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POWER SCREWS

Introduction
Power screw is a mechanical screw used for power transmission rather than fastening. A mechanical screw is a cylinder or cone that has a helical ridge called a thread. A helix has one or more turns, so a screw can have several turns. Power screws provide high mechanical advantage; allow a relatively small force to be amplified for application. Common power screws include square, acme, trapezoidal, and buttress power screws. Power screws are commonly used in devices such as hand presses, vices, C-clamps, jack screws, hoisting screws, and lead screws. They are also used as positive positioners for control rod drives nuclear power reactors and compactions for home garbage compactors. Hand presses operate at low speed, jack screws operate less than 2.5 m/min usually, hoisting screws operate between 6 to 12 m/min, and lead screws may operate above 15 m/min.

Power Screws
The main advantage of a power screw is its large mechanical advantage. It has the ability to greatly magnify an effort load so that a small force can be used to move a much larger load along its axis. In precision and heavy duty applications, balls are placed inside a screw-nut assembly to obtain a ball screw drive. A stream of balls flows in a semicircular groove within the nut-screw unit converting the sliding motion between the threads of the nut and screws into rolling motion. This greatly improves the efficiency of the mechanism. The thread profiles and proportions of these screws are shown in Fig. 1.

Square thread: Fig. 1a) shows the profile and proportions of a square thread. The thread has straight flanks that are perpendicular or nearly so to the thread axis. A slight taper on the flanks makes for easier engagement of screw and nut. Square thread provides best strength and efficiency but is not easy to manufacture, so it is not commonly used, rather a modified square thread screw is preferred. The modified square thread screw has an included angle of 10°, similar to acme or trapezoidal thread screw. This small angle makes manufacturing square thread easier. It may be used for jack screws, presses, and clamping devices.

![Fig. 1: Power screw types](image-url)
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**Acme thread:** Fig. 1b) shows the profile and proportions of an acme thread. The thread has straight flanks with 29° included angle. Acme thread is a modification of the square thread and provides for stronger and easily machined threads that engages and disengages easily. It permits the use of split nut which is adjustable for wear. Acme thread is used in jack screws, vices, and lead screws. Lead screws are common in machine tools.

**Trapezoidal thread:** Fig. 1c) shows the profile and proportions of a trapezoidal thread. The thread has straight flanks with 30° included angle. This is the ISO power screw standard. Like the Acme thread, it is a modification of the square thread and provides for stronger and easily machined threads that engage and disengage easily. Trapezoidal screws are used in similar applications like acme screws.

**Buttress Thread:** This is a special power screw thread that allows power transmission in only one direction. It can carry heavy loads in one direction. The front or load bearing flank of the thread is usually inclined within 7° while the rear flank is inclined within 45°. Buttress threads are used in guns, jacks, and other mechanical devices. Fig. 1d) shows the profile and proportions of a buttress thread. Buttress screws are used in vices where force is applied mainly in one direction. They are ideal for connecting tubular components that carry large forces such as connecting barrels to housing in anti-aircraft guns.

**Lead Screws**
A lead screw is a mechanical screw designed for motion transmission instead of power transmission. The force required for operation is low and good translation and position features are desired. They have high helix angle and thus provide fast motion. Some are made with fine pitches for high resolution or precise motion control. Self-lubrication polymer nuts can be used so eliminating the need for periodic lubrication. Lead screws are common in machine tools such as lathe and milling machines for worktable positioning. A central issue in lead screw or ball screw applications is the critical speed which is the speed that excites the natural frequency of the screw. The operating speed of the screw is typically limited to 80% of the estimated critical speed. For a steel lead screw or steel ball screw, the critical speed may be estimated as:

\[
N_c = \frac{121 k_f d_r}{L^2}
\]

- \(N_c\) = critical speed of screw (rpm)
- \(d_r\) = root diameter of screw (mm)
- \(L\) = length between bearing supports (mm)
- \(k_f\) = end fixation factor

- \(k_f = 0.36\) for one end fixed, other free
- \(k_f = 1.0\) for both ends pinned
- \(k_f = 1.47\) for one end fixed, other pinned
- \(k_f = 2.23\) for both ends fixed

**Ball Screws**
Ball screws are power or lead screws that have nuts with ball casing. The balls are placed between the shaft and nut threads and re-circulated in a helical raceway during operation. The balls convert conventional sliding friction in the screw to rolling friction which greatly reduces power loss. They made to close tolerances and are suitable for use in situations in which high precision is necessary. The axial load is distributed amongst many balls, allowing for heavier loads to be processed with less power. Ball screws are able to apply or resist high thrust loads with minimum internal friction. They tend to be rather bulky because of the ball assembly. Ball screws have efficiencies of about 90 to 95%, compared with conventional power screws that have efficiency in the range of 30 to 70%. Ball screws are the most common drives in CNC control units.

**Materials**
Materials for power screws and nuts need good compressive strength, fatigue strength, ductility, thermal conductivity, and compatibility between mating surfaces. Ball screw material surfaces are very hard and with good fatigue resistance. Power screws are often manufactured from low carbon steels and low-carbon carburizing
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grade alloy steel grades. The screws are carburized and heat treated and common materials are AISI 1010, 3310, 4620, and 8620. Nuts are generally made of soft ductile materials such as bronzes and brasses and cast iron due to its rather low friction coefficient.

Jack screws are proof tested after manufacture with a load 50% above rated load through approximately 90% of its stroke. A full stroke test is done at rated load [ASME B 30.1, ASME PALD]. Thus a service factor above 1.5 is need for design load for jack screws. A higher factor is expected for other types of power screws except hand screws.

**Power Screws**

\( \gamma \) = lead angle  
\( \phi \) = thread angle  
\( \mu_t \) = thread friction  
\( \mu_o \) = lead angle factor  
\( \mu_c \) = collar friction  
\( z_s \) = number of thread starts  
\( z_t \) = number of threads in nut  
\( h_s \) = nut height  
\( h_t \) = thread height  
\( h_n \) = nut height  
\( t_p \) = thread pitch  
\( t_r \) = thread root thickness  
\( F_c \) = axial load or weight  
\( F_e \) = effort load  
\( d_r \) = root diameter  
\( d_m \) = mean diameter  
\( D_o \) = nut outside diameter  
\( D_c \) = mean collar diameter  
\( D_i \) = collar outside diameter  
\( T'_l \) = screw torque to raise load  
\( T_c \) = collar friction torque  
\( T_n \) = total torque to raise load  
\( T'_g \) = screw torque to lower load  
\( T_g \) = total torque to lower load  
\( \alpha_1 \) = nut height diameter factor  
\( \alpha_2 \) = thread height pitch factor  
\( p_o \) = allowable bearing pressure  
\( p_{co} \) = allowable bearing pressure between collar and load support  
\( l_s \) = screw length

For jack screw, the screw stroke \( l_s \), is 8 to 10 times the screw mean diameter.

**Screw Sizing: Bearing Serviceability**

\[
p_o = \frac{4K_mF_c}{\pi \alpha_1 \alpha_2 d_m^2} \\
\]

\[
d_m \geq \sqrt[4]{\frac{K_mF_c}{\pi \alpha_1 \alpha_2 p_o}} \\
\]

\( \alpha_1 = 1.2 \) to 2.5 for solid nut  
\( \alpha_1 = 2.5 \) to 3.5 for split nut  
\( \alpha_2 = 0.5 \) for square, trapezoidal, and acme thread  
\( \alpha_2 = 0.66 \) for buttress thread  
\( K_m = 1.35 - 1.82 \) load-distribution factor [p. 417, Petrov]

\( d_o = 1.375d_m \) (for square, trapezoidal, and acme thread)

Brass can take about same bearing pressure as cast iron but tolerates higher speed.

Choose standard \( d_o \) and \( t_p \)

**Nut**

\[
s_c = \frac{4K_mF_c}{\pi(D_o^2 - d_o^2)} \leq S_c \\
\]

\[
D_o \geq \sqrt[4]{\frac{4K_mF_c}{\pi S_c} + d_o^2} \\
\]
\( S_c \) is between 34 to 44 MPa for bronze nut and 20 to 24 MPa for cast iron nut [Petrov, p. 22].

**Collar**

A collar is required between a stationary load support and a rotating member such as the screw. The collar is usually made integral with the screw and rotates with it. A thrust plate of a low friction material is often placed on top of the collar plate to reduce collar frictional torque. The collar is sized based on allowable bearing pressure between the collar and the load support materials. The collar friction is often determined based on uniform wear theory which is a reasonable assumption after initial wear-in period. A thrust bearing is used to support the load in some applications. This helps to reduce collar friction torque greatly.

**Collar Sizing**

\[
p_c = \frac{4K_K_mF_z}{\pi(D_1^2 - D_o^2)} \leq p_{oc} \\
D_1 \geq \sqrt{\frac{4K_K_mF_z}{\mp p_{oc}} + D_o^2} \\
D_c = 0.5(D_1 + D_o)
\]

\( p_{oc} \) is between 42 to 55 MPa for bronze-steel or cast iron-steel material pair. Collar height is \( \frac{1}{4} \) to \( \frac{1}{3} \) of \( h_n \) to ensure uniform load distribution in threads [Petrov, p. 226].

**Effort Load Arm Length**

For manually lever operated power screw

\[
L = \text{effort load arm length} \\
F_e = \text{effort load} \\
T_u = L F_e \\
L = \frac{T_u}{F_e}
\]

**Design Sizing: Bending Strength**

\[
d_1 = \text{diameter of effort lever} \\
d_1 = \left[ \frac{32n_s K_T u}{\pi S_{vt}} \right]^{1/3}
\]

**Effective Normal Stress**

\[
\sigma_b = \frac{32T_u}{\pi d_1^2} + \frac{4F_e}{\pi d_1^2} \leq \frac{S_{vt}}{n_o}
\]

\( \mu_e = \text{lead angle factor} \)

\( \phi_o = 0.5\phi \)

\( \phi = \text{thread angle} \)

\( \mu_t \geq \mu_o \cos \phi_o \) (self-locking thread)

**Screw Torques**

**Collar Torque**

\[
T_c = \frac{\mu_e F_e D_c}{2000}
\]

**Torque to Raise Load:**

\[
T_u' = F_e \frac{d_m}{2000} \left[ \frac{\mu_t + \mu_o \cos \phi_o}{\cos \phi_o - \mu_t \mu_o} \right]
\]

\[
T_u = T_u' + T_c
\]

\[
\tan \gamma = \frac{z_{tp}}{m t_m} = \mu_o
\]
Torque to Lower Load:
\[ T_d' = \frac{F_c \cdot d_m}{2000} \left[ \mu_i - \mu_o \cos \phi_o \right] \cos \phi_o + \mu_i \mu_o \]
\[ T_d = T_d' + T_c \]

Stresses in Screw

a) Bearing Stress
\[ p_s = \frac{4K_F z}{\pi \ell_r (d_o^2 - d_r^2)} \leq p_o \]
b) Crushing Stress
\[ \sigma_{cc} = \frac{4K_\sigma F_z}{\pi \ell_r^2} \]

K_\sigma = stress concentration factor
\[ = 4 - 5 \text{ (Brown, p. 16.9, if no fillet at root)} \]
c) Screw stem bending
\[ l_s = l + h_n \]
\[ \sigma_{bs} = \frac{32K_\sigma K_F z l_s}{\pi \ell_r^2} \]
d) Thread bending
\[ \sigma_{bt} = \frac{3K_\sigma K_F z (d_n - d_r)}{\pi \ell_r d_f t_r^2} \]
\[ \sigma_{bt} = \frac{3K_\sigma K_F z h_n}{\pi \ell_r d_f t_r^2} \]
e) Direct Shear Stress
\[ \tau_{sc} = \frac{4K_F z}{\pi c_d t_r} \]
f) Torsional Stress
\[ \tau_c = \frac{16K_T' \cdot 10^3}{\pi d_r^3} \]
g) Equivalent normal stress
\[ \sigma_i = \sqrt{(\sigma_{zz} + \sigma_{bs} + \sigma_{bt})^2 + 3(\tau_{sc} + \tau_c)^2} \leq \frac{S_{st}}{n_o} \]

Buckling Check
Treat as column if screw longer than 6xroot diameter (Brown, p. 16.9)
\[ \lambda_c = \pi \frac{2E}{S_{yc}} \]
\[ L_c = k_f l_s \]
\[ k_x = \left[ 0.375 + 0.625 \frac{d_o}{d_r} \right] \text{ (Petrov, p. 228)} \]
\[ k_x = \text{outerside diameter factor} \]
\[ r_s = \frac{k_x d_r}{4} \]
\[ \lambda = \frac{L_x}{r_s} = \frac{4k_f l_s}{k_x d_r} \]

Intermediate Column: \(1 \leq \lambda \leq \lambda_c\)
\[ \varphi = \frac{\lambda}{\lambda_c} \leq 1 \]
\[ \beta_c = \frac{2 - \varphi^2}{2 + 0.15 \varphi (3 - \varphi^2)} \]
\[ F_z \leq \frac{\pi \ell_r^2}{4n_o K_s \beta_c S_{yc}} \]

Table 1: Allowable Bearing Pressure in Power Screws (Budynas, p. 421)

<table>
<thead>
<tr>
<th>Screw Material</th>
<th>Nut Material</th>
<th>Safe Pressure: ( p_o ) (MPa)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel: Hand screw</td>
<td>Bronze</td>
<td>24</td>
<td>Low speed</td>
</tr>
<tr>
<td>Steel: Jack screw</td>
<td>Bronze</td>
<td>17</td>
<td>( \leq 3 \text{ m/min} )</td>
</tr>
<tr>
<td>Steel: Jack screw</td>
<td>Cast iron</td>
<td>17</td>
<td>( \leq 2.5 \text{ m/min} )</td>
</tr>
<tr>
<td>Steel: Hoisting screw</td>
<td>Bronze</td>
<td>10</td>
<td>6 - 12 \text{ m/min}</td>
</tr>
<tr>
<td>Steel: Hoisting screw</td>
<td>Cast iron</td>
<td>7</td>
<td>6 - 12 \text{ m/min}</td>
</tr>
<tr>
<td>Steel: Lead screw</td>
<td>Bronze</td>
<td>1.7</td>
<td>( \geq 15 \text{ m/min} )</td>
</tr>
</tbody>
</table>

\( p_o = 8 - 10 \text{ MPa for soft steel on bronze} \)
\( p_o = 4 - 6 \text{ MPa for soft steel on cast iron} \)
### Table 2: Metric Square and Trapezoidal Screw

<table>
<thead>
<tr>
<th>Nominal Diameter (mm)</th>
<th>Pitch: ( t_p ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>24, 28</td>
<td>5</td>
</tr>
<tr>
<td>32, 36</td>
<td>6</td>
</tr>
<tr>
<td>40, 44</td>
<td>7</td>
</tr>
<tr>
<td>48, 52</td>
<td>8</td>
</tr>
<tr>
<td>60</td>
<td>9</td>
</tr>
<tr>
<td>70, 80</td>
<td>10</td>
</tr>
<tr>
<td>90, 100</td>
<td>12</td>
</tr>
</tbody>
</table>

### Table 3: Average Thread Friction Coefficient

<table>
<thead>
<tr>
<th>Nut Material</th>
<th>Screw Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel: Dry</td>
</tr>
<tr>
<td>Brass</td>
<td>0.17</td>
</tr>
<tr>
<td>Bronze</td>
<td>0.20</td>
</tr>
<tr>
<td>Cast iron</td>
<td>0.21</td>
</tr>
<tr>
<td>Steel</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Table 4: Thrust-Collar Friction

<table>
<thead>
<tr>
<th>Material Combination</th>
<th>Running</th>
<th>Starting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard steel on bronze</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>Soft steel on bronze</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Hard steel on cast iron</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
<td>Soft steel on cast iron</td>
<td>0.12</td>
<td>0.17</td>
</tr>
</tbody>
</table>

### Table 5: Column End Fixation Factor

<table>
<thead>
<tr>
<th>End Conditions</th>
<th>Fixation Factor ((k_f))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both ends fixed</td>
<td>0.50</td>
</tr>
<tr>
<td>One fixed end &amp; other pinned</td>
<td>0.70</td>
</tr>
<tr>
<td>Both ends pinned</td>
<td>1.0</td>
</tr>
<tr>
<td>One fixed end &amp; other free</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Table 6: English Screw Thread Sizes

<table>
<thead>
<tr>
<th>Nominal Diameter (in.)</th>
<th>Acme</th>
<th>Modified Sq.</th>
<th>Buttress</th>
</tr>
</thead>
<tbody>
<tr>
<td>¼</td>
<td>1/16</td>
<td>1/10</td>
<td>-</td>
</tr>
<tr>
<td>5/16</td>
<td>1/14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3/8</td>
<td>1/12</td>
<td>1/8</td>
<td>-</td>
</tr>
<tr>
<td>½</td>
<td>1/10</td>
<td>1/6.5</td>
<td>1/16</td>
</tr>
<tr>
<td>5/8</td>
<td>1/8</td>
<td>1/5.5</td>
<td>1/16</td>
</tr>
<tr>
<td>¾</td>
<td>1/6</td>
<td>1/5</td>
<td>1/16</td>
</tr>
<tr>
<td>7/8</td>
<td>1/6</td>
<td>1/4.5</td>
<td>1/12</td>
</tr>
<tr>
<td>1</td>
<td>1/5</td>
<td>¼</td>
<td>1/12</td>
</tr>
<tr>
<td>1-1/4</td>
<td>1/5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1-1/2</td>
<td>¼</td>
<td>1/3</td>
<td>1/10</td>
</tr>
<tr>
<td>1-3/4</td>
<td>¼</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>¼</td>
<td>1/2.25</td>
<td>1/8</td>
</tr>
<tr>
<td>2-1/2</td>
<td>1/3</td>
<td>½</td>
<td>1/8</td>
</tr>
<tr>
<td>3</td>
<td>½</td>
<td>1/1.75</td>
<td>1/6</td>
</tr>
<tr>
<td>3-1/2</td>
<td>½</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>½</td>
<td>1/1.5</td>
<td>1/6</td>
</tr>
<tr>
<td>4-1/2</td>
<td>½</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>½</td>
<td>-</td>
<td>1/5</td>
</tr>
</tbody>
</table>

Conversion: 1 in. = 25.4 mm