MACHINE TOOL DRIVES

Learning Objectives:

- Broadly Classification of transmission of rotary motion
- Stepped Speed Drives in Machine Tools
  - Belt
  - Pick-Off Gears
  - Gear boxes
    - AP &GP for steeping speeds of gears
    - Structural formula & structural diagrams
- Feed gear boxes
- Steeples Speed Drives in Machine Tools.

MACHINE TOOL DRIVES

To obtain a machined part by a machine tool, coordinated motions must be imparted to its working members. These motions are either primary (cutting and feed) movements, which removes the chips from the WP or auxiliary motions that are required to prepare for machining and ensure the successive machining of several surfaces of one WP or a similar surface of different WPs. Principal motions may be either rotating or straight reciprocating. In some machine tools, this motion is a combination of rotating and reciprocating motions. Feed movement may be continuous (lathes, milling machine, drilling machine) or intermittent (shapers, planers). As shown in Figure 1., stepped motions are obtained using belting or gearing. Stepless speeds are achieved by mechanical, hydraulic, and electrical methods.

Fig 1. Classification of transmission of rotary motion.
STEPPED SPEED DRIVES:

Belting:

The belting system, shown in Figure 2, is used to produce four running rotational speeds \(n_1, n_2, n_3,\) and \(n_4.\) It is cheap and absorbs vibrations. It has the limitation of the low-speed changing, slip, and the need for more space. Based on the driver speed \(n_1,\) the following speeds can be obtained in a decreasing order:

\[
\begin{align*}
  n_1 &= n - \frac{d_1}{d_5} \\
  n_2 &= n - \frac{d_2}{d_6} \\
  n_3 &= n - \frac{d_3}{d_7}
\end{align*}
\]

![Fig 2.Belting transmission](image)

This type is commonly used for grinding and bench-type drilling machines.

Pick-Off Gears

Pick-off gears are used for machine tools of mass and batch production (automatic and semiautomatic machines, special-purpose machines, and so on) when the changeover from job to job is comparatively rare. Pick-off gears may be used in speed or feed gearboxes. As shown in Figure 3, the change of speed is achieved by setting gears A and B on the adjacent shafts. As the center distance is constant, correct gear meshing occurs if the sum of teeth of gears A and B is constant.

![Fig 3.Pick-Off Gears](image)
Gearboxes

Machine tools are characterized by their large number of spindle speeds and feeds to cope with the requirements of machining parts of different materials and dimensions using different types of cutting tool materials and geometries. The cutting speed is determined on the bases of the cutting ability of the tool used, surface finish required, and economical considerations.

A wide variety of gearboxes utilize sliding gears or friction or jaw coupling. The selection of a particular mechanism depends on the purpose of the machine tool, the frequency of speed change, and the duration of the working movement. The advantage of a sliding gear transmission is that it is capable of transmitting higher torque and is small in radial dimensions. Among the disadvantages of these gearboxes is the impossibility of changing speeds during running. Clutch-type gearboxes require small axial displacement needed for speed changing, less engagement force compared with sliding gear mechanisms, and therefore can employ helical gears. The extreme spindle speeds of a machine tool main gearbox \( n_{\text{max}} \) and \( n_{\text{min}} \) can be determined by

\[
\begin{align*}
n_{\text{max}} &= \frac{1000V_{\text{max}}}{\pi d_{\text{min}}} \\
n_{\text{min}} &= \frac{1000V_{\text{min}}}{\pi d_{\text{max}}}
\end{align*}
\]

where

- \( V_{\text{max}} \) = maximum cutting speed (m/min) used for machining the most soft and machinable material with a cutting tool of the best cutting property
- \( V_{\text{min}} \) = minimum cutting speed (m/min) used for machining the hardest material using a cutting tool of the lowest cutting property or the necessary speed for thread cutting
- \( d_{\text{max}}, d_{\text{min}} \) = maximum and minimum diameters (mm) of WP to be machined

The speed range \( R_n \) becomes

\[
R_n = \frac{n_{\text{max}}}{n_{\text{min}}} = \frac{V_{\text{max}}}{V_{\text{min}}} \cdot \frac{d_{\text{min}}}{d_{\text{max}}} = R_v \cdot R_d
\]

where

- \( R_v \) = cutting speed range
- \( R_d \) = diameter range

In case of machine tools having rectilinear main motion (planers and shapers), the speed range \( R_n \) is dependent only on \( R_v \). For other machine tools, \( R_n \) is a function of \( R_v \) and \( R_d \), large cutting speeds and diameter ranges are required. Generally, when selecting a machine tool, the speed range \( R_n \) is increased by 25% for future developments in the cutting tool materials. Table 1 shows the maximum speed ranges in modern machine tools.

### Table 1

<table>
<thead>
<tr>
<th>Machine</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerically controlled lathes</td>
<td>250</td>
</tr>
<tr>
<td>Boring</td>
<td>100</td>
</tr>
<tr>
<td>Milling</td>
<td>50</td>
</tr>
<tr>
<td>Drilling</td>
<td>10</td>
</tr>
<tr>
<td>Surface grinding</td>
<td>4</td>
</tr>
</tbody>
</table>
Stepping of Speeds According to Arithmetic Progression:

Let \( n_1, n_2, \ldots, n_z \) be arranged according to arithmetic progression. Then

\[
\begin{align*}
n_1 - n_2 &= n_3 - n_2 &= \text{constant}
\end{align*}
\]

The saw tooth diagram in such a case is shown in Figure 4. Accordingly, for an economical Cutting speed \( v_0 \), the lowest speed \( v_1 \) is not constant; it decreases with increasing diameter. Therefore, the arithmetic progression does not permit economical machining at large diameter ranges.

The main disadvantage of such an arrangement is that the percentage drop from step to step \( \delta n \) decreases as the speed increases. Thus the speeds are not evenly distributed and more concentrated and closely stepped, in the small diameter range than in the large one. Stepping speeds according to arithmetic progression are used in Norton gearboxes or gearboxes with a sliding key when the number of shafts is only two.

![Speed stepping according to arithmetic progression.](image)

Stepping of Speeds According to Geometric Progression

As shown in Figure, the percentage drop from one step to the other is constant, and the absolute loss of economically expedient cutting speed \( \Delta v \) is constant all over the whole diameter range. The relative loss of cutting speed \( \Delta v_{\text{max}}/v_0 \) is also constant. Geometric progression, therefore, allows machining to take place between limits \( v_0 \) and \( v_u \) independent of the WP diameter, where \( v_0 \) is the economical cutting speed and \( v_u \) is the allowable minimum cutting speed. Now suppose that \( n_1, n_2, n_3, \ldots, n_z \) are the spindle speeds. According to the geometric progression,

\[
\frac{n_2}{n_1} = \frac{n_3}{n_2} = \phi
\]

Where \( \phi \) is the progression ratio. The spindle speeds can be expressed in terms of the minimal speed \( n_1 \) and progression ratio \( \phi \).

\[
\begin{align*}
n_1 & \quad n_2 & \quad n_3 & \quad n_4 & \quad n_z \\
n_1 & \quad n_1\phi & \quad n_1\phi^2 & \quad n_1\phi^3 & \quad n_1\phi^{z-1}
\end{align*}
\]

Hence, the maximum spindle speed \( n_z \) is given by

\[
n_z = n_1\phi^{z-1}
\]
Where \( z \) is the number of spindle speeds, therefore,

\[
\varphi = \left[ \frac{R}{n_z} \right] = \left( \frac{R}{n_1} \right)^{1/(z-1)}
\]

From which

\[
z = \frac{\log R}{\log \varphi} + 1
\]

ISO Standard values of progression ratios \( \varphi \) (1.06, 1.12, 1.26, 1.4, 1.6, 1.78, 2.0)

**Breakup Speed steps:**

\[
Z: \text{ No of speed steps} \\
\Phi: \text{ No of transmissions}
\]

\[
z = P_1 \times P_2 \times P_3 \times \ldots \times P_u
\]

\( P \): no of speeds in each transmission

To obtain the \( Z \) speeds with minimum no of gears \( Z = P^u \).

When \( P = Z^{1/u} \) is not a whole no divide the speed steps in such away that

\[
z = 2^{E_1} \times 3^{E_2} \quad \ldots \quad (1)
\]

Eqn 1 is satisfied by the numbers \( Z = 2, 3, 4, 6, 8, 9, 12, 16, 18, 24, 27, 32, 36, \) etc

**Structural formulae & Structural Diagrams:**

Suppose a speed on one shaft yields two speed values on the next shaft. The noo of speed steps of the particular transmission group is \( p = 2 \). If the transmission is through gears, the transmission ratios that provide the two new speed values must lie in the following range:

\[
n_1/nz = i_{\text{max}} = 2 \quad \text{(maximum increase in speed)}
\]

\[
n_2/nz = i_{\text{min}} = 1/4 \quad \text{(max reduction in speed)}
\]
Transmission range for any stage: $i_g = \frac{i_{\text{max}}}{i_{\text{min}}} = 8$

For any stage: if there are $Z^1$ steps:

$$\frac{n_1}{n_2} = \frac{n_2}{n_3} = \ldots = \frac{n_{z-1}}{n_z} = K$$

Since speeds are to be in GP $K = \phi^X$.

X characteristics of the transmission stage.

$Z = P_1 \cdot P_2 \cdot \ldots \cdot P_u$

$Z = P_1(x_1) \cdot P_2(x_2) \cdot \ldots \cdot P_u(x_u)$.

Structural Formula

$P_1$ speed steps in stage. $x_1$ characteristic of stage.

Where $X_1 = 1$, $X_2 = P_1$, $X_3 = P_1 \cdot P_2$, \ldots \ldots $X_n = P_1 \cdot P_2 \cdot P_{n-1}$.

Ex: $Z = 12$, $u = 3$

\[
\begin{align*}
Z &= 2 \cdot 2 \cdot 3 \\
   &= 2 \cdot 3 \cdot 2 \\
   &= 3 \cdot 2 \cdot 2
\end{align*}
\]

Structural formula:

$X_1 = 1$, $X_2 = P_1$, $X_3 = P_1 \cdot P_2$.

$Z = 2(1) \cdot 2(2) \cdot 3(4)$

$= 2(1) \cdot 3(2) \cdot 2(6)$

$= 3(1) \cdot 2(3) \cdot 2(6)$

**GUIDELINES FOR SELECTING BEST STRUCTURAL FORMULA:**

1. Transmission ratio $i_{\text{max}} = 2$, $i_{\text{min}} = 1/4$, $i_g = \frac{i_{\text{max}}}{i_{\text{min}}} = 8$.
2. Minimum total shaft size:

   The torque transmitted by a shaft is given by $T \alpha \frac{1}{N}$;

   From the strength consideration: $(d_1/d_2) = (N_2/N_1)^{1/3}$

3. For least radial dimensions of gear box $i_{\text{max}} \cdot i_{\text{min}} = 1$.
4. No of gears on last shaft should be minimum.
5. No of gears on any shaft should be limited to three.

**Limiting values of transmission intervals for different $\phi$:**

<table>
<thead>
<tr>
<th>Type of transmission $\phi$</th>
<th>1.06</th>
<th>1.12</th>
<th>1.26</th>
<th>1.41</th>
<th>1.58</th>
<th>1.78</th>
<th>2.0</th>
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<tr>
<td>Speed reduction $i &lt; 1$</td>
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<td>Speed increases $i &gt; 1$</td>
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Feed Gearboxes:

Feed gearboxes are designed to provide the feed rates required for the machining operation. The values of feed rates are determined by the specified surface finish, tool life, and the rate of material removal.

The classification of feed gearboxes according to the type of mechanism used to change the rate of feed is as follows:

1. **Feed gearboxes with pick-off gears.** Used in batch-production machine tools with infrequent change over from job to job, such as automatic, semiautomatic, single-purpose, and special-purpose machine tools. These gearboxes are simple in design and are similar to those used for speed changing.

2. **Feed gearboxes with sliding gears.** These gearboxes are widely used in general-purpose machine tools, transmit high torques, and operate at high speeds. Figure shows a typical gearbox that provides four different ratios. Accordingly, gears Z2, Z4, Z6, and Z8 are keyed to the drive shaft and mesh, respectively, with gears Z1, Z3, Z5, and Z7, which are mounted freely on the driven key shaft. The sliding key engages any gear on the driven shaft. The engaged gear transmits the motion to the driven shaft while the rest of the gears remain idle. The main drawbacks of such feed boxes are the power loss and wear occurring due to the rotation of idle gears and insufficient rigidity of the sliding key shaft. Feed boxes with sliding gears are used in small- and medium-size drilling machines and turret lathes.
3. **Norton gearboxes.** These gearboxes provide an arithmetic series of feed steps that is suitable for cutting threads and so are widely used in engine lathe feed gearboxes as shown in FIG

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**STEPLESS SPEED DRIVES:**

Stepless speed drives may be mechanical, hydraulic, or electric. The selection of the suitable drive depends on the purpose of the machine tool, power requirements, speed range ratio, mechanical characteristics of the machining operation, and cost of the variable speed unit. In most stepless drives, the torque transmission is not positive. Their operation involves friction
and slip losses. However, they are more compact, less expensive, and quieter in operation than the stepped speed control elements

**Mechanical Stepless Drives:**

Infinitely variable speed (stepless) drives provide output speeds, forming infinitely variable ratios to the input ones. Such units are used for main as well as feed drives to provide the most suitable speed or feed for each job, thereby reducing the machining time. They also enable machining to be achieved at a constant cutting speed, which leads to an increased tool life and ensures uniform surface finish.

Mechanical stepless drives are 4 types:
- Friction Stepless Drive
- Kopp Variator
- Toroidal and Reeves Mechanisms
- Positive Infinitely Variable Drive

**Friction Stepless Drive**

The disk-type friction stepless mechanism. Accordingly, the drive shaft rotates at a constant speed $n_1$ as well as the friction roller of diameter $d$. The output speed of the driven shaft rotates at a variable speed $n_2$ that depends on the instantaneous diameter $D$.

Because $n_1 d = n_2 D$

Hence $n_2 = n_1 \frac{d}{D}$.

The diameter ratio $d/D$ can be varied in infinitely small steps by the axial displacement of the friction roller. If the friction force between the friction roller and the disk is $F$,

$$F = \frac{\text{input torque (T1)}}{\text{input radius (d/2)}} = \frac{\text{output torque (T2)}}{\text{output radius (D/2)}}$$

If the power, contact pressure, transmission force, and efficiency are constant, the output torque $T_2$ is inversely proportional to the speed of the output shaft $n_2$.

$$T_2 \propto \frac{T_1 n_1}{n_2}$$

Due to the small contact area, a certain amount of slip occurs, which makes this arrangement suitable for transmitting small torques and is limited to reduction ratios not more than 1:4.

**Kopp Variator**

The drive balls (4) mounted on inclinable axes (3) run in contact with identical, effective radii $r_1 = r_2$, and drive cones (1 and 2) are fixed on coaxial input and output shafts. When the axes of the drive balls (3) are parallel to the drive shaft axes, the input and output speeds are the same. When they are tilted, $r_1$ and $r_2$ change, which leads to the increase or decrease of the speed.

Using Kopp mechanism, a speed range of 9:1, efficiency of higher than 80% and 0.25–12 hp
capacity are obtainable.

Kopp stepless speed mechanism: (a) $n_2 < n_1$, (b) $n_2 = n_1$, and (c) $n_2 > n_1$.

**Toroidal and Reeves Mechanisms**

The principle of toroidal stepless speed transmission. Figure shows the Reeves variable speed transmission, which consists of a pair of pulleys connected by a V-shaped belt; each pulley is made up of two conical disks. These disks slide equally and simultaneously along the shaft and rotate with it. To adjust the diameter of the pulley, the two disks on the shaft are made to approach each other so that the diameter is increased or decreased. The ratio of the driving diameter to the driven one can be easily changed and, therefore, any desired speed can be obtained without stopping the machine. Drives of this type are available with up to 8:1 speed range and 10 hp capacity.

Reeves variable speed transmission.

Toroidal stepless speed transmission (a) $n_2 < n_1$, (b) $n_2 = n_1$, and (c) $n_2 > n_1$. 
Positive Infinitely Variable Drive

Positive torque transmission arrangement that consists of two chain wheels, each of which consists of a pair of cones that are movable along the shafts in the axial direction. The teeth of the chain wheels are connected by a special chain. By rotating the screw, the levers get moved thus changing the location of the chain pulleys, and hence the speed of rotation provides a speed ratio of up to 6 and is available with power rating up to 50 hp. The use of infinite variable speed units in machine tool drives and feed units is limited by their higher cost and lower efficiency or speed range.

Electrical Stepless Speed Drive

Figure shows the Leonard set, which consists of an induction motor that drives the direct current generator and an exciter (E). The dc generator provides the armature current for the dc motor, and the exciter provides the field current; both are necessary for the dc motors that drive the machine tool.
The speed control of the dc motor takes place by adjusting both the armature and the field voltages by means of the variable resistances A and F, respectively. By varying the resistance A, the terminal voltage of the dc generator and hence the rotor voltage of the dc motor can be adjusted between zero and a maximum value. The Leonard set has a limited efficiency: it is large, expensive, and noisy. Nowadays, dc motors and thyrestors that permit direct supply to the dc motors from alternating current (ac) mains are available and, therefore, the Leonard set can be completely eliminated. Thyrestor feed drives can be regulated such that the system offers infinitely variable speed control.

Hydraulic Stepless Speed Drive

The speeds of machine tools can be hydraulically regulated by controlling the oil discharge circulated in a hydraulic system consisting of a pump and hydraulic motor, both of the vane type, as shown in fig. This is achieved by changing either the eccentricity of the pump \( e_p \) or the eccentricity of the hydraulic motor \( e_m \) or both. The vane pump running approximately at a constant speed delivers the pressurized oil to the vane type hydraulic motor, which is coupled to the machine tool spindle.

To change the direction of rotation of the hydraulic motor, the reversal of the pump eccentricity is preferred. Speed control in hydraulic circuits can be accomplished by throttling the quantity of fluid flowing into or out of the hydro cylinders or hydro motor. The advantages of the hydraulic systems are as follows:
1. Has a wide range of speed variation
2. Changes in the magnitude and direction of speed can be easily performed
3. Provides smooth and quiet operation
4. Ensures self-lubrication
5. Has automatic protection against overloads

The major drawback to a hydraulic system is that the operation of the hydraulic drive becomes unstable at low speeds. Additionally, the oil viscosity varies with temperature and may cause fluctuations in feed and speed rates.