Mechanics of Machines

Kinematics of gear train

Module 3: Gear terminologies, law of gearing, Interference and undercutting

Tapan Kumar Mahanta, Ph.D.
SMEC Chennai Campus

Gear

A gear is a rotating circular machine part having cut teeth or, in the case of a cogwheel or gearwheel, inserted teeth (called cogs), which mesh with another toothed part to transmit torque.

Advantages

1. It transmits exact velocity ratio.

2. It may be used to transmit large power.

3. It has high efficiency.

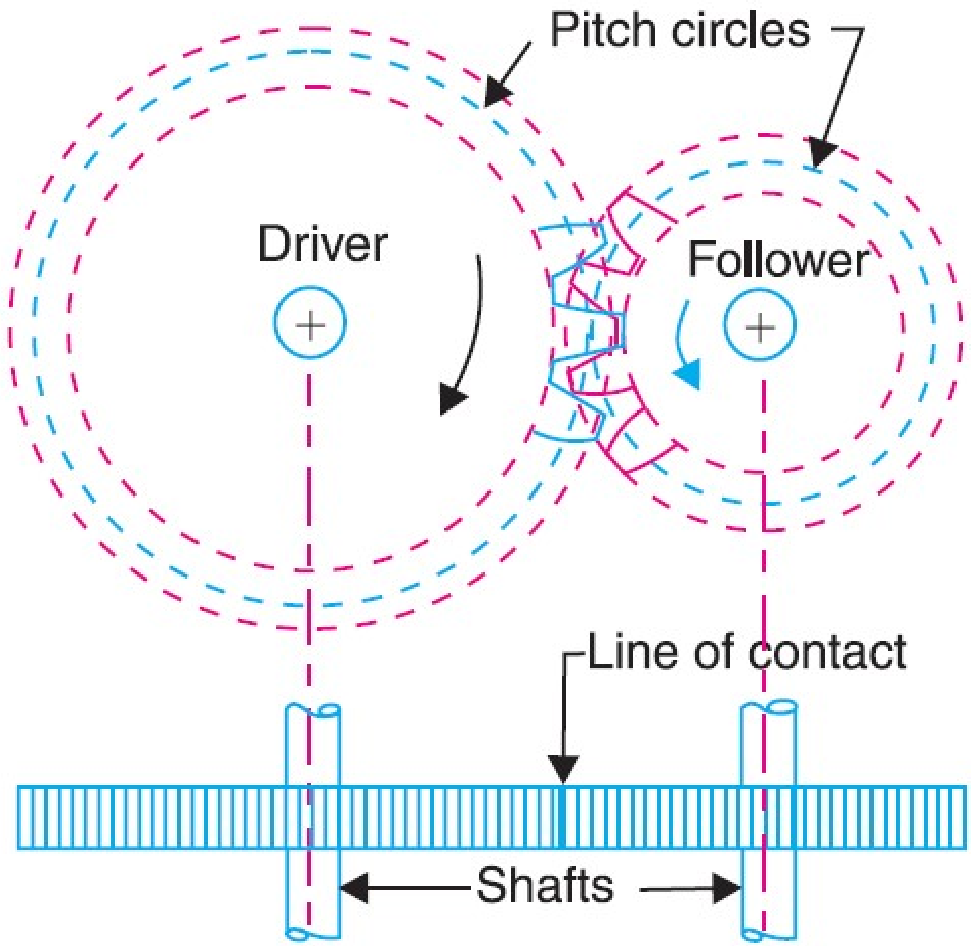
4. It has reliable service.

5. It has compact layout.

Disadvantages

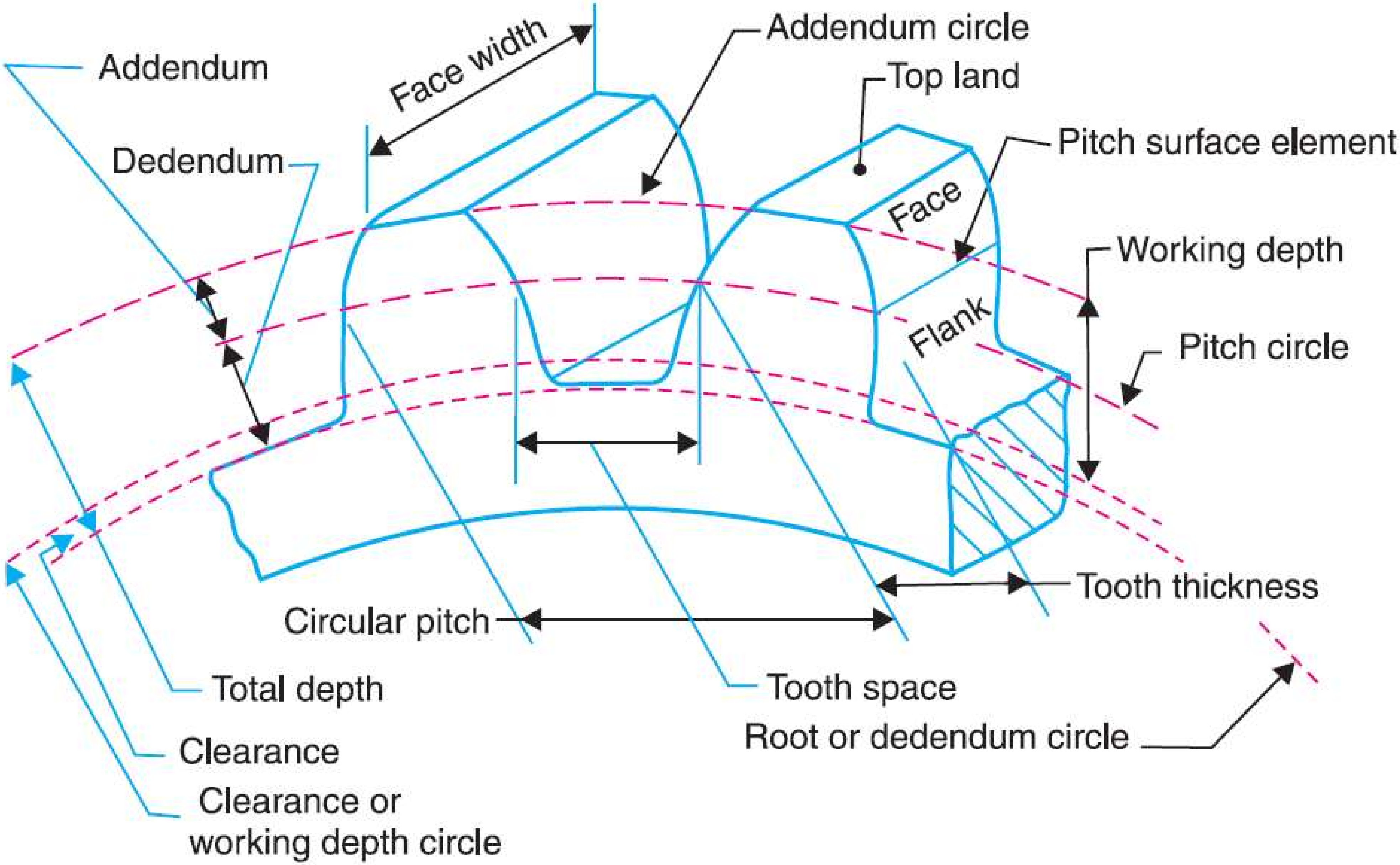
1. The manufacture of gears require special tools and equipment.

2. The error in cutting teeth may cause vibrations and noise during operation



Types of Gear

Gear terminologies

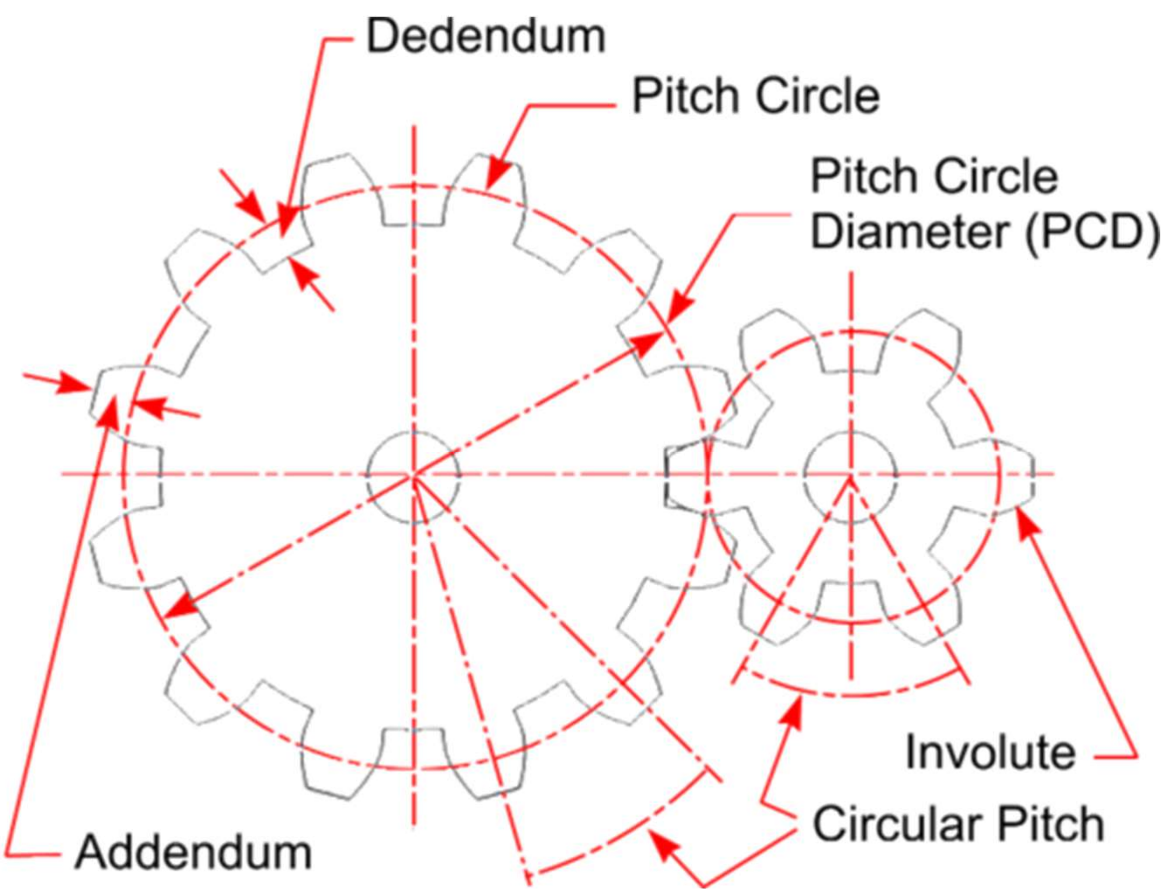


Gear terminologies

Pitch circle. It is an imaginary circle which by pure rolling action, would give the same motion as the actual gear.

Pitch circle diameter. It is the diameter of the pitch circle. The size of the gear is usually specified by the pitch circle diameter. It is also known as ***pitch diameter***.

Pitch point. It is a common point of contact between two pitch circles.

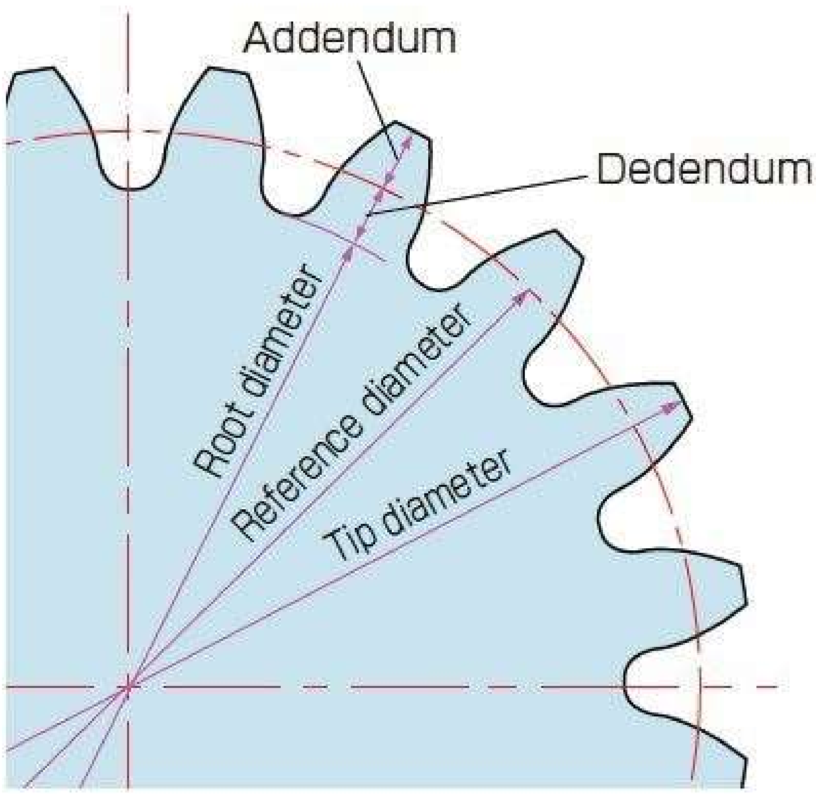


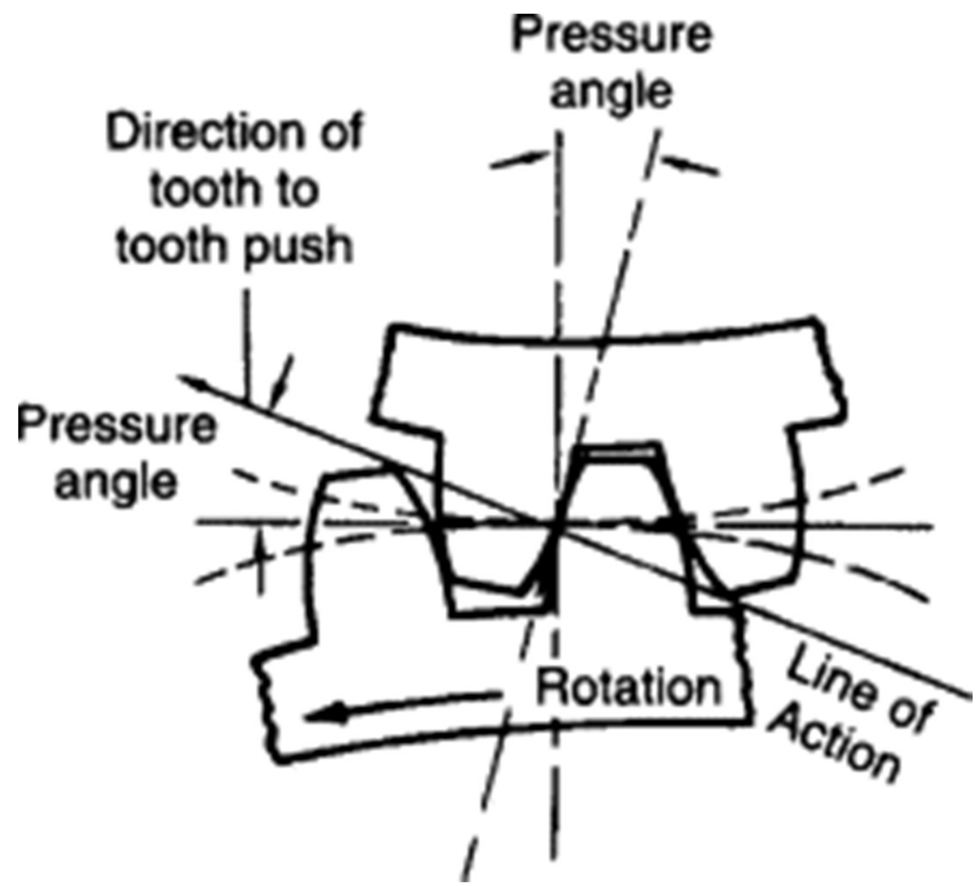
Gear terminologies

Pressure angle or angle of obliquity. It is the angle between the common normal to two gear teeth at the point of contact and the common tangent at the pitch point. The standard pressure angles are 14 .5° and 20°.

***Addendum*.** It is the radial distance of a tooth from the pitch circle to the top of the tooth.

***Dedendum*.** It is the radial distance of a tooth from the pitch circle to the bottom of the tooth.





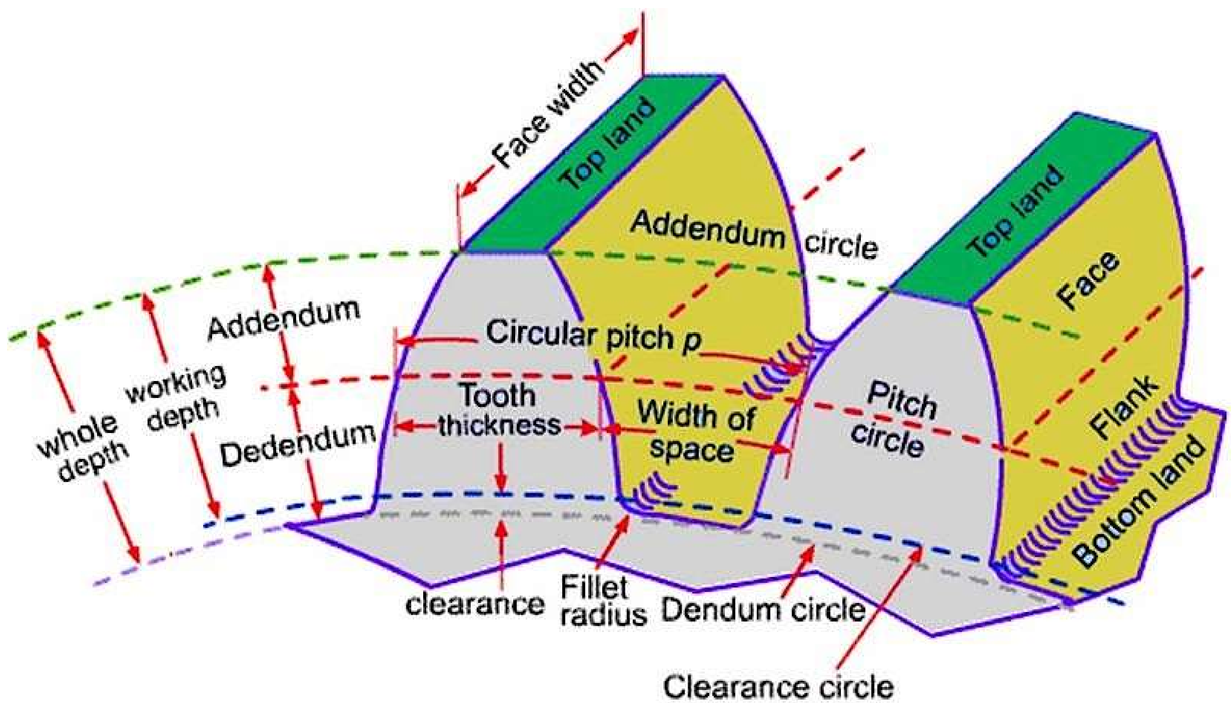
Gear terminologies

Addendum circle. It is the circle drawn through the top of the teeth and is concentric with the pitch circle.

Dedendum circle. It is the circle drawn through the bottom of the teeth. It is also called root circle.

Circular pitch(p_c) It is the distance measured on the circumference of the pitch circle from a point of one tooth to the corresponding point on the next tooth.

$$p_c = \frac{\pi D}{T}$$

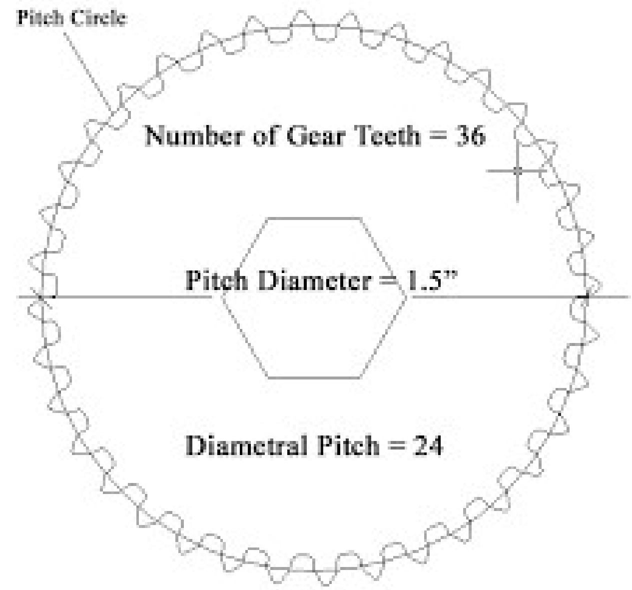


D = Diameter of the pitch circle,

T = Number of teeth on the wheel

Gear terminologies

Diametral pitch (p_d) It is the ratio of number of teeth to the pitch circle diameter in millimetres.

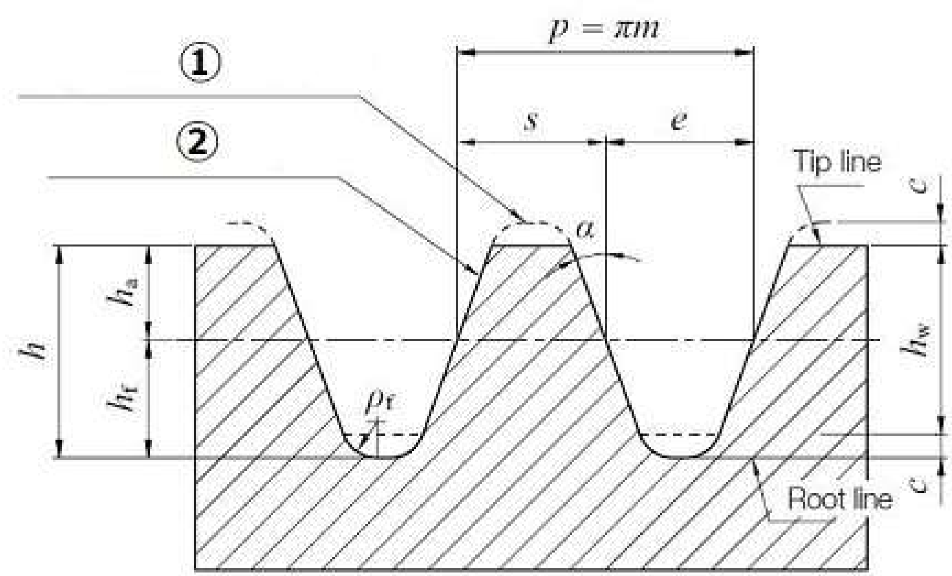


$$p_d = \frac{T}{D} = \frac{\pi}{p_c}$$

T = Number of teeth, and

D = Pitch circle diameter.

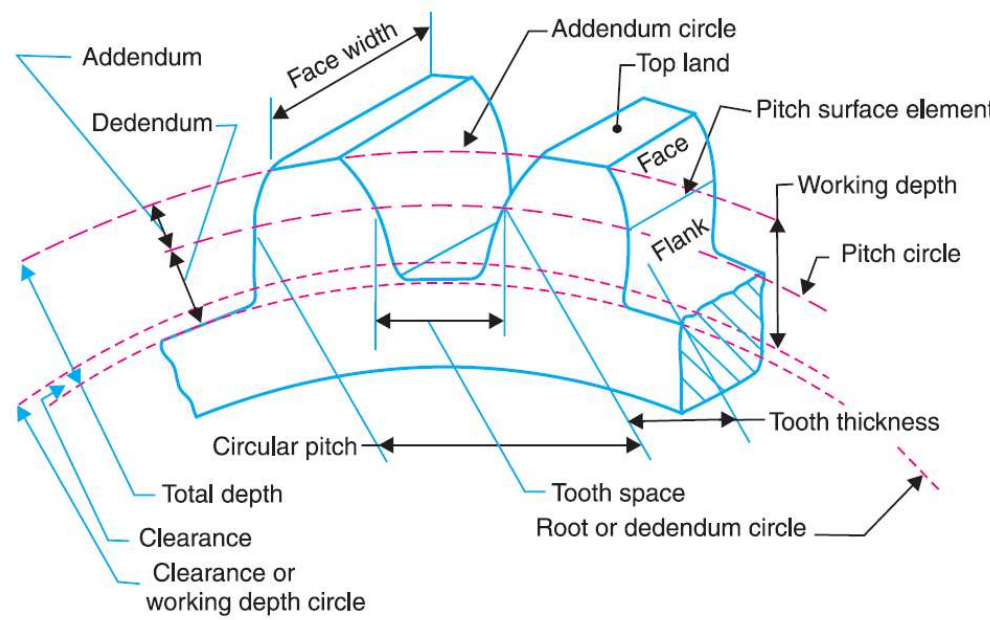
Module **(m)** It is the ratio of the pitch circle diameter to the number of teeth. Inverse of Diametral pitch.



$$m = \frac{D}{T} = \frac{p_c}{\pi}$$

Gear terminologies

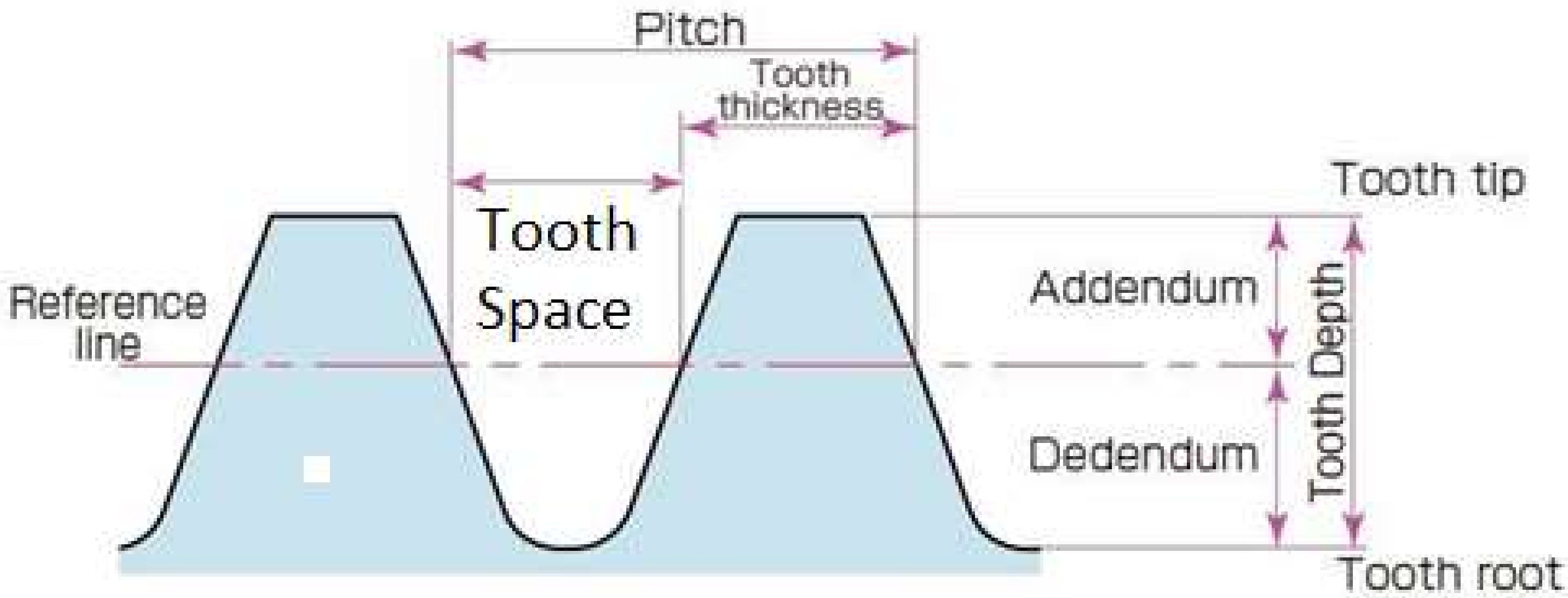
Clearance It is the radial distance from the top of the tooth to the bottom of the tooth, in a meshing gear. A circle passing through the top of the meshing gear is known as **clearance circle**



Total depth. It is the radial distance between the addendum and the dedendum circles of a gear. It is equal to the sum of the addendum and dedendum.

Working depth. It is the radial distance from the addendum circle to the clearance circle. It is equal to the sum of the addendum of the two meshing gears.

Gear terminologies

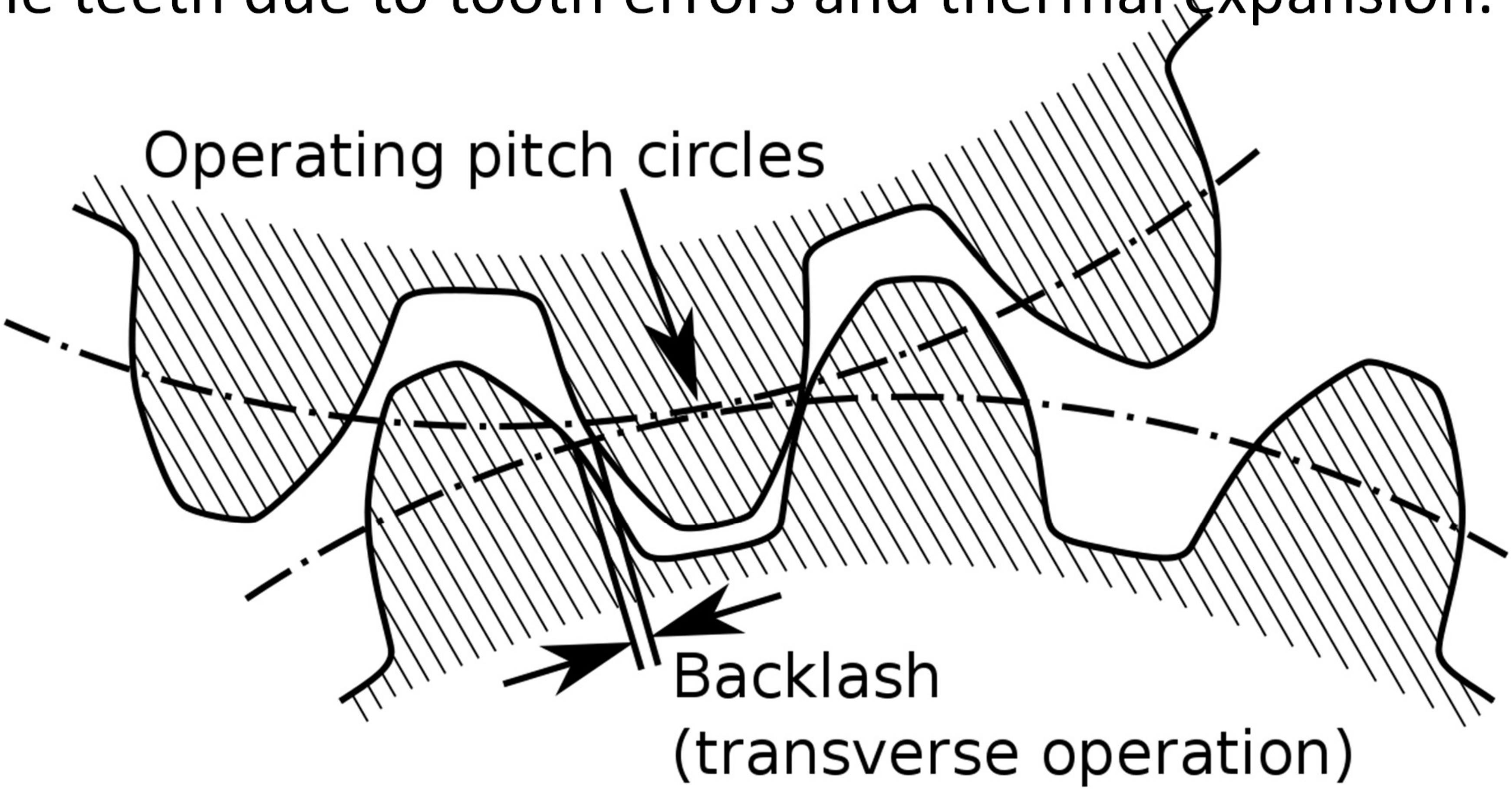


Tooth thickness. It is the width of the tooth measured along the pitch circle.

Tooth space . It is the width of space between the two adjacent teeth measured along the pitch circle.

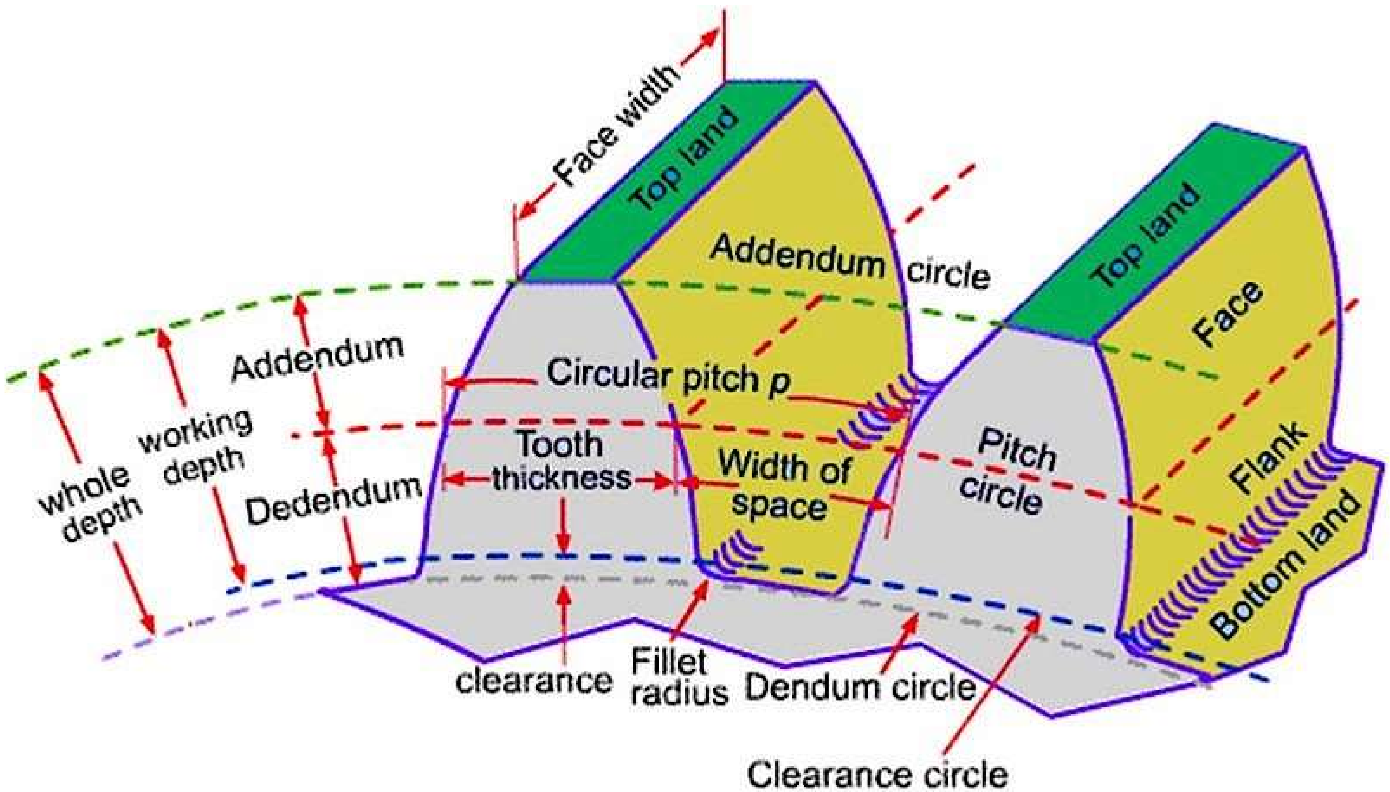
Gear terminologies

Backlash. It is the difference between the tooth space and the tooth thickness, as measured along the pitch circle. Theoretically, the backlash should be zero, but in actual practice some backlash must be allowed to prevent jamming of the teeth due to tooth errors and thermal expansion.



Gear terminologies

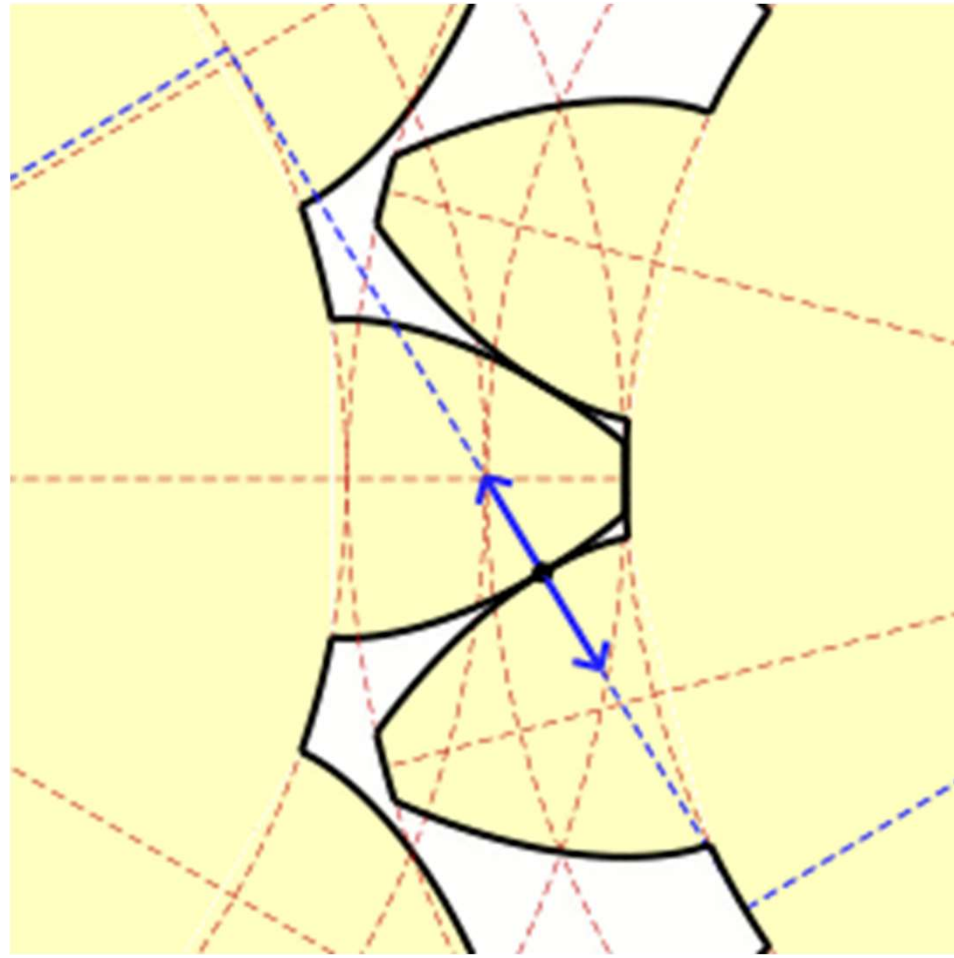
Face of tooth. It is the surface of the gear tooth above the pitch surface.
Flank of tooth. It is the surface of the gear tooth below the pitch surface.
Top land. It is the surface of the top of the tooth.
Face width. It is the width of the gear tooth measured parallel to its axis.
Profile. It is the curve formed by the face and flank of the tooth.
Fillet radius. It is the radius that connects the root circle to the profile of the tooth.



Gear terminologies

Path of contact. It is the path traced by the point of contact of two teeth from the beginning to the end of engagement.

Length of the path of contact. It is the length of the common normal cut-off by the addendum circles of the wheel and pinion.



Gear terminologies

Arc of contact. It is the path traced by a point on the pitch circle from the beginning to the end of engagement of a given pair of teeth. The arc of contact consists of two parts, *i.e*.

(*a*) ***Arc of approach***. It is the portion of the path of contact from the beginning of the engagement to the pitch point.

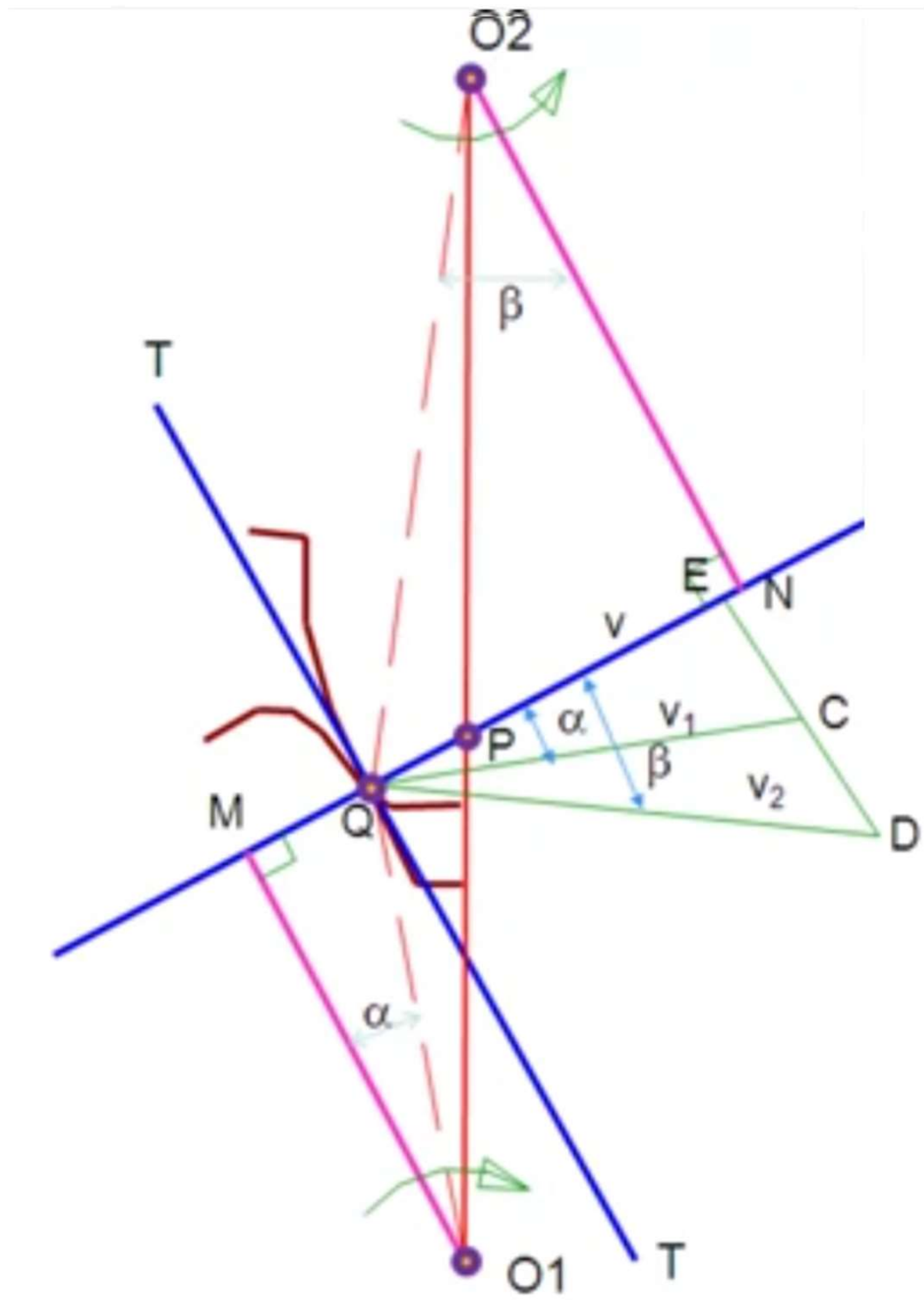
(*b*) ***Arc of recess***. It is the portion of the path of contact from the pitch point to the end of the engagement of a pair of teeth.

Note : The ratio of the length of arc of contact to the circular pitch is known as ***contact ratio*** *i.e*. number of pairs of teeth in contact.

Law of Gearing

The common normal at the point of contact between a pair of teeth must always pass through the fixed point. That fixed point is pitch point.

This is the fundamental condition which must be satisfied while designing the profiles for the teeth of gear wheels. It is also known as law of gearing.



Law of Gearing

$$v = v_1 \cos\alpha = v_2 \cos\beta$$

$$v_1 = O_1Q\omega_1$$

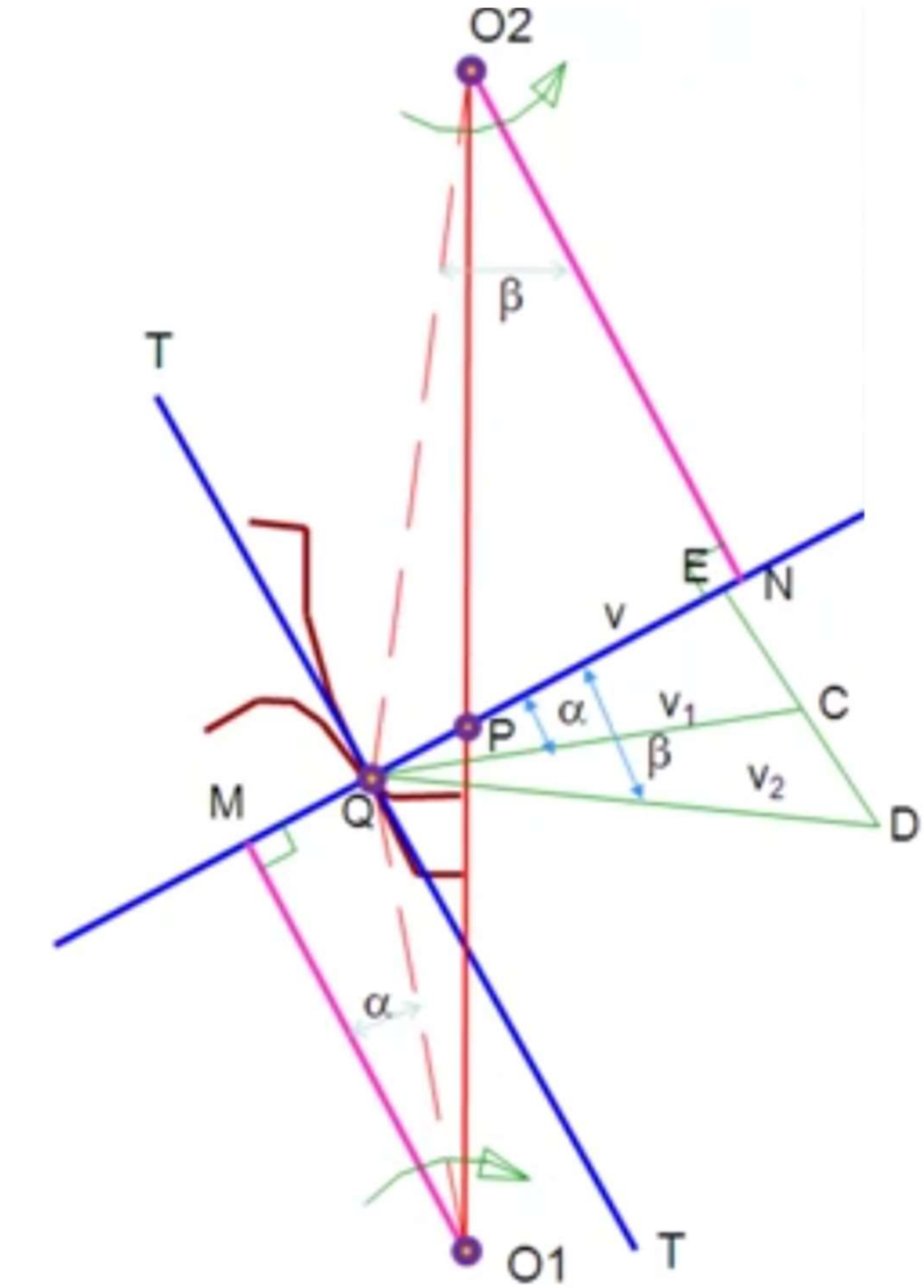
$$v_2 = O_2Q\omega_2$$

$$v = O_1Q\,\omega_1 \cos\alpha = O_2Q\,\omega_2 \cos\beta$$

$$\cos\alpha = \frac{O_1M}{O_1Q}$$

$$\cos\beta = \frac{O_2N}{O_2Q}$$

$$O_1Q\,\omega_1 \frac{O_1M}{O_1Q} = O_2Q\,\omega_2 \frac{O_2N}{O_2Q}$$

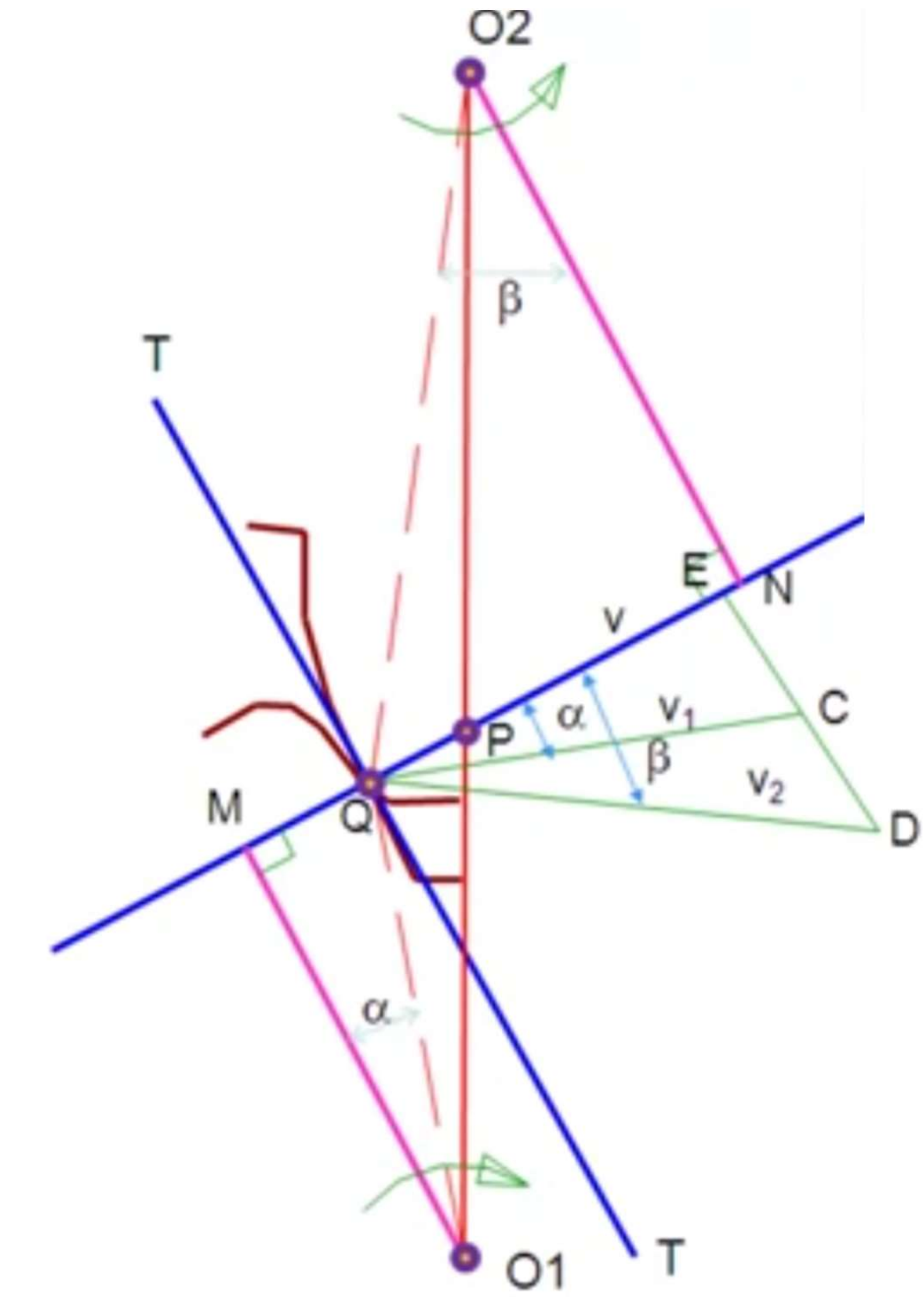


Law of Gearing

$$O_1Q\,\omega_1\,\frac{O_1M}{O_1Q} = O_2Q\,\omega_2\,\frac{O_2N}{O_2Q}$$

$$\cancel{O_1Q}\,\omega_1\,\frac{O_1M}{\cancel{O_1Q}} = \cancel{O_2Q}\,\omega_2\,\frac{O_2N}{\cancel{O_2Q}}$$

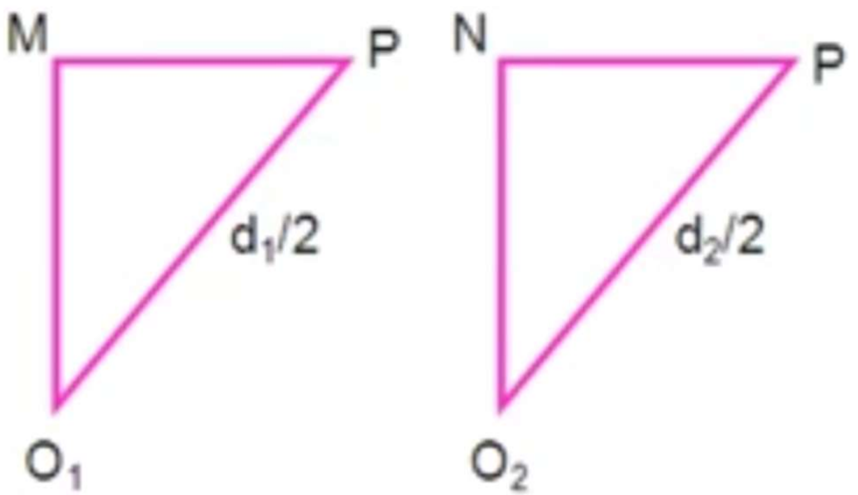
$$\frac{\omega_1}{\omega_2} = \frac{O_2N}{O_1M}$$



Law of Gearing

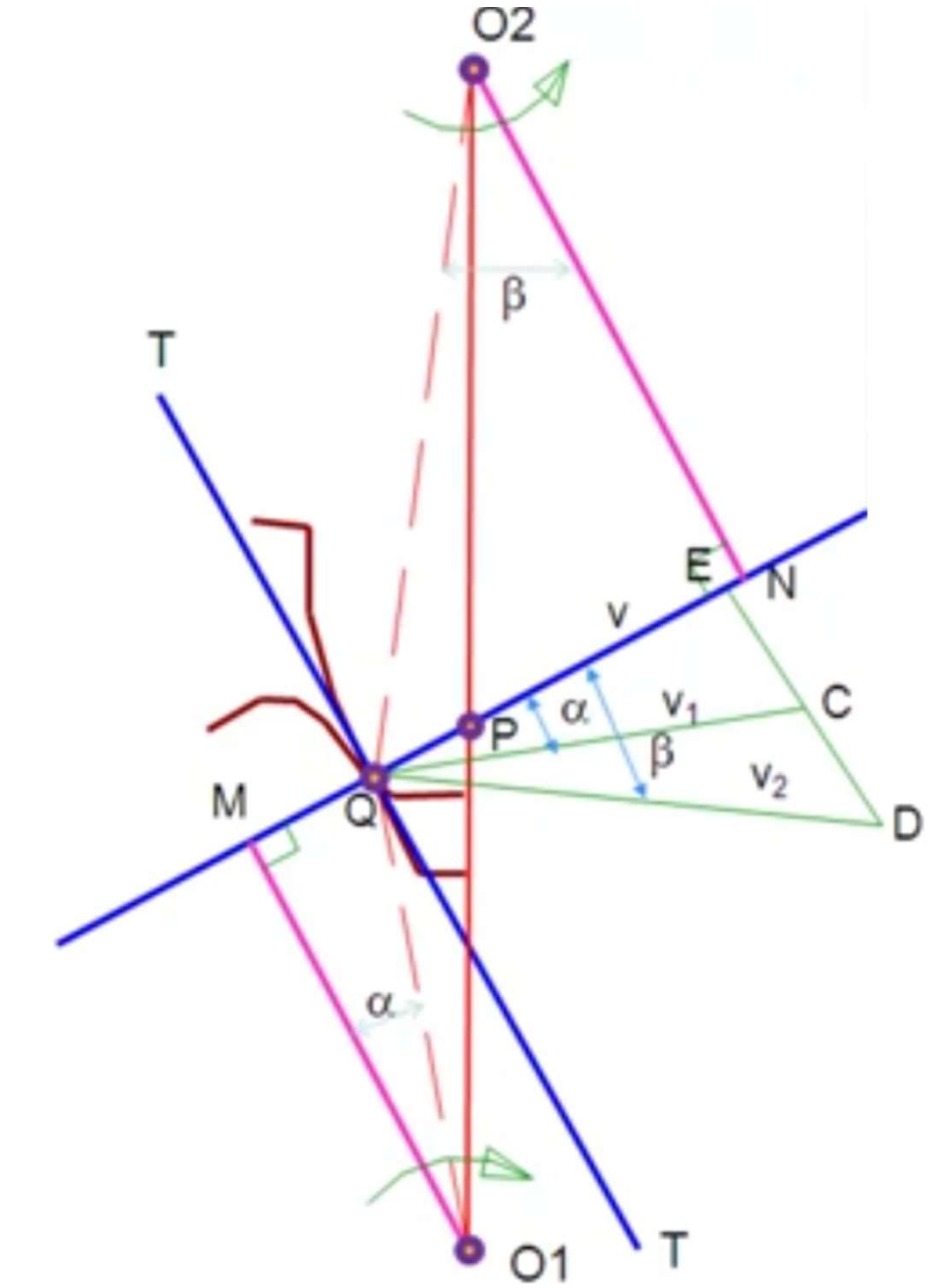
$$\frac{\omega_1}{\omega_2} = \frac{O_2N}{O_1M}$$

Consider similar Triangles O_1MP and O_2NP as shown below



$$\frac{O_2N}{O_1M} = \frac{d_2}{d_1}$$

where, ***d₂*** and ***d₁*** are pitch circle diameters of two gears



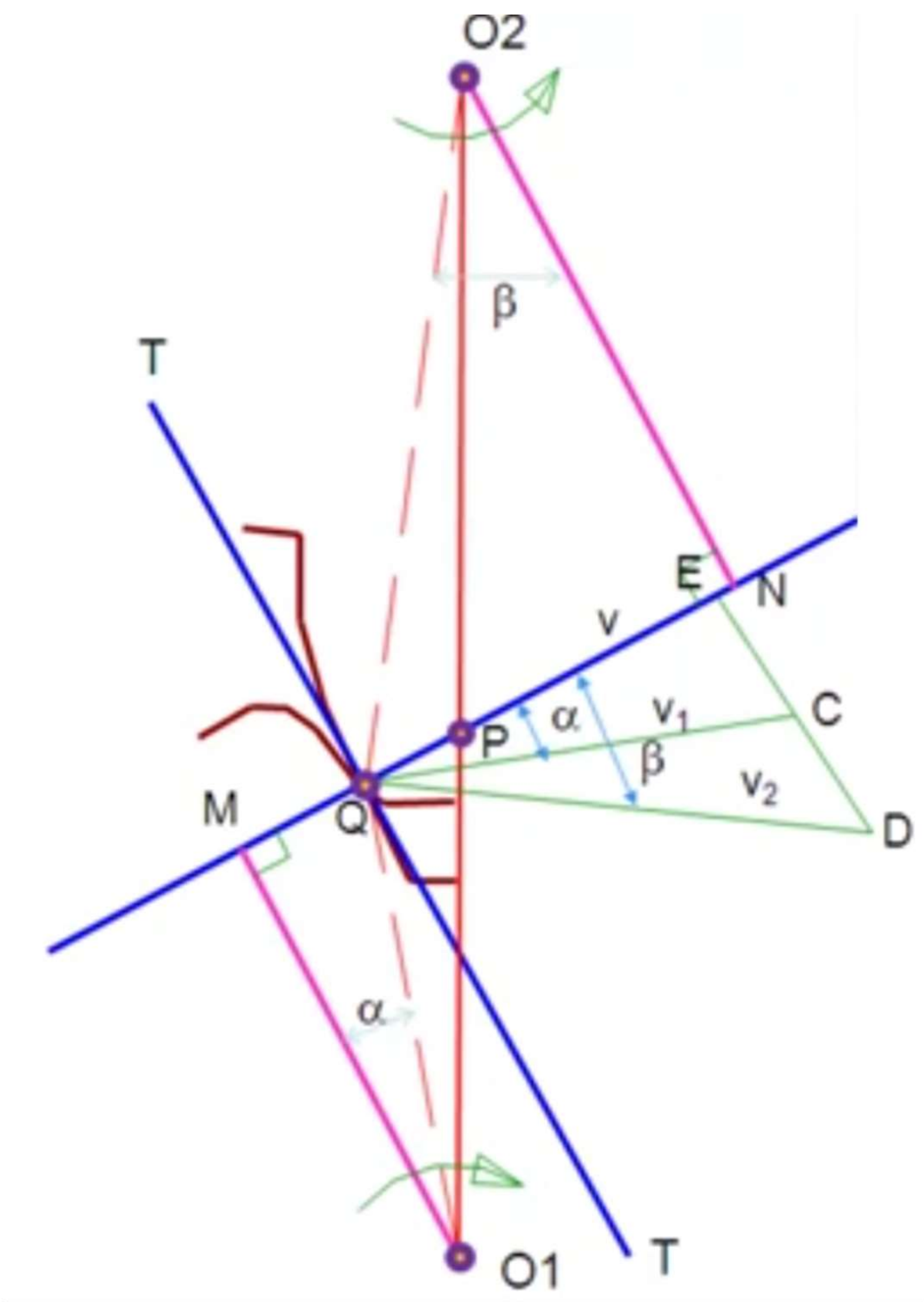
Law of Gearing

$$\frac{O_2N}{O_1M} = \frac{d_2}{d_1}$$

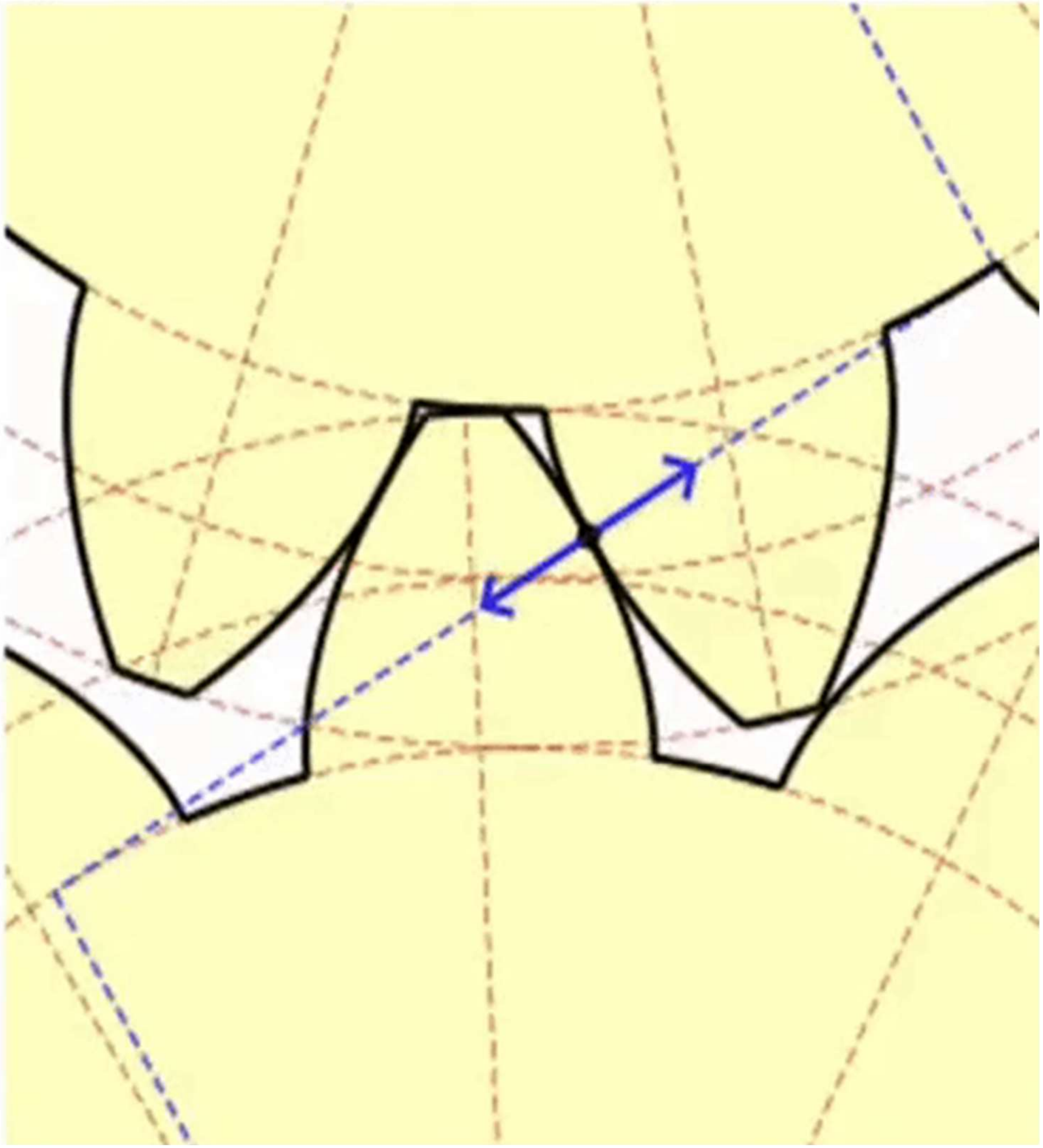
$$d_1 = mT_1$$

$$d_2 = mT_2$$

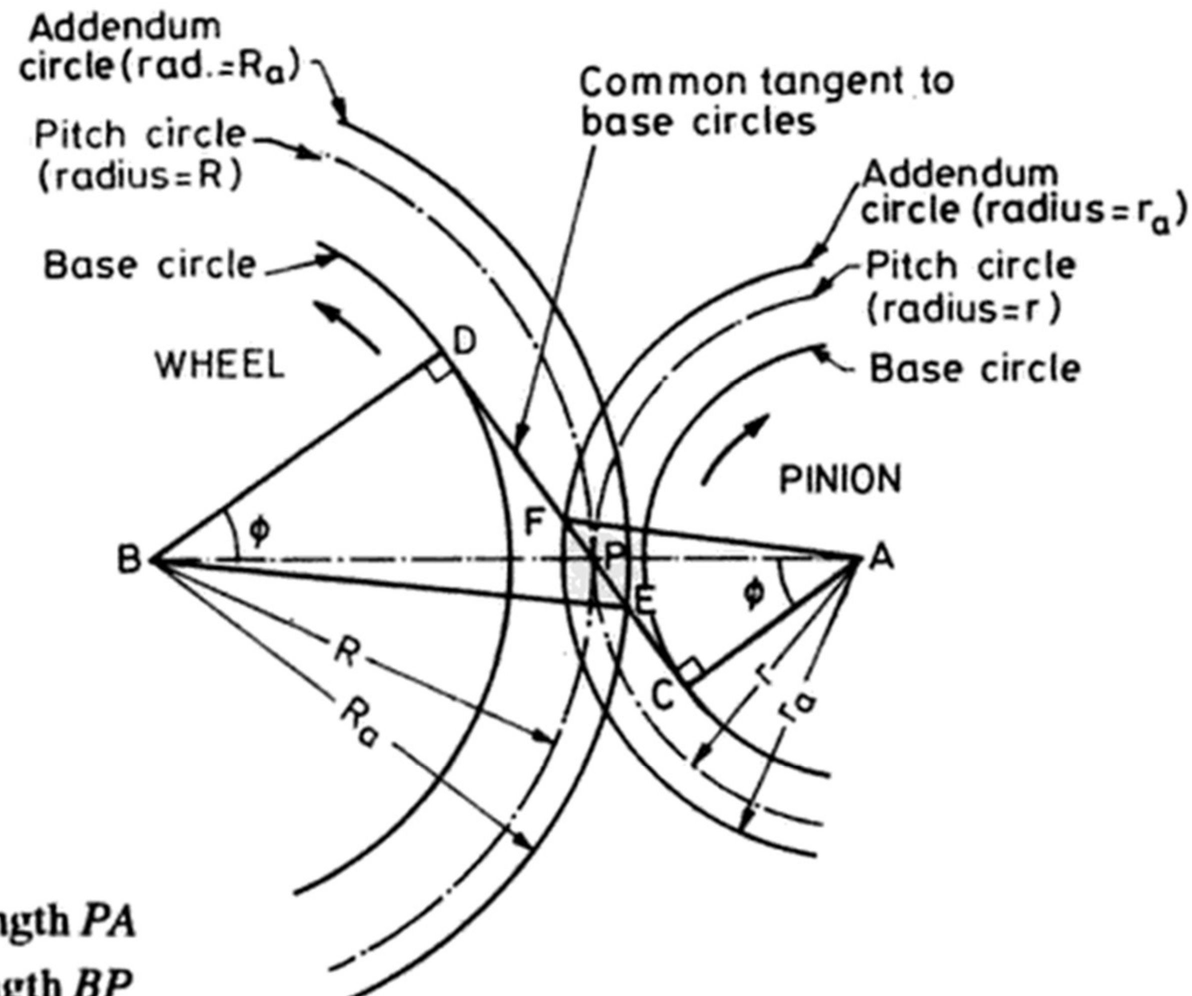
$$\frac{O_2N}{O_1M} = \frac{d_2}{d_1} = \frac{T_2}{T_1}$$



Length of Path of Contact



Length of Path of Contact



r = Radius of pitch circle of pinion *i.e.* length *PA*

R = Radius of pitch circle of wheel *i.e.* length *BP*

r_a = Addendum circle radius of pinion *i.e.* length *AF*

R_a = Addendum circle radius of wheel *i.e.* length *BE*

Length of Path of Contact

Length of path of contact = path of approach + path of recess

$$EF = EP + PF$$

$$= (ED - PD) + (CF - CP)$$

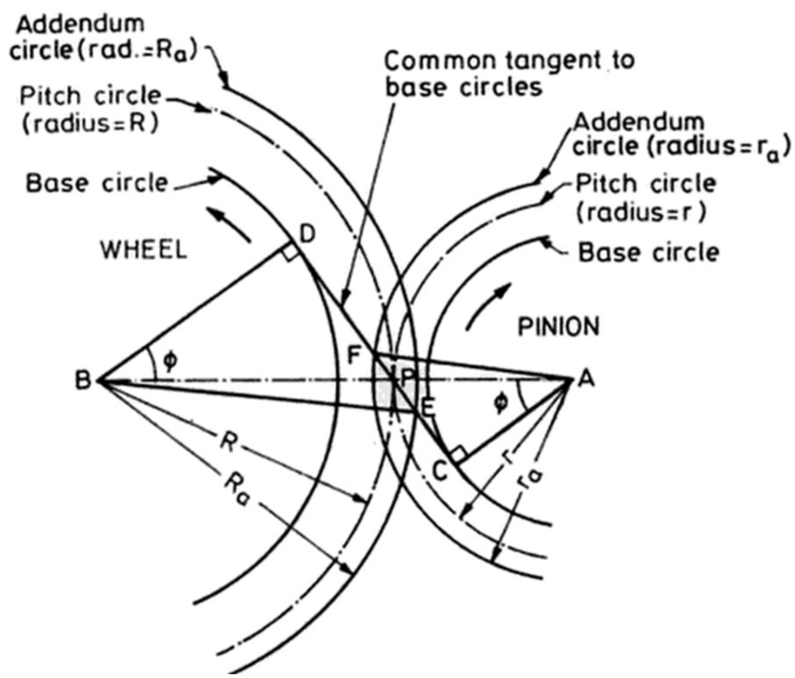
In right angled triangle *BPD*,

$$PD = BP \sin\phi = R \sin\phi$$

$$BD = BP \cos\phi = R \cos\phi$$

In right angled triangle *BED*,

$$ED = \sqrt{(BE)^2 - (BD)^2} = \sqrt{R_a^{\,2} - R^2 \cos^2\phi}$$



Length of Path of Contact

In right angled triangle ACP,

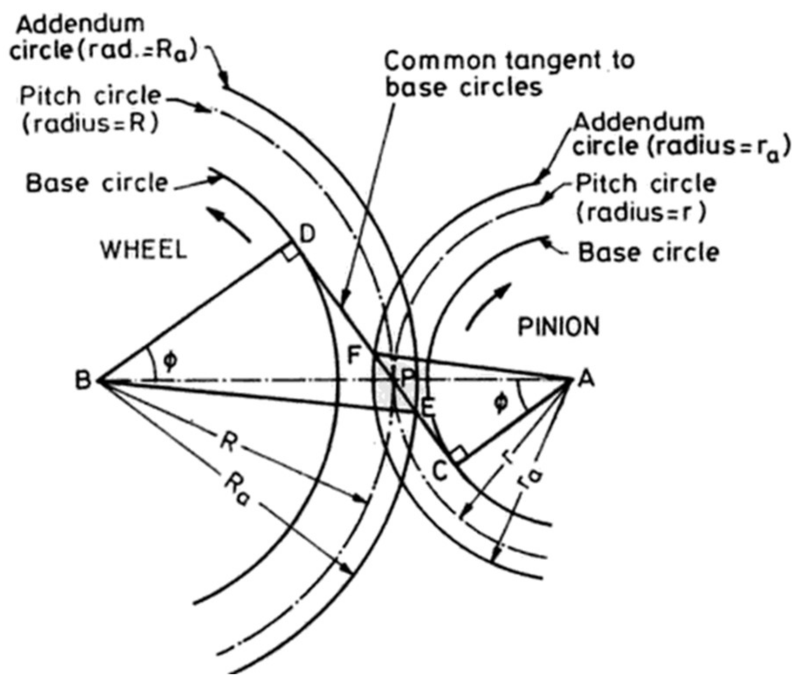
$$CP = PA \sin \phi = r \sin \phi$$

$$CA = PA \cos \phi = r \cos \phi$$

In right angled triangle FCA,

$$CF = \sqrt{(AF)^2 - (CA)^2}$$

$$= \sqrt{r_a{}^2 - r^2 \cos^2 \phi}$$



Length of Path of Contact

Path of approach $= EP = ED - PD$

$$= \sqrt{R_a^2 - R^2 \cos^2 \phi} - R \sin \phi$$

Path of recess $= PF = CF - CP$

$$= \sqrt{r_a^2 - r^2 \cos^2 \phi} - r \sin \phi$$

Length of path of contacts,

$$EF = \left(\sqrt{R_a^2 - R^2 \cos^2 \phi} - R \sin \phi\right) + \sqrt{r_a^2 - r^2 \cos^2 \phi} - r \sin \phi$$

$$= \sqrt{R_a^2 - R^2 \cos^2 \phi} + \sqrt{r_a^2 - r^2 \cos^2 \phi} - (R + r) \sin \phi$$

Length of path of contacts, $\boxed{= \sqrt{R_a^2 - R^2 \cos^2 \phi} + \sqrt{r_a^2 - r^2 \cos^2 \phi} - (R + r) \sin \phi}$

Length of Arc of Contact

The length of the arc of approach (**p’pp’’**)

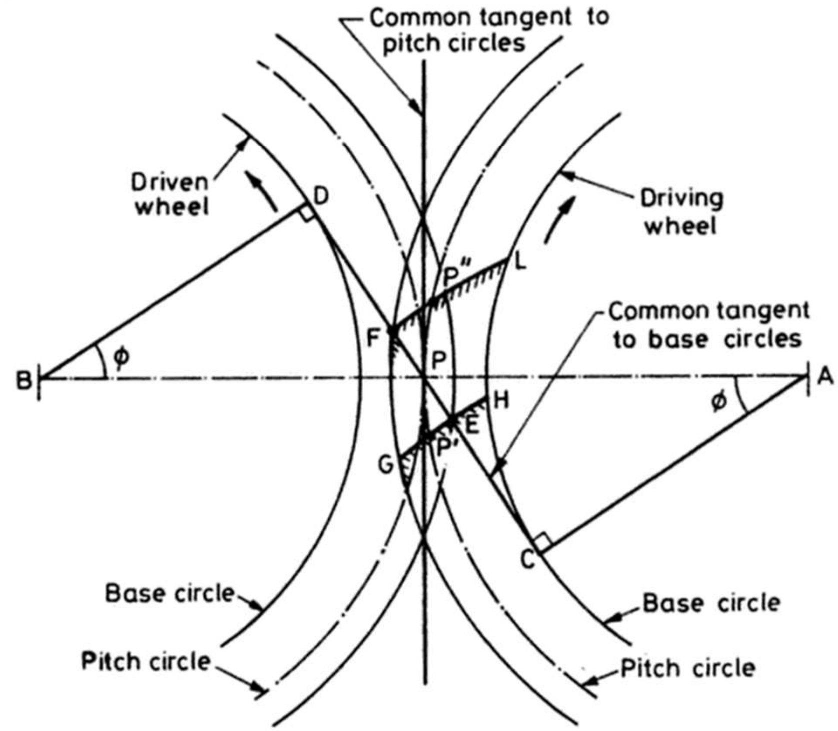
Arc of approach $= \text{Arc } P'P = \dfrac{EP}{\cos\phi}$

Arc of recess $= \text{Arc } PP'' = \dfrac{FP}{\cos\phi}$

Now length of arc of contact $= \text{Arc } P'P + \text{Arc } PP''$

$$= \frac{EP}{\cos\phi} + \frac{FP}{\cos\phi} = \frac{EP + FP}{\cos\phi}$$

$$= \frac{EF}{\cos\phi}$$



Length of the arc of contact

$$\boxed{= \frac{\text{Length of path of contact}}{\cos\phi}}$$

Number of pairs of teeth in Contact or Contact Ratio:

Contact Ratio (or Number of Pairs of Teeth in Contact)

The **ratio of the length of the arc of contact to the circular pitch.**

$$\text{Contact ratio} = \frac{\text{Length of the arc of contact}}{p_c}$$

$$p_c = \text{Circular pitch} = \pi m$$

$$m = \text{Module.}$$

Number of pairs of teeth in contact

$$= \frac{EF}{\cos\phi} \times \frac{1}{\pi m}$$

Problem 1:

A pinion having 23 teeth drives a gear having 57 teeth. The profile of the gears is involute with 20° pressure angle, 8 mm module and addendum equal to module. Find the length of path of contact, arc of contact and the contact ratio.

Problem 2:

The number of teeth on each of the two equal spur gears in mesh is 40. The teeth have 20^0 involute profile and module 6 mm. If the arc of contact is 1.75 times the circular pitch, find the addendum

Problem 3:

Two mating spur gear with module pitch of 6.5mm have 19 and 47 teeth of 20^0 pressure angle, and 6.5 mm addendum. Determine the number of pairs of teeth in contact and the angle turned through by the large wheel for one pair of teeth in contact. Determine sliding velocity at instant, engagement commences, engagement terminates at the pitch point, when pitch line velocity is 1.2 m/s

Numerical

The number of teeth on each of the two equal spur gears in mesh are 40. The teeth have 20° involute profile and the module is 6 mm. If the arc of contact is 1.75 times the circular pitch, find the addendum.

Given : $T = t = 40$; $\phi = 20°$; $m = 6$ mm

circular pitch,

$$p_c = \pi\, m = \pi \times 6 = 18.85 \text{ mm}$$

Length of arc of contact

$$= 1.75\, p_c = 1.75 \times 18.85 = 33 \text{ mm}$$

length of path of contact

$$= \text{Length of arc of contact} \times \cos\phi$$

$$= 33 \cos 20° = 31 \text{ mm}$$

$R_A = r_A$ = Radius of the addendum circle of each wheel

pitch circle radii of each wheel,

$$R = r = m.T / 2 = 6 \times 40/2 = 120 \text{ mm}$$

length of path of contact

$$31 = \sqrt{(R_A)^2 - R^2 \cos^2\phi} + \sqrt{(r_A)^2 - r^2\cos^2\phi} - (R + r)\sin\phi$$

$$= 2\left[\sqrt{(R_A)^2 - R^2 \cos^2\phi} - R\sin\phi\right] \quad ...(\because R = r, \text{ and } R_A = r_A)$$

$$\frac{31}{2} = \sqrt{(R_A)^2 - (120)^2\cos^2 20°} - 120 \sin 20°$$

$$15.5 = \sqrt{(R_A)^2 - 12\,715} - 41$$

$$(15.5 + 41)^2 = (R_A)^2 - 12\,715$$

$$3192 + 12\,715 = (R_A)^2 \qquad \text{or} \qquad R_A = 126.12 \text{ mm}$$

addendum of the wheel,

$$= R_A - R = 126.12 - 120 = 6.12 \text{ mm}$$

Numerical

A pinion having 30 teeth drives a gear having 80 teeth. The profile of the gears is involute with 20° pressure angle, 12 mm module and 10 mm addendum. Find the length of path of contact, arc of contact and the contact ratio.

$$KL = \sqrt{(R_A)^2 - R^2 \cos^2\phi} + \sqrt{(r_A)^2 - r^2 \cos^2\phi} - (R + r)\sin\phi$$

Given : $t = 30$; $T = 80$; $\phi = 20°$;
$m = 12$ mm ; Addendum = 10 mm

Length of path of contact

pitch circle radius of pinion,

$$r = m.t / 2 = 12 \times 30 / 2 = 180 \text{ mm}$$

pitch circle radius of gear,

$$R = m.T / 2 = 12 \times 80 / 2 = 480 \text{ mm}$$

Radius of addendum circle of pinion,

$$r_A = r + \text{ Addendum} = 180 + 10 = 190 \text{ mm}$$

radius of addendum circle of gear,

$$R_A = R + \text{Addendum} = 480 + 10 = 490 \text{ mm}$$

length of the path of approach,

$$KP = \sqrt{(R_A)^2 - R^2\cos^2\phi} - R\sin\phi$$

$$= \sqrt{(490)^2 - (480)^2\cos^2 20°} - 480\sin 20°$$

$$= 191.5 - 164.2 = 27.3 \text{ mm}$$

length of the path of recess,

$$PL = \sqrt{(r_A)^2 - r^2\cos^2\phi} - r\sin\phi$$

$$= \sqrt{(190)^2 - (180)^2\cos^2 20°} - 180\sin 20°$$

$$= 86.6 - 61.6 = 25 \text{ mm}$$

length of path of contact,

$$KL = KP + PL = 27.3 + 25 = 52.3 \text{ mm}$$

length of arc of contact

$$= \frac{\text{Length of path of contact}}{\cos\phi}$$

$$= \frac{52.3}{\cos 20°} = 55.66 \text{ mm}$$

circular pitch,

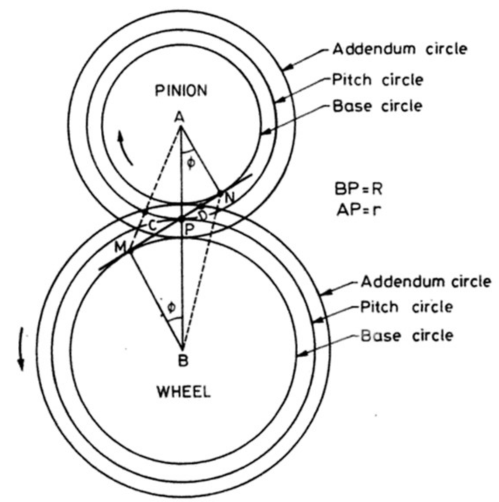
$$p_c = \pi.m = \pi \times 12 = 37.7 \text{ mm}$$

$$\text{Contact ratio} = \frac{\text{Length of arc of contact}}{p_c}$$

$$= \frac{55.66}{37.7} = 1.5 \text{ say } 2$$

Interference and Undercutting

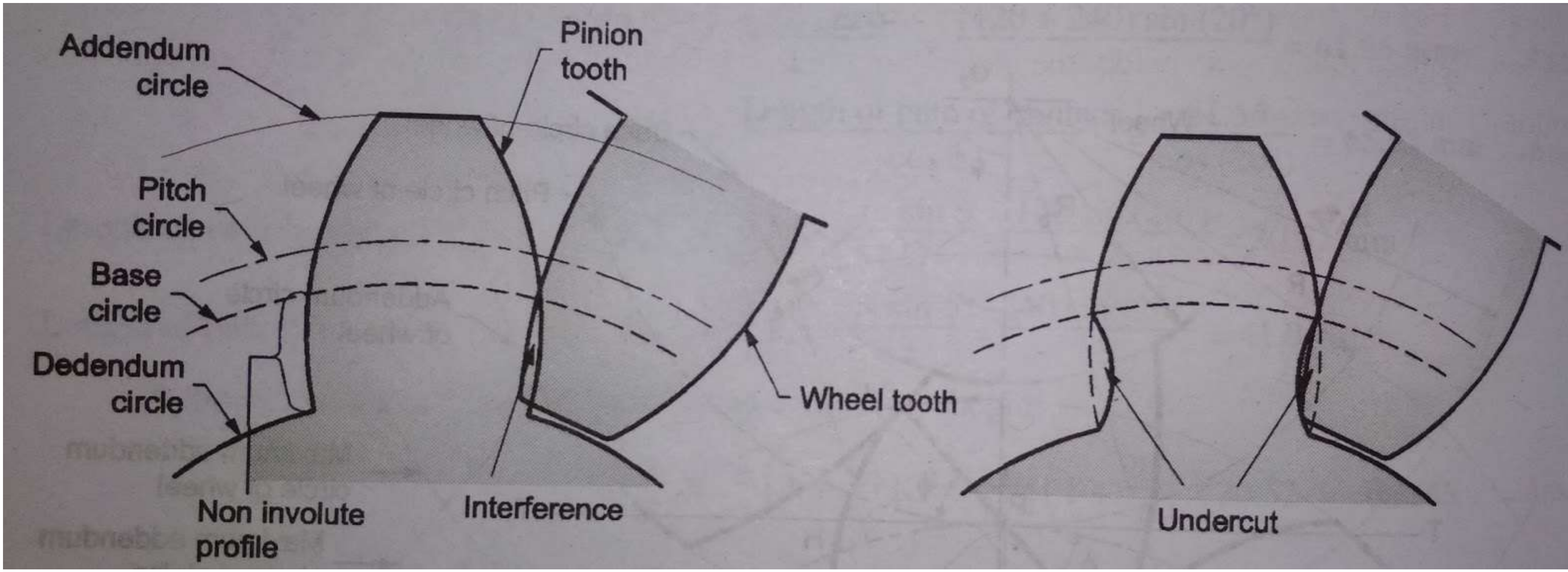
- When tip of the tooth undercuts the roots on its mating gear is known as interference.
- The line of action MN will be along the common tangent to the base circle of two gears.

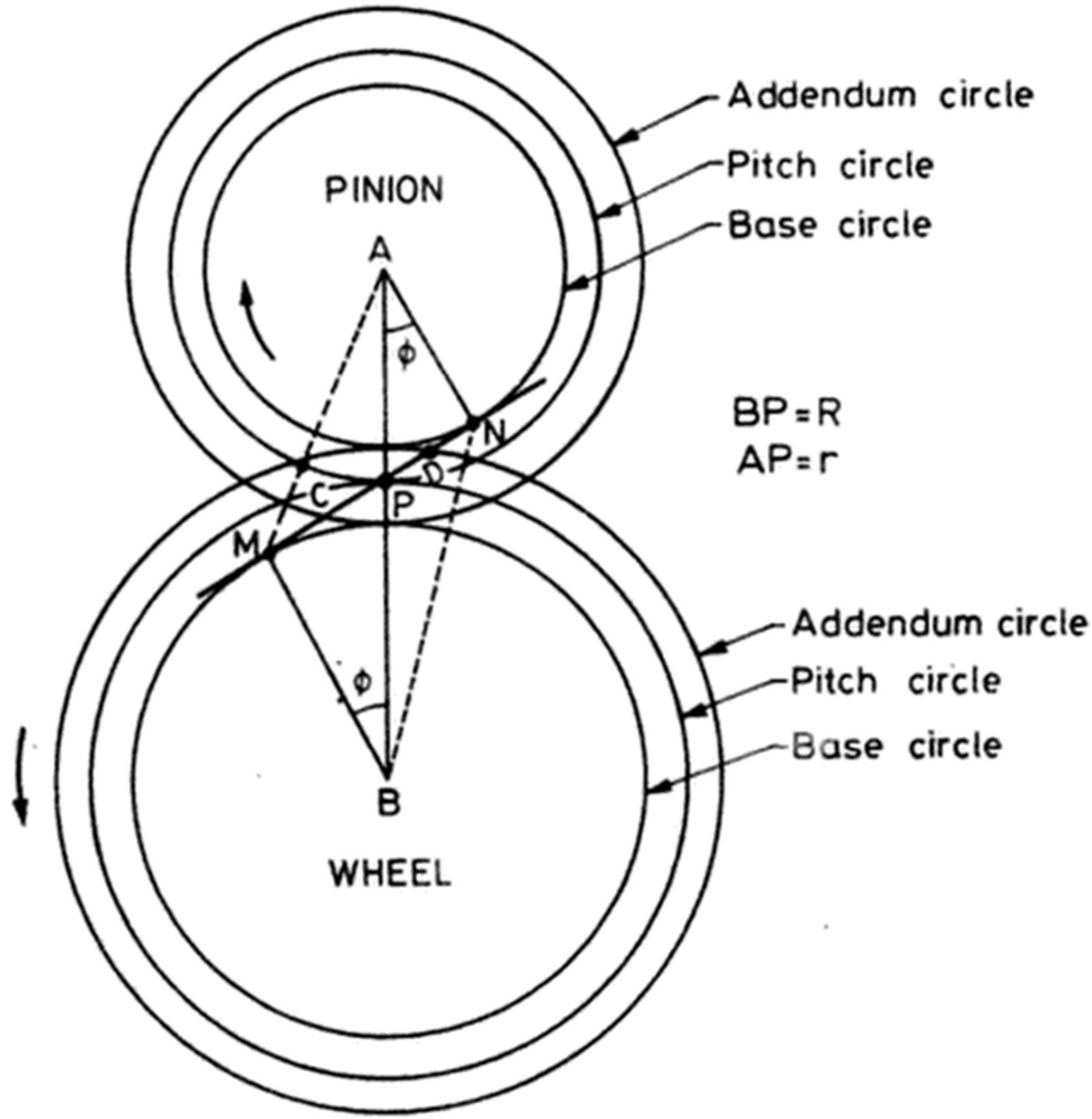


  - CD is the path of contact.
  - AC addendum radius of pinion.
  - BD addendum radius of wheel.
  - Engagement & disengagement happened at D & C respectively.

- Now radius of addendum circle of pinion increased, the point C shifts to M. Radius of addendum=AM.
- The AM is further increased, the point of contact will be on the inside of the base circle of the wheel.
- Then tooth on the pinion will under cut the tooth on the wheel at root and removes material on the wheel.

Interference and Undercutting





Addendum circle
Pitch circle
Base circle
PINION
A
ϕ
N
D
C
P
M
BP=R
AP=r
Addendum circle
Pitch circle
Base circle
ϕ
B
WHEEL

Interference of Gear

From right angled triangle APN, we have

$$PN = AP \sin \phi$$

$$= r \sin \phi$$

Max. length of path of approach

$$= r \sin \phi$$

from right angled triangle BMP, we have

$$PM = BP \sin \phi$$

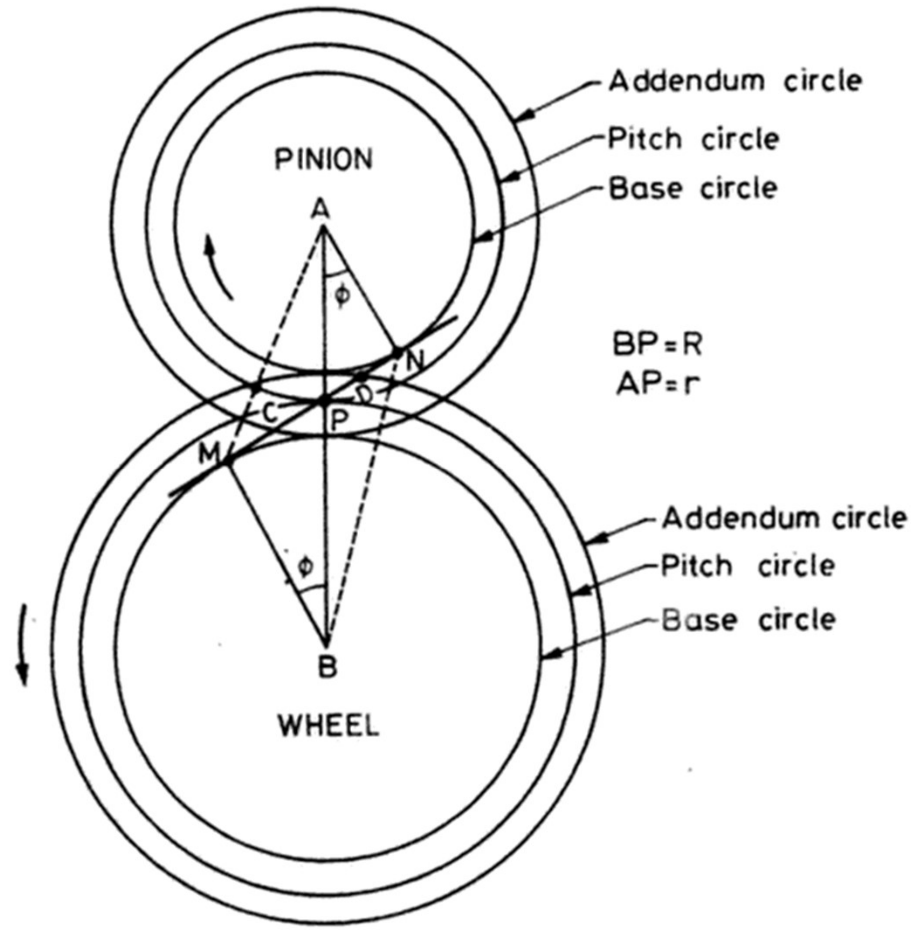
$$= R \sin \phi$$

Max. length of path of recess $= R \sin \phi$

Maximum length of path of contact,

$$MN = PN + PM = r \sin \phi + R \sin \phi$$

$$= (r + R) \sin \phi$$



Interference of Gear

Maximum length of path of contact,

$$MN = PN + PM = r \sin \phi + R \sin \phi$$
$$= (r + R) \sin \phi$$

Maximum length of arc of contact

$$= \frac{\text{Max length of path of contact}}{\cos \phi} = \frac{(r + R) \sin \phi}{\cos \phi}$$
$$= (r + R) \tan \phi$$

Problem 4:

Two mating gears have 50 & 13 involute teeth of module 10mm and 20^0 pressure angle. The addendum is one module. Does the interference occur? If occurs, to what value should the pressure angle should be changed to eliminate interference.

Minimum Number of Teeth on the Pinion (small gear) in Order to Avoid Interference

T = Number of teeth on the wheel (or on larger gear)

t = Number of teeth on the pinion (or on smaller gear)

m = Module of teeth

d = Pitch circle diameter of pinion = $m \times t$

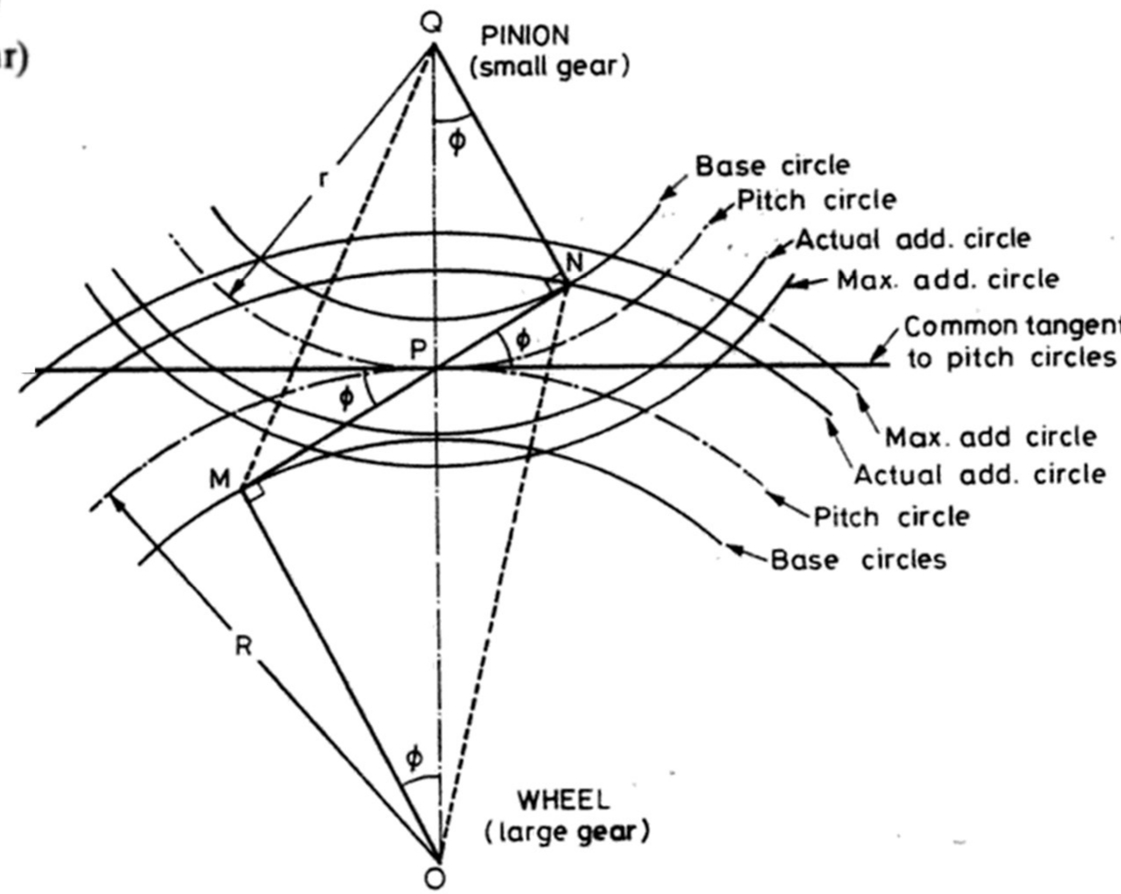
r = Pitch circle radius of pinion = $\dfrac{d}{2} = \dfrac{m \times t}{2}$

D = Pitch circle diameter of the wheel = $m \times T$

R = Pitch circle radius of the wheel = $\dfrac{D}{2} = \dfrac{m \times T}{2}$

G = Gear ratio = $\dfrac{T}{t}$ also = $\dfrac{R}{r}$

ϕ = Pressure angle or angle of obliquity.



Continued...

triangle MPQ,

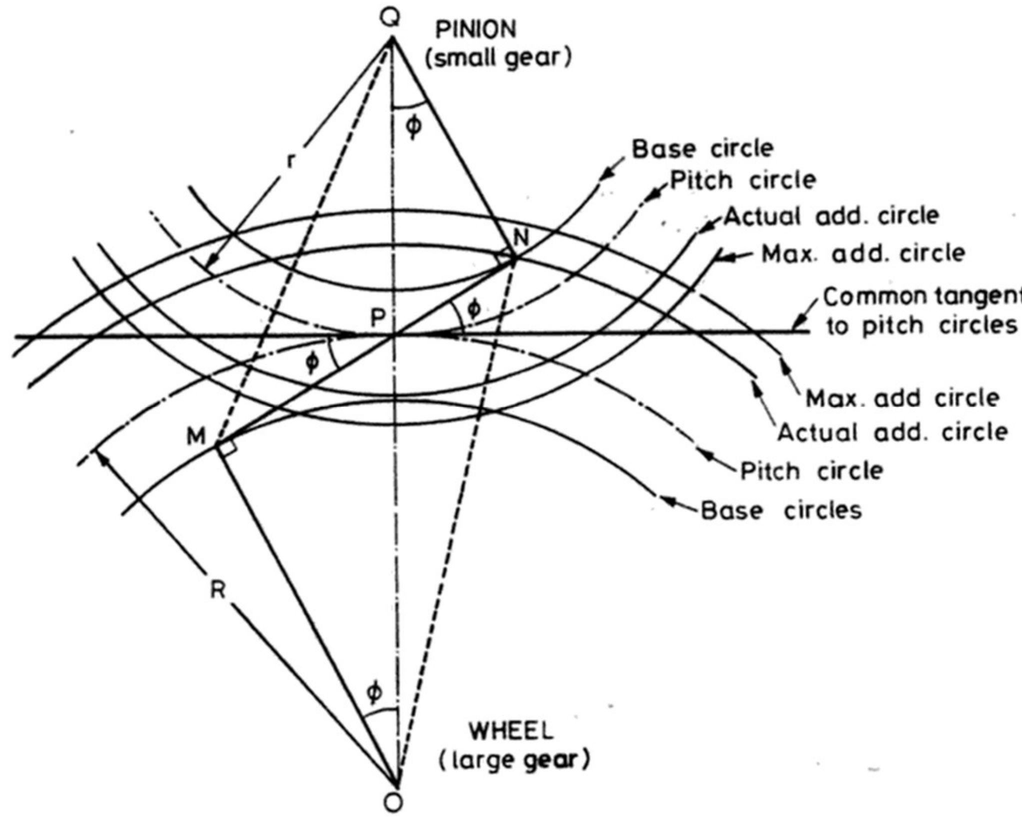
$$QM^2 = PM^2 + QP^2 + 2 \times PM \times PQ \times Cos(90 - \emptyset)$$

$$= r^2 + R^2 \sin^2 \phi + 2rR \sin^2 \phi$$

$$= r^2 \left[1 + \frac{R^2 \sin^2 \phi}{r^2} + \frac{2rR \sin^2 \phi}{r^2} \right]$$

$$= r^2 \left[1 + \frac{R^2 \sin^2 \phi}{r^2} + \frac{2R \sin^2 \phi}{r} \right]$$

$$= r^2 \left[1 + \frac{R}{r} \left(\frac{R}{r} + 2 \right) \sin^2 \phi \right]$$



$QP = r, PM = R \sin \phi$

Continued...

$$QM = r\sqrt{1+\frac{R}{r}\left(\frac{R}{r}+2\right)\sin^2\phi}$$

$$= \frac{m\times t}{2}\sqrt{1+\frac{R}{r}\left(\frac{R}{r}+2\right)\sin^2\phi}$$

$$= \frac{m\times t}{2}\sqrt{1+\frac{T}{t}\left(\frac{T}{t}+2\right)\sin^2\phi} \qquad \left(\because \frac{R}{r}=\frac{T}{t}=G\right)$$

Now we know that the addendum of the pinion

$$= QM - QP$$

$$= QM - r$$

$$= QM - \frac{m\times t}{2}$$

$$= \frac{m\times t}{2}\sqrt{1+\frac{T}{t}\left(\frac{T}{t}+2\right)\sin^2\phi} - \frac{m\times t}{2}$$

Continued...

addendum of the pinion $= \frac{m \times t}{2}\left[\sqrt{1 + \frac{T}{t}\left(\frac{T}{t} + 2\right)\sin^2\phi} - 1\right]$

$$\frac{mt}{2}\left[\sqrt{1 + G(G+2)sin^2\emptyset} - 1\right] \geq a_p m$$

$$\left(\because \frac{R}{r} = \frac{T}{t} = G\right)$$

$$t \geq \frac{2a_p}{\sqrt{1 + G(G+2)sin^2\emptyset} - 1}$$

$$\boxed{t = \frac{2a_p}{\sqrt{1 + G(G+2)sin^2\emptyset} - 1}}$$

Minimum Number of Teeth on the Wheel (big gear) in Order to Avoid Interference:

triangle OPN,

$$ON^2 = NP^2 + OP^2 + 2 \times NP \times OP \times Cos(90 - \emptyset)$$

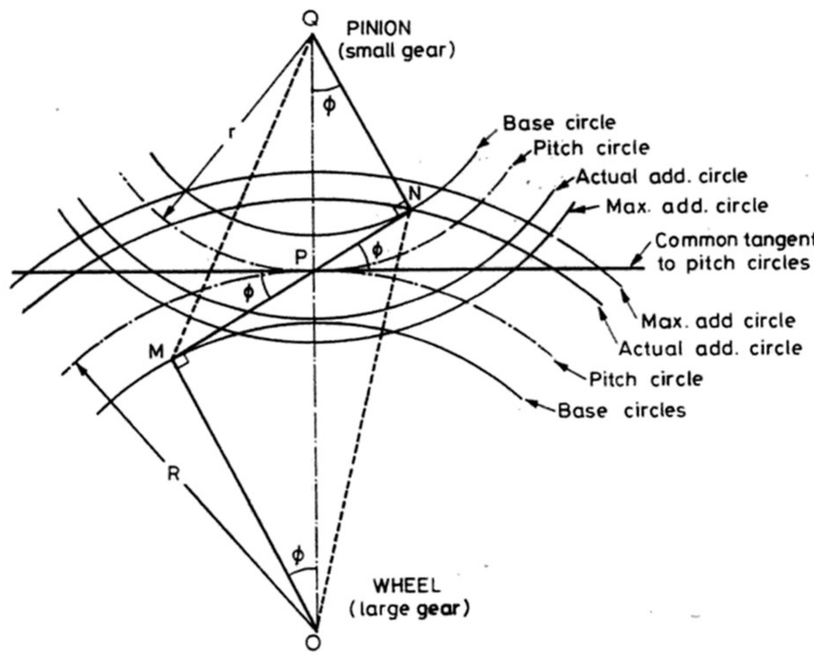
$$= R^2 + r^2 \sin^2\phi + 2R \times r \sin^2\phi$$

$$= R^2\left[1 + \frac{r^2 \sin^2\phi}{R^2} + \frac{2R \times r \times \sin^2\phi}{R^2}\right]$$

$$= R^2\left[1 + \frac{r^2 \sin^2\phi}{R^2} + \frac{2r \sin^2\phi}{R}\right]$$

$$= R^2\left[1 + \frac{r}{R}\left(\frac{r}{R} + 2\right)\sin^2\phi\right]$$

$$ON = R\sqrt{\left[1 + \frac{r}{R}\left(\frac{r}{R} + 2\right)\sin^2\phi\right]}$$



$$OP = R,\ PN = QP \sin\phi = r \sin\phi$$

Continued...

We know that the addendum of the wheel

$$= ON - OP$$

$$= ON - R$$

$$= ON - \frac{m \times T}{2}$$

$$= R\sqrt{1 + \frac{r}{R}\left(\frac{r}{R} + 2\right)\sin^2 \phi} - \frac{m \times T}{2}$$

$$= \frac{m \times T}{2}\sqrt{1 + \frac{r}{R}\left(\frac{r}{R} + 2\right)\sin^2 \phi} - \frac{m \times T}{2}$$

$$a_{w\max} = \frac{mT}{2}\left[\sqrt{1 + \frac{t}{T}\left(\frac{t}{T} + 2\right)\sin^2 \varphi} - 1\right]$$

Continued...

$$a_{w\max} = \frac{mT}{2}\left[\sqrt{1+\frac{t}{T}\left(\frac{t}{T}+2\right)\sin^2\varphi} - 1\right] \geq a_w m$$

$$T \geq \frac{2a_w}{\sqrt{1+\frac{1}{G}\left(\frac{1}{G}+2\right)\sin^2\varphi} - 1}$$

$$\boxed{T = \frac{2a_w}{\sqrt{1+\frac{1}{G}\left(\frac{1}{G}+2\right)\sin^2\varphi} - 1}}$$

Pinion minimum teeth

$$a_p = \frac{t}{2}\left[\sqrt{1 + \frac{T}{t}\left(\frac{T}{t} + 2\right)\sin^2\emptyset} - 1\right]$$

$$t = \frac{2a_p}{\sqrt{1 + \frac{T}{t}\left(\frac{T}{t} + 2\right)\sin^2\emptyset} - 1} =$$

$$\boxed{t = \frac{2a_p}{\sqrt{1 + G(G+2)\sin^2\emptyset} - 1}}$$

Gear minimum teeth

$$a_w = \frac{T}{2}\left[\sqrt{1 + \frac{t}{T}\left(\frac{t}{T} + 2\right)\sin^2\varphi} - 1\right]$$

$$T = \frac{2a_w}{\sqrt{1 + \frac{t}{T}\left(\frac{t}{T} + 2\right)\sin^2\phi} - 1}$$

$$\boxed{T \quad \frac{2a_w}{\sqrt{1 + \frac{1}{G}\left(\frac{1}{G} + 2\right)\sin^2\varphi} - 1}}$$

Numerical

Determine the minimum number of teeth required on a pinion, in order to avoid interference which is to gear with, a wheel to give a gear ratio of 3 to 1 . The pressure angle is 20° and a standard addendum of 1 module for the wheel may be assumed.

$$\text{Given} : G = T / t = 3 \; ; \phi = 20°$$

Minimum number of teeth required on a Wheel

$$T = \frac{2A_W}{\sqrt{1 + \frac{t}{T}\left(\frac{t}{T} + 2\right)\sin^2\phi} - 1} = \frac{2A_W}{\sqrt{1 + \frac{1}{G}\left(\frac{1}{G} + 2\right)\sin^2\phi} - 1}$$

$$T \times \frac{t}{T} = \frac{2A_W \times \frac{t}{T}}{\sqrt{1 + \frac{1}{G}\left(\frac{1}{G} + 2\right)\sin^2\phi} - 1}$$

Minimum number of teeth required on a pinion

$$t = \frac{2A_W}{G\left[\sqrt{1 + \frac{1}{G}\left(\frac{1}{G} + 2\right)\sin^2\phi} - 1\right]} = \frac{2 \times 1}{3\left[\sqrt{1 + \frac{1}{3}\left(\frac{1}{3} + 2\right)\sin^2 20°} - 1\right]}$$

$$= \frac{2}{0.133} = 15.04 \text{ or } 16$$

Measures to reduce gear interference

- **Use of a larger pressure angle**
- Interference can be eliminated by **under-cutting of tooth**.
- Elimination of interference is possible by **tooth stubbing**.
- **Increasing the number of teeth** on the gear can also eliminate the chances of interference.
- **Increasing slightly the center distance** between the meshing gears would also eliminate interference.
- Cutting the gears with long and short addendum gear teeth.