GEARED MOTORS – PRINCIPLES, STRUCTURE AND APPLICATIONS

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1. FROM TRANSMISSION BELT TO INTELLIGENT GEARED MOTOR

A retrospect:

1764: James Watt invents the steam engine
1850: Pittler builds the first turret lathe
1867: Wernher von Siemens builds the first dynamo
1872: F. v. Hefner-Alteneck builds the first DC motor
1880: Wernher von Siemens builds the first electric elevator
1887: N. Tesla invents the AC motor
1889: J. H. Northop invents the automatic loom

... the modern industrial age has begun.

Dawn of the Industrial Age

The dawn of this new age saw a previously unimaginable level of mechanization and automation of repetitive processes. Processes which used to be performed by people – often involving great physical exertion – were now taken over by machines.

During the early years, mechanization was achieved using systems called transmission belts: power was carried by leather belts from a central prime mover via reversing sheaves and intermediate shafts. In this way, the power was made available where it was needed by the corresponding machine tool (Fig. 1). The central prime mover was a gas engine or a waterwheel, later replaced by the electric motor. Its speed of rotation and the level of torque were adapted to the particular application by intervening gear units employing either belts or gears. A major disadvantage was that the central prime mover had to operate even when only one machine was running. In addition, the rotating shafts and belts had no covers or guards and not only represented a significant safety hazard but were also very noisy.
Breakthrough of the Decentralized Electric Motor

Following the invention of the decentralized electric motor, it was the above disadvantages which provided the impetus for these motors to become more widespread in use. The motor speed and torque still had to be adapted to the application, initially by mounting a gear unit on the motor output: both were mounted on a common baseplate and connected with a coupling. The combination of motor, coupling and gear unit made it possible to use individual drives and to provide motive force where it was needed.

However, this combination still harbored room for improvement. The couplings only permitted minor angular and axial tolerances. This meant the common mounting surface for the motor and gear unit had to be machined with great precision. Also, the combination of motor, coupling and gear unit was too bulky for many jobs. The large number of components was also a problem, since it made fault-finding more difficult in the case of a breakdown.

1928: Invention of the Countershaft Motor

No doubt it was considerations such as these which, in 1928, prompted Albert Moser to patent the predecessor of the geared motor – the countershaft motor (Fig. 2) – as patent number N576.436. The patent states that “The present invention relates to a motor/gear unit with a motor body flange-mounted on the gear unit housing, in which one end of the motor shaft is mounted in the wall of the gear unit housing instead of in a bearing end shield, and the countershaft is mounted in two walls of the same part of this housing. A motor/gear unit of this type is characterized in that it facilitates the task of establishing an accurate and fixed reciprocal position of the gears within the gear unit housing, something which makes it possible to achieve completely smooth running.”

Further Development: The Intelligent Geared Motor

The principle of the geared motor was developed steadily over the following years. New manufacturing processes led to increased power and improvements in quality. The dominance of the helical geared motor was followed by geared motors with helical-worm gears and then with helical-bevel gears. Variable-speed geared motors were included between the motor and the gear unit, enabling speed changes to be made within wide ranges.

Fig. 2 – The predecessor of the geared motor: the countershaft motor

The success of all geared motors is based on being a homogeneous and compact unit, having a simple design and almost unlimited combinations between motors and gear units (Fig. 3).

Fig. 3 – Current generation of geared motors
Combining the electric motor with a planetary gear unit opened the door to even more possible applications, as did the use of frequency inverters. Today, geared motors and electronic speed control represent a well adapted entity. Physically speaking too, motors and frequency inverters have become closer. Integrated frequency inverters are mounted directly on the geared motor. There is no need for cables between the inverter and the motor. The result is a compact and optimized drive unit (Fig. 4).

![Fig. 4 – One unit: geared motor with integrated frequency inverter](image)

There are innumerable uses for geared motors in our technical world. Geared motors are used in almost all areas of industrial production, manufacturing and transportation. The geared motor is used for both simple and complex drive applications. It undertakes control and process functions in conjunction with inverter technology, and has thus evolved into the intelligent geared motor.

2. The Geared Motor in Everyday Use

Properties of the Geared Motor

The flexibility of the geared motor means it can be used in a wide range of applications in all aspects of daily life. Sometimes, it can even be used where you wouldn’t imagine a geared motor would be responsible for the movement of a machine. The following examples indicate a few applications which exploit the most important properties of the geared motor:

- Robust, compact structure
- Reliability
- Reasonable price

Directional Antenna Drive

The requirements: A directional antenna drive has to satisfy very demanding requirements. The operator wants absolutely reliable operation and permanent serviceability no matter what the weather conditions, e.g. heat, rain, frost – even after months of standing unused. It must be possible to position the directional antenna (Fig.5) precisely and such that it does not move out of position. In addition, the mass of the antenna may double due to icing. On top of all this, wind acting on the antenna can exert very high transverse forces.

![Fig. 5 - Directional antenna](image)
The solution: The multi-stage helical geared motor with a pole-changing AC asynchronous motor, mechanical brake and flywheel fan as additional flywheel mass.

A multi-stage gear unit is selected so that low output speeds can be achieved. The pole-changing motor permits different speeds for rapid slewing and moving to final position accurately. The brake is only used as a holding brake, because the combination of the high inherent friction of the directional antenna system and the low speed of the drive permits exact positioning. The flywheel fan on the motor ensures jolt-free starting and a smooth transition between speeds. The drive combination represents a simple and reliable unit.

Drives in the Beverage Industry

The requirements: It takes a lot of individual processing steps before a new crate of drinks arrives in the shop. In the bottling company, the used bottles have to be taken out of their crates, cleaned and refilled. Once the stoppers have been fitted, the bottles are given new labels, packed into crates and stacked on pallets for dispatch. There are long transport distances to be overcome between the starting and finishing points in the production sequence. Bottles are singled out and put into packs as required. Manual handling would be unable to cope with the high volume output and precision processing demanded nowadays.

The solution: A large number of geared motors are used for movement, whether in the individual processing machines or for transport from one to the next (Fig. 6). More than 100 helical-worm, helical-bevel and helical geared motors ensure that production runs smoothly. Geared motors with variable drive speeds are used alongside constant-speed drives with a specified fixed transport speed. Frequency inverters make it possible to adapt the working procedures as required when there is a change of product. Dynamically switched geared motors are operated using field-oriented control loops – they position the labels at exactly the right place on the bottles.

Fig. 6 – Pallet attacker and unstacker for 150 barrels/hour

In some cases, the drives are exposed to extreme ambient conditions. They have to function whether in the wet or dry area. Also, the use of cleaning agents must not damage the geared motor. Special anticorrosive paint offers protection against the aggressive environment. Temperature sensors installed in the electric motor protect the drive against thermal load. Drive units for vertical motion are equipped with a mechanical brake to provide the degree of safety required for stacking pallets.

The long-term performance and long service life offered by geared motors are prerequisites for reliable, productive operation of the system.
Drives in the Automotive Industry

The requirements: The work areas in an automotive plant are rigidly structured. The “body shop” is where the body is built, while the body-in-white is painted with environmentally friendly, water-soluble paint in the “paint-shop”. It is a special moment when body and engine are brought together on the assembly line. Vehicles are manufactured according to individual customer requirements throughout the entire production process. The level of automation achieved in a modern production facility enables 800 vehicles to be manufactured every day. Conveyor systems of various kinds – roller tracks, overhead trolley systems, floor conveyors and lifts – transport the units through the various processing zones. Subassemblies and individual parts are brought to the assembly line just in time. Welding, painting and the installation of seats, windows and doors take place largely automatically.

The solution: More than 2500 geared motors of various types ensure movements take place at just the right time in all areas of the plant (Fig. 7). The majority of drives, in the power range between 0.25 and 11 KW, is equipped with 4-pole AC geared motors powered directly from the power supply system. More than 300 frequency inverters are used in applications with variable speeds. However, pole-changing geared motors are used as well. These drives permit fast and slow movement with direct power supply operation. Fast movement is achieved with a low pole count while slow motion involves switching in the winding with a high number of poles. This operating mode is used for simple positioning with proximity switches.

3. Modular Geared Motors

The previous chapter contained only a brief selection of the many possible geared motor application. This broad spectrum of applications makes it practically impossible to manufacture geared motors from specially fabricated individual components. This would be very expensive and involve long delivery times. This is why SEW and the other most important geared motors suppliers have the modular concept, enabling the individual components of the motor and gear unit to be selected and combined into a geared motor.

Fig. 7 – Scissor lift for car bodies
Combination of Individual Components

The objective of a modular concept is to enable as few components as possible to be combined into as many final products as possible. Modern technology uses modular concepts in an extremely wide range of areas:

- The term “modular” is used in machine tool construction when subassemblies can be mounted on different types or sizes of machines.
- The term “motor module” is used in the automotive industry when motors of the same type can be installed in different models of cars.
- Subassemblies (printed circuit boards) are integrated in various electronic devices thereby forming a modular unit.

When transferred to the geared motor, the modular unit principle means that motors, gear units and mount-on components of various types and different sizes can be combined with each other (Fig 8).

Motor Types

The motor in this case may be designed as:
- AC asynchronous motor
- DC motor
- Asynchronous or synchronous servomotor

Gear Unit Types

The gear units most frequently mounted on it are:
- Helical gear units – also as parallel-shaft designs
- Helical-bevel gear units
- Helical-worm gear units
- Planetary gear units.
These combinations represent “classic” geared motors. There are also requirements in which an additional module is inserted between the motor and gear unit:

- Variable-speed gear unit for changing speeds
- Universal adapter, e.g. torque limiting couplings
- Helical gear unit as a primary gear unit for especially low output speeds.

The considerations below show what possible combinations are offered by a modular concept, taking the example of a helical geared motor comprising a helical gear unit and an AC asynchronous motor. The same thing applies to combinations of other gear units and motor types. According to an IEC standard, the sizes of AC asynchronous motors are classified according to the axis height of the shaft (Fig. 9).

![Fig. 9 – Definition of electric motor sizes](image)

The SEW-EURODRIVE series incorporates 13 axis heights from 63 to 280 mm, with power of the motor increasing as the size increases (Fig. 10).

![Fig. 10 – Different sizes of AC asynchronous motors](image)

Addicional power steps can be achieved by having different lengths, which means that more than 200 different motor power levels are avalable for mounting on one gear unit (Table 1).

![Table 1 – Power increments of AC asynchronous motors](image)
The gear units are also graded by size. The designations for the sizes are not standardized in this case; they are used at the manufacturer's discretion. Figure 11 shows four representatives of a helical gear unit series containing a total of 13 sizes. Gear units of the same type but a different size have a similar geometrical structure.

![Fig. 11 – Different sizes of helical geared motors with different power ratings (lower and upper power range)](image)

The transmitted torque increases as the size increases, just as with the power of the AC asynchronous motor. Figure 12 illustrates the correlation between gear unit size and output torque.

![Fig. 12 – The amount of torque which can be transmitted rises in the line with the size of the gear unit](image)

The modular gear unit system makes it possible to install different gears into the same housing, which means that 30 to 40 different ratios between i approx. = 4 and i approx. =200 are possible for each gear unit size.

In theory, geared motors can be assembled from all available motors and gear units (Fig. 13). In practice, however, the manufacturers try to use the performance of the geared motor to optimum effect, and this means the range of combinations is somewhat restricted. For example:

- Combining an excessively large motor with a small gear unit overloads the gear unit.
- Combining an excessively small motor with a large gear unit does not utilize the full capability of the gear unit.

![Fig. 13 – Size 97 helical geared motor combined with size 80 and 160 motors](image)
Gear units of any one size can be sensibly combined with four to six different motor sizes. Together with the different ratios, this gives about 150 geared motor combinations for each size of gear unit. Taking the pole-changing motor into consideration will result in about 10 000 geared motor combinations with 13 gear unit sizes. By considering all the options presented in Figure 8 (see pages ?) the modular concept permits well over one million geared motors to be assembled for every use.

4. Gear Units

Converter for Torque and Speed

The gear unit, in its function as a converter of torque and speed, is the central component in the geared motor. Depending on the direction of the power flow, gear units are called coaxial or parallel-shaft gear units and right-angle gear units.

In the case of coaxial and parallel-shaft gear units the input and output shaft are located in the same plane – the power flow is in a straight line. With right-angle gear units, the input and output shafts are located perpendicular to one another. The power flow is vectored at a right angle (Fig. 14).

Fig. 14 – Force vectors in the most important types of gear unit

Coaxial and Parallel-shaft Gear Units

Gear pairings, referred to as the gear ratios, transmit power from the input end to the output end. Helical gears play the major role as the most important positive force transmission elements used in engineering. Helical gears are usually produced with involute gearing, since this makes it possible to manufacture them in reliable and low-cost processes using uncomplicated tools. As a result, helical gear units containing only helical gear ratios represent the most frequently encountered gear unit. The usual configuration has two or three gear stages in one housing and permits a space-saving layout. As a result, the entire drive can be narrow and low height (Fig. 15). The simple and robust construction of the helical gear unit means it meets the requirements of most applications.

Fig. 15 – Helical geared motor
In parallel-shaft helical gear units, the input and output shafts are parallel to each other. This makes the entire drive short and narrow, and explains why these gear units are predominantly used where little space is available (Fig. 16). In the parallel-shaft arrangement, it is an advantage to design the output shaft as a hollow shaft. This advantage comes into play in travel drives, because power can be transmitted to both drive wheels synchronously using an axle inserted within the hollow shaft.

![Parallell-shaft helical geared motor](image)

**Fig. 16 – Parallell-shaft helical geared motor**

**Planetary Gear Units**

Planetary gear units are epicyclic gear units. Three or more planet gears rotate about the central sun gear (Fig 17). The input and output shafts of these very compact coaxial gear units rotate in the same direction.

![Functional principle of planetary gear units](image)

**Fig. 17 – Functional principle of planetary gear units**

Depending on their use, planetary gear units are referred to as:

- *Precision Planetary Gear Units*, e.g. for dynamic handling machines requiring exact positioning.
- *Industrial Planetary Gear Units*, e.g. for large mixers

Precision planetary gear units are characterized by a high torsional rigidity and low circumferential backlash (Fig. 18).

![Precision planetary geared motor](image)

**Fig. 18 – Precision planetary geared motor**
Industrial planetary gear units have a high power-to-weight ratio and can be used for high torques. The SEW-EURODRIVE Q Series covers a torque range from 25,000 up to 1,000,000 de KNm (Fig. 19).

Right-angle Gear Units

In many applications, only right-angle gear units can be optimally integrated into the plant or the machine. Complicated gearing has to be used for right-angle gear units in order to vector the power flow at a right angle. The most important gearing types are:

- SPIROPLAN gearing
- Worm gearing
- Bevel gearing

Either hollow shafts or solid shafts can be used as drive shafts in these right-angle gear units. Applications involving low drive power levels and ratios up to $i = 75$ can be achieved at a reasonable cost using the single-stage SPIROPLAN gear unit (Fig. 19). In these gear units, the position of the pinion in relation to the gear lies between the two extremes represented by bevel and worm gearing.

Helical worm gear units can be used to advantage if the gear unit is also expected to offer good vibration damping properties (Fig. 21).
It is better to use helical-bevel gear units for large drives in which power loss plays a role. This because helical-worm gear units are less efficient than helical-bevel gear units – depending on the ratio (Fig. 22).

Helical-worm and helical-bevel gear units are largely equivalent in the medium power range. It should be noted that helical-worm gear units are subject to natural wear when they operate under high loads.
Helical-worm gear units with a high gear ratio have a static self-locking effect. Occasionally, this feature is used as an additional safety brake.

Table 2 shows a comparison between the most important types of gear units.

<table>
<thead>
<tr>
<th>Gear unit type</th>
<th>Helical</th>
<th>Parallel</th>
<th>Planetary</th>
<th>Bevel</th>
<th>Worm</th>
<th>SPIROPLAN(^0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEW abbreviation</td>
<td>R</td>
<td>F</td>
<td>PSF</td>
<td>K</td>
<td>S</td>
<td>W</td>
</tr>
<tr>
<td>Power flow</td>
<td>Straight-lined</td>
<td>Right-angled</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. torque [Nm]</td>
<td>16,000</td>
<td>18,000</td>
<td>3200</td>
<td>50,000</td>
<td>4000</td>
<td>90</td>
</tr>
<tr>
<td>2nd shaft extension</td>
<td>–</td>
<td>Possible</td>
<td>–</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>Output hollow shaft</td>
<td>–</td>
<td>Possible</td>
<td>–</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>No. of stages</td>
<td>2/3</td>
<td>2/3</td>
<td>1/2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Max. ratio per stage</td>
<td>6.5</td>
<td>6.7</td>
<td>10</td>
<td>4.2</td>
<td>42</td>
<td>78</td>
</tr>
<tr>
<td>Min. ratio per stage</td>
<td>1.5</td>
<td>1.5</td>
<td>4</td>
<td>1.4</td>
<td>5.5</td>
<td>8.2</td>
</tr>
<tr>
<td>Ratio range (without multi-stage gear unit)</td>
<td>3.4 – 269.7</td>
<td>3.8 – 281.7</td>
<td>4 – 100</td>
<td>5.4 – 197.4</td>
<td>6.8 – 288</td>
<td>8.2 – 75</td>
</tr>
<tr>
<td>Efficiency</td>
<td>97%</td>
<td>97%</td>
<td>98%</td>
<td>96%</td>
<td>40–93%</td>
<td>45–90%</td>
</tr>
<tr>
<td>As 4-pole geared motor</td>
<td>Max. input power in kW</td>
<td>160</td>
<td>160</td>
<td>22</td>
<td>200</td>
<td>22</td>
</tr>
<tr>
<td>Lowest speed in rpm (as multi-stage gear unit)</td>
<td>0.05</td>
<td>0.18</td>
<td>14</td>
<td>0.11</td>
<td>0.13</td>
<td>18</td>
</tr>
<tr>
<td>Highest speed in rpm (2-stage gear unit)</td>
<td>418</td>
<td>246</td>
<td>350</td>
<td>224</td>
<td>221</td>
<td>168</td>
</tr>
</tbody>
</table>

Table 2 – Comparison between the most important gear unit types

**Mechanical Variable-speed Gear Units**

Many drive engineering applications require a constant speed and can be accomplished by using a gear unit with a fixed reduction ratio. However, there are other applications in which the speed of the drive must be infinitely variable, for example to adapt the speed of conveyor belts to different processing sequences. Mechanical variable-speed geared motors have retained their place in the drive engineering arsenal despite the immense progress made in the field of electronically controlled drives.

The wide V-belt gear unit permits step-down ratios of up to \(i = 1:3\), as well as step-up ratios of up to \(i = 1:2.7\). The effective running diameter of the V-belt on the variable driving sheave is altered by changing the axial position of the variable sheaves. The running diameter on the variable driven sheave alters by an equivalent amount. The center distance between both belt sheaves remains the same (Fig. 23).

![Fig. 23 – Wide V-belt variable speed geared motor](image-url)

The friction disk gear unit represents another possibility of varying the speed mechanically. A friction ring made from a suitable nonmetallic material is mounted on the output shaft. A spring presses the ring against the drive disk which is made of steel. The drive disk is mounted on the drive motor shaft. It is
guided against the friction ring using the adjustment spindle. The effective radius are thus varied and, with them, the gear ratio. This principle permits step-down ratios of up to $i = 3:1$, as well as step-up ratios of up to $i = 1:1.6$ (Fig 24).

![Friction disc variable speed geared motor](image)

**Fig. 24 – Friction disc variable speed geared motor**

With both types of variable speed gear unit, the speed can be set manually, hydraulically or using an electric auxiliary drive.

### 5. Gear Unit Design

The gear unit designer has to consider the following points before a gear unit is able to undertake its function in a machine:

- Gear case
- Gears
- Shafts
- Bearings
- Lubrification and Seals

#### Gearcase

Various factors influence the design and shape of the gearcase:

- The strength of the housing to resist deformation and vibration
- Sealing the housing
- The number of gear stages installed
- Production processes
- Assembly requirements
- Housing variants

Gearcases (gear unit housings) are predominantly made from gray-cast iron GG20. Gray-cast iron is torsionally rigid and also does not vibrate even during machining. This means the housing can be machined efficiently and to accurate dimensions in one chucking operation. The good sliding properties of GG20 make it easier to press anti-friction bearings into bores provided for them.

Housings have internal reinforcements ribs or else a middle wall is integrated into the casting. This also reduces noise output due to vibration.

Aluminium is frequently used as a material for the housing of smaller gear units. Die-cast aluminium offers similar ease of machining but weighs much less. These “lightweight” gear units are particularly advantageous for drive units mounted on moving components. Modern tools such as finite element
methods (FEM) are used for calculating the design of housings and gears. In this way, the shape can be optimized (Fig. 25).

![Load calculation for a gearcase using the finite element method (FEM)](image)

Ideally, gearcases are designed to accommodate the maximum number of gear stages intended for each type of gear unit. The size of the gear unit is ultimately determined by the size of the gears and shafts, i.e. by the maximum torque which can be transmitted.

The mounting position of the housing depends on the variants offered (Fig. 26):

- Foot-mounted housing (1)
- Flange-mounted housing (2)
- Foot/flange-mounted housing (3)
- Flange-mounted housing with extended flange (4)

![Various gearcases on helical gear units](image)

**Gears**

Gears are the most important components of a gear unit. Selecting the correct materials, machining processes and design criteria is extremely important for subsequent operation of the gear unit.

**Material**

Helical gears, bevel gears and worms used in gear units are generally manufactured from an alloyed case-hardening steel (16 MnCr 5 or 20 MoCr 4). The gear material is given an extremely strong, homogeneous structure by pre-forging the blanks. Bronze (SnBz 12) is used for the worm gear. It offers good sliding properties – even when there is insufficient lubrication. Helical-worm gear units are members of the family of rolling helical gear units in which constant sliding contact occurs between the tooth flanks of the worm and the worm gear.
Machining Processes

The forged blanks are processed to finished gears by milling and grinding of the gearing. Continuing developments in machine tools for gears are leading to a uniform production quality. In turn, this allows the properties of the materials to be exploited more effectively (Fig. 27). Theoretical calculation processes such as FEM make it possible to design the gears for given transmission torque to be smaller and thus to reduce the consumption of natural resources.

Fig. 27 – High-quality machining processes are the order of the day for gears exposed to high loads: the workroom of a CNC helical gear grinding machine

Principal Steps in Gear Design

The principal steps in gear units design are:

1. Define the required maximum output torque of the gear unit
   This also roughly establishes the center distance between the shafts, since they are proportional to the torque.

2. Specify the required overall range and ratio steps $\varphi$
   In practice, ratios between $i_{\text{min}} \approx 4$ and $i_{\text{max}} \approx 200$ are required. $\varphi \approx 1.2$ is a sufficiently closely spaced value for the minimum graduation between two successive ratios. As a result, the sequence of ratios of a gear unit might be something like this:

   \[
   \begin{align*}
   i_{\text{min}} &= 5 \\
   i_2 &= \varphi \cdot i_1 = 6 \\
   i_3 &= \varphi \cdot i_2 = 7.2 \\
   ... \\
   i_{n-1} &= 159.74 \\
   i_{\text{max}} &= 191.69 \\
   \end{align*}
   \]

   In turn, these overall ratios are the product of the ratios of the individual gear stages which are derived from the ratio between the numbers of teeth:

   \[
   i_{\text{tot}} = (Z_2/Z_1) \cdot (Z_4/Z_3) \cdot (Z_6/Z_5) \cdot \ldots \cdot (Z_{2m}/Z_{2m-1})
   \]

   $m$ Number of gear stages

3. Define the number of gear stages
   In practice, 2- and 3-stage units in the same housing have proven to be a good compromise (Fig. 28).
4. **Restrict the number of teeth**

Where gears have very few teeth, this leads to what is referred to as an “undercut” at the tooth root. This represents a risk of tooth breakage under full load. On the other hand, gears with lots of teeth take a long time to machine. As a result, a range $11 < z < 118$ is adhered to for the number of teeth. A further restriction derives from the requirement that the number of teeth in a gear pair must not share a common divisor: no common divisor means different teeth are always in mesh, so gearing deviations have less of an effect.

5. **Calculate possible number of teeth**

The possible number of teeth is calculated with regard to the boundary conditions in steps 1 to 4. The result serves as the basis for the subsequent process of determining the gear geometry.

6. **Determine the gear geometry**

Geometric values such as gear diameter, tooth width, hub thickness, etc. are defined on the basis of experience. The availability of tools and machine tools is the factor in these considerations.

7. **Calculate safety factors**

Given the load specified in point 1, the next step for each gear pair is to calculate the tooth root safety factor against tooth breakage and the tooth flank safety factor against pitting. This is done on the basis of DIN 3990. Provided that the calculation results are within the permitted range, the gear pair is accepted and the next pairing is then checked. Either the gear geometry has to be corrected or even the number of teeth altered if the permitted limits are exceeded.

This iterative sequence results in the matrix shown in Table 3. The internal components of the new gear unit have been specified.

### Table 3 – Ratios and gear pairings in a fictitious helical gear unit

<table>
<thead>
<tr>
<th>$i_{in}$</th>
<th>$i_{1}$</th>
<th>$i_{2}/i_{1}$</th>
<th>$z_1$</th>
<th>$i_3$</th>
<th>$i_4$/$i_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>238.49</td>
<td>5.94</td>
<td>163/95</td>
<td>4.47</td>
<td>179/93</td>
<td>7.25</td>
</tr>
<tr>
<td>221.61</td>
<td>5.08</td>
<td>125/11</td>
<td>4.20</td>
<td>159/93</td>
<td>7.04</td>
</tr>
<tr>
<td>168.98</td>
<td>4.29</td>
<td>21/09</td>
<td>3.93</td>
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**Shafts**
The shafts in a gear are used for mounting the gears – usually with a keyed connection – and connecting the individual gear stages with each other. The input shaft is connected to the motor while the output shaft is connected to the driven machine.

The shafts are exposed to external forces from the driven machine and reaction forces from the gears. As a result, the shafts must be checked for compliance with safety values and they must be large enough to afford the necessary strength. Manufacturers who are concerned with quality manufacture gear unit shafts exclusively from unalloyed C45 steel. The material has to regard to shaft strength, fatigue strength under reversed bending stresses and impact toughness. Usually material used is C45 or 42CrMo4V for bigger units.

**Bearings**

Bearings enable the shafts to rotate in the housing with low friction. Forces acting on the shafts are transmitted to gear case via the bearings. Anti-friction bearings are the design of choice in gear unit construction. They are available as inexpensive standard parts and are easy to install. They develop their maximum load bearing capacity even at low speeds.

There are two different ways of arranging the gear, shaft and bearing (Fig.29): on both ends and in a cantilever mounting.

![Fig. 29 – Helical gear output stage with mounting points on both ends and in cantilever mounting](image)

Figure 29 also shows the forces acting on the output stage of a helical gear pair with the bearings of the final gear on both ends and in a cantilever mounting. The bearings are exposed to the tooth forces of the output stage gear pair (internal forces) and the external forces $F$. Given the same gearing and the same overall distance $l$, a shaft with bearings on both ends can accept a 40% higher load. Furthermore, the cantilever mounting results in poorer tooth meshing relationships because of the flexure of the shaft and the corresponding inclined position of the final gear. As a result, the final gears in gear units have bearings on both ends. This allows for a greater load acceptance as well as increasing the bearing service life.

**Lubrication and Seals**

Lubrication of a gear unit ensure that an oil film is maintained between the meshing tooth flanks, thereby preventing metal-on-metal contact as much as possible. Furthermore, the lubricant removes heat from friction to the surface of the housing and protects the unit from corrosion during operation and when not in use.

Oil is optimum lubricant from point of view of splash lubrication. The oil volume is selected so that the gears at the bottom fling the lubrication out of the oil bath into the meshing points of the top gears. The pressure is equalized via a breather valve at the highest point in the gearcase. Otherwise, the heat build-up would result in excessive pressure inside the gear unit. Gear units have oil lever and oil drain plugs to facilitate maintenance.

Sealing is a particularly important aspect of the design. This is because leaking lubricant contaminates the environment at the same time as endangering adequate lubrication of the gears and bearings. All seal points has to be equipped with high-quality, state-of-the-art oil seals, closing caps and gaskets.

The position of the oil seals can be seen in the exploded view (Fig 30).
6. Geared Motor Selection

Drive Unit for Vertical Motion

By way of example, this chapter describes the project planning process for a drive unit for vertical motion used in a storage and retrieval unit (Fig. 31).

The task: To automatically load pallets into and out of shelves in a warehouse. The loader head reaches the individual shelf bay through a combination of horizontal and vertical movements. Pallets are loaded by a telescopic drive.
Solution 1: Pole-changing geared motor operated directly from the power supply system, with movement to the required shelf level at high speed (low pole count) and positioning based on proximity switches to the greatest possible degree of accuracy at creep speed (high pole count). The drive unit for vertical motion is operated with a cyclic duration factor of 60% and a cycle time of one minute.

Solution 2: Single-speed 4-pole geared motor which can be operated in field-oriented mode at variable speeds using a frequency inverter (electronic controller). In contrast to solution 1, this task calls for a more dynamic load: a cyclic duration factor of 60% with a cycle time of 20 seconds.

System description for project planning
The empty weight of the load handling equipment of the vertical-motion drive unit is supplemented by the weight of fully loaded pallet at maximum load. A counterweight is connected via a drum in order to compensate for this total load. The required acceleration should be not exceeded in order to suppress vibration in the mechanism. Fine positioning takes place at minimum motor speed so that the unit can be positioned as accurately as possible with the proximity switches. The storage and retrieval unit is to be used in single-shift operation. The mechanical system necessitates the use of a right-angle gear unit. Refer to Table 4 for the data on the drive unit for vertical motion.

| Weight of load handling equipment | 300 kg |
| Weight of pallet                  | 500 kg |
| Counterweight                     | 550 kg |
| Output diameter                   | 120 mm |
| Max. velocity                     | 1.5 m/s |
| Required acceleration             | 0.6 m/s² |
| System efficiency                 | 90%    |
| Cyclic duration factor            | 60%    |
| Operations per hour (solution 1)  | 60 h⁻¹ |
| Operations per hour (solution 1)  | 180 h⁻¹ |

Table 4 – Data of the drive unit for vertical motion

Computer-aided Calculation
The calculations of the required motor power, acceleration values, start-up and braking distances as well as the permitted starting frequency are performed by a computer program (PRODRIVE Calculation Program).

The necessary static power demand is calculated for the operating statuses (Table 5) as follows.

| Without Load up | 3.1 kW regenerative |
| Without Load down | 4.3 kW motor       |
| With Load up    | 4.3 kW motor       |
| With Load down  | 3.1 kW regenerative |

Table 5 – Required static power demand
The calculation program presents a selection of 8/2-pole geared motors. The DV132M8/2-BM motor is selected. The next step is to plan a gear unit of sufficient size. The following criteria influence the selection:

- Operating time/day (here: 8h/day)
- Starts/hour
- Shocks arising

The diagram in Figure 32 is used to determine the service factor fs which takes account of all specified parameters.

Use of the pole-changing motor means there is a non-uniform load. The required service factor fsreq of 1.25 can be read off the diagram. A permitted service factor fsperm is assigned to each geared motor. This takes account of the limits of the materials used and the loads arising due to the output and the motor. Fsreq must be less than fsperm. A helical-bevel geared motor K57DDV132M8/2-BM with a gear unit reduction ratio of i = 11.92 and fsperm = 2.3 is selected for the drive unit for vertical motion.

The start-up acceleration of the planned motor varies between 0.8 m/s² (full load) and 3.2 m/s² (no load), depending on the load weight. Greater speed changes arise during the changeover from high speed to creep speed. These can be limited by using a smooth pole-change unit. A difference of ∆ 15 mm in the braking travel from creep speed also occurs and is dependent on the load. The requirements of the specifications for solution 1 are met with permitted 78 starts/hour.

Solution 2:
Specifying operation with frequency inverter results in the selection of geared motor K47DT100L4-BMG/TF. The ratio selected is i = 8.56. It is possible to select a much smaller drive than in solution 1, despite the fact that the requirements are more exacting in terms of shorter cycle times. This can only be achieved by using the field-oriented control mode without encoder, involving a frequency inverter (MOVIDRIVE, MOVITRAC). The defined acceleration of 0.8 m/s² reduces the strain on the mechanism and ensures that the motor operates under optimum dynamic load (uniform load, fsreq = 1.0; fsperm = 1.6). It is even possible to select a motor three sizes smaller, because the fast speed has been planned for the (base) frequency of 87 Hz. This means the motor is utilized at 1.73 times its power. In turn, the smaller motor size makes it possible to fit a smaller K47 gear unit – with consideration for fs.

A pleasant side-effect: The weight of the geared motor is 35% less than in solution 1. It is possible to deliberately influence the speed with which the holding brake is applied, because of the minimum frequency at which the motors are operated.

In solution 2, it is about one tenth of the speed of the pole-changing solution. This also reduces the braking work and the brake service life is boosted several times over.

This comparison reveals that project planning with a frequency inverter represents the better solution. Furthermore, the drive unit for vertical motion has fewer drive elements and takes less time assemble.
is also lighter and less expensive. In operation, the brake service life of frequency-inverter-controlled motors exceeds that of pole-changing motors many times over.

This also pays off in terms of follow-on costs for brake maintenance. It is clear that modern frequency inverters represent a valuable addition to the classic geared motor (Fig. 33).

![Fig. 33 – Frequency inverter with geared motor](image-url)