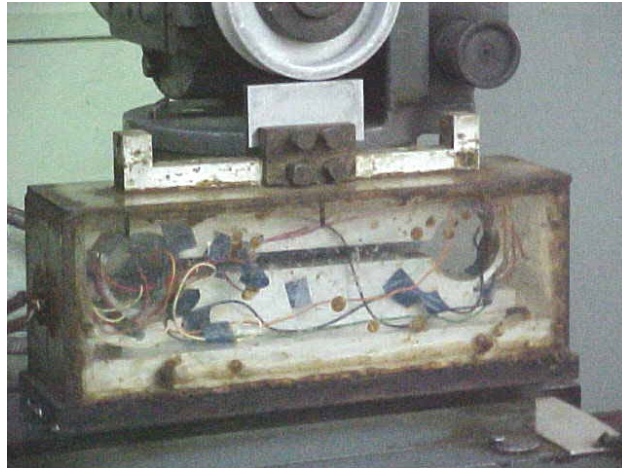


Fig. 10.15 A typical strain – gauge type 2 – D grinding dynamometer

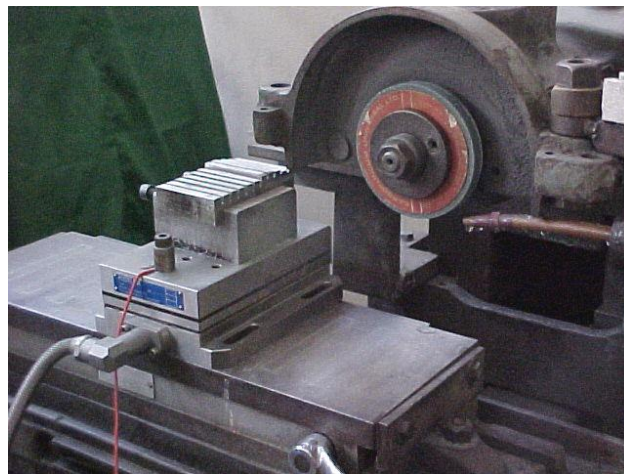


Fig. 10.16 Piezoelectric type grinding dynamometer in operation.

Unlike strain gauge type dynamometers, the sophisticated piezoelectric type (KISTLER) dynamometers can be used directly more accurately and reliably even without calibration by the user.