



# **Worm and Worm Wheel Design, Analysis, and Applications**

**An Online Continuing Education Course for Engineers**

**Course Number: M-2101**

**Credit: 2 Hours / 2 PDH / 2 CPD**

# Worm and Worm Wheel Design, Analysis, and Applications

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## 1. Objectives

- Familiarity with worm and worm wheel arrangement
- Advantages and disadvantages of worm gears
- Common worm and worm wheel nomenclatures for design calculations
- Gear classifications and worm gear design considerations
- Worm and worm wheel material and heat treatment process
- Design calculations and wear rate of worm and worm wheel
- Lubrication of worm and worm wheel
- Gear tooth failure mechanism
- Gear force and stress analysis
- Gear shaft and support bearing arrangement
- Cause and mitigation of gear noise

## 2. Introduction

This course is primarily devoted to the design and applications of worm gears and their analysis and properties. In this course, we will learn about the following aspects of bevel gear design and applications:

- Properties and characteristics of worm gears
- Nomenclatures of worm and worm gear sets as per AGMA
- The strength horsepower of worm gear sets
- Durability horsepower of worm gear sets
- Worm and worm wheel set design principles
- Worm and worm wheel teeth forces
- Design strength and wear rate considerations for gears in general
- Worm gear noise reductions

Proper use, strength calculations, prevention of excessive wear and pitting failures of gear teeth, gear materials, noise mitigation, lubrication methods, etc., have been recommended by the American Gear Manufacturers Association (AGMA) for a long time in the United States. Whenever required, AGMA practices have been mentioned in this course also. This course is a simplification of AGMA

recommended procedures, but important procedures have been simplified for practicing design engineers. The focus of this course has been to explain the behavior and application of worm gears for practicing engineers. Previous courses by this author explained similar procedures for spur, helical, and bevel gears. It is hard to imagine a production machinery or automobile transmission, without having a set of worm gears in it. Worm gear, like other types of gear, is a basic mechanical element for speed or torque transmission.

Worm and worm wheel sets are always necessary for any applications where a high gear ratio is required and when the shaft angle is 90 degrees, similar to bevel gears. Due to high load-carrying capacity at a lower speed, worm gear sets have been widely accepted in the industry. It is especially required when the shaft angle is 90 degrees. The teeth actions in the worm and worm wheel set consist of sliding and rolling actions. The worm is basically a screw shaft that rotates about its axis giving rotary motion to the worm wheel, whose output shaft is at a right angle to the worm input shaft. The sliding and rolling action of the teeth are similar to those of the rack and pinion set. Because of the screw action, the worm gear set is very quiet during operation and vibration free. The speed transmission is very smooth and shock-free. The worm can rotate back and forth, causing a smooth worm wheel rotation without any impact loading.

It is also a fact that even today, designers and manufacturers are constantly working to improve the gear design and manufacturing process to produce the best set of worm gears for various applications throughout the marine, earth-moving equipment, and machine tool industries. Gear design started way back in the Renaissance, and it is still going on as we speak.

Another very important advantage of a worm gear set is the high-speed ratio using a comparatively smaller space than other gear sets. To get a speed ratio of 50:1, other gear arrangements need two or three steps, whereas a worm gear can achieve that speed ratio in one step. In other words, worm gears have the smallest center distance with the highest speed ratio. Worm gears provide the highest possible speed reduction ratio using the lowest number of parts. Another specific advantage of a worm gear set is “self-locking” capability, i.e. worm wheel cannot drive a worm. The drive is unidirectional, i.e. worm can drive a worm wheel but not otherwise. When the lead angle of the worm is less than 5 degrees, the set is completely self-locking.

The worm wheel and worm shafts are at a right angle. For a 90-degree power transfer, the worm wheel and worm gear set take the minimum space with the self-locking arrangement. The worm is normally fixed with bearings on either side. These bearings take the axial thrust created during transmission. The worm wheel also has bearings at both ends. The only disadvantage of such gears is the fact the set creates comparatively large amount of heat due to teeth sliding action. Due to heat loss, worm gear set is comparatively less efficient than other gear sets. In order to reduce sliding friction, worm gears need an adequate amount of lubrication and cooling. The gear transmission box or housing should have high heat dissipation capability.

Such gear sets are normally hobbled, and such tooling is special. To take advantage of normally available tooling, available gears with standard ratios should be used to keep the cost down and reduce manufacturing time. Using standard gear available from gear manufacturers minimizes tooling costs greatly.

At this point, several types of gears and gear arrangements have been used in machine design. The author has also been associated with several such gearbox designs using spur, helical, bevel, and worm gears throughout his professional career over fifty years. The present course will reflect some of those experiences to help future designers design worm gears. The author, during his professional time, always depended on feedback and help from several gear manufacturers such as Philadelphia Gear Corporation, Arrow Gear Corporations, etc., to name a few. The contents of this course are very much guided by the inputs received from gear manufacturing companies with special comments, if necessary, from the author.

The contents have been put together to focus on two aspects: worm gear design principles and applications to be applied for machine tool industries and automobile applications. This course will contain force analysis, durability analysis, and noise reduction for gear applications and will also contain the methods to design worm gears for durability analysis techniques. The principles of gear nomenclatures and manufacturing will be covered in brief since designers are not required to know that, and the gear manufacturers will help the designers to that extent.

The size of standardly available gears for various ratios are available with the gear manufacturers, and they are manufacturer-specific. For example, in Philadelphia Gear Corporation, the maximum pitch diameter for the worm is 12 inches and 300 inches for the worm wheel; the minimum pitch diameter is  $\frac{1}{2}$  " and 2" for the worm and worm wheel, respectively. Maximum circular pitch is 4" for both types of gears. Maximum diametral pitch is 32" for both types of gears.

The simple shortcut formulas for designing worm gears will be demonstrated in this course. It will demonstrate the methods and processes that the author used to design worm gears and gearboxes for machine tools and earth-moving equipment applications only. For various applications, durability, strength, horsepower of worm gear sets, noise reduction, etc., are very pertinent requirements that designers have to satisfy. Worm gear design principles will be explained very briefly for a typical torque reducer that the author has applied in the indexing unit of a CNC turning center. Many of the contributors are very well-known in the gear industry, such as Darle Dudley, Elliott Buckingham, Gene Shipley, Prof. M F Spotts, and many others.

The contents should help the designers to a great extent in applying the design principles for their design efforts. Details of gear classifications as per the American Gear Manufacturers Association (AGMA) will be briefly explained as and when necessary. In general, designers need to know the design approach and design process for gears for machine tools and marine and automobile applications where durability, cost, and noise reduction are very important design considerations.

Applications, examples, and design discussions will be limited to helical gears, which are mostly used in machine tool applications. Worm gears are found to be very suitable and cost-effective when very high-speed reduction is necessary for applications such as heavy earth-moving equipment, ship engines, automobile transmission, etc.

### 3. Materials for Worm Wheel Set

Normally, the material for the worm shaft is different from that for the worm wheel. Hence, material selection is a very important consideration so that the sliding friction becomes minimum for the set. Too much friction coefficient will reduce the life of the set due to seizure caused by extreme heat and reduce its efficiency. Worm gears are normally manufactured using AGMA-recommended strength bronze material, and worm shafts are manufactured using AGMA-recommended steel.

Carburizing and worm shafts are normally hardened. When worm shafts are hardened using carburizing and hardening, SAE 4620 or 4320 is used. If the worm shaft is thoroughly hardened, SAE 4140 alloy steel is used. The primary reason for using a combination of steel and brass or bronze is that the wheel can be replaced relatively easily at a lower cost. The wheel wears out much faster than the worm shaft.

Lubrication of the gear set using extreme pressure oil lubricant (EP additives) creates different problems for the gear and worm shaft. EP additives create a film or coating in the mating surface of worm teeth, providing extra protection against wear. However, the sulfur contents in the EP oil create problems for the bronze wheel. EP additives break out due to high temperatures and create different conditions for the set. The sulfur and phosphorous in the EP additives create corrosion of the worm wheel teeth in a very short time. These additives protect the worm teeth due to oxidation of the steel material of the worm. Hence, proper selection of lubricants is very critical for the long life and functioning of the worm gears.

Since making a worm is much more costly and time-consuming, the design calls for earlier wear out of the worm wheel, which is made out of brass or bronze. It is much easier to replace the wheel than the worm. The wheel wears out much faster in any worm wheel design. Other than the steel-brass combination of materials, there are several other material combinations possible for worm gear designs, such as Steel worm and steel worm wheel, bronze worm and bronze worm wheel, brass worm and brass worm wheel, plastic wheel and gear, etc. These are fewer common combinations of material, but they are feasible. For steel-steel combinations, both gear and wheel wear out, and they need to be replaced at the same time. This is a very costly proposition and should be avoided for industrial applications.

Brass-Brass material combination is useful when load is not very high. Plastic materials for worms and wheels are used in case of extremely light loads, as found in robotics and machinery. For plastics, the selection of lubricants is very important since lubricants might attack the plastic material to reduce the life of the set. Depending on the rotational direction, the axial could be towards bearing or away from bearings. Proper bearing arrangements must be designed to resist axial loadings in both directions.

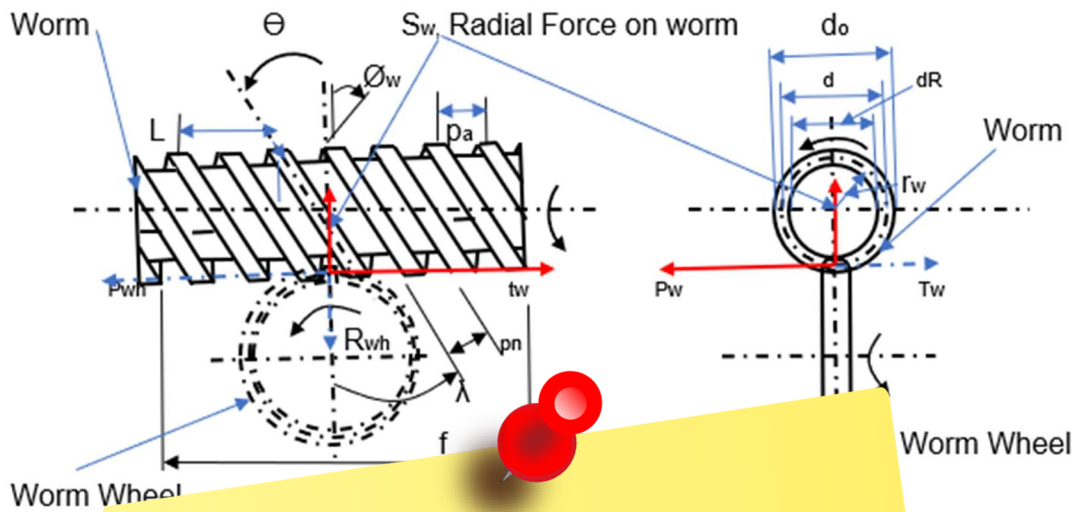
Normally, shim thicknesses and lapping points are punched or etched in the gear and pinion so that assembly can be made after the gears are dismantled for maintenance purposes.

#### 4. Lubrication and Lubricants for Worm Gear

For any speed reduction ratio higher than 20:1, a worm gear set is mostly used for industrial applications to save space, time, and cost. During power transfer, sliding and rolling occur between teeth, and more than one tooth remains in contact. The spiral angle of the worm creates sliding and is also responsible for high-speed reduction. This action is somewhat similar to the helical gear tooth action. This sliding action also wears out the teeth and reduces the life of the set. Due to high friction, pitch line velocity for worm gear applications is much lower than that for other possible gear arrangements. Pure rolling has much lower friction than sliding action. Sliding velocity is much higher than rolling velocity.

This sliding motion between teeth removes or squeezes out lubricant from the teeth's surfaces. Due to starving of lubrication in the critical area, teeth wear out much faster. Obviously, the wheel wears out faster because of its material, which has much less hardness than the steel worm. In industrial design, a portion of the worm wheel remains submerged in an oil pool and carries the lubricant to the teeth contact area due to rotation. This also helps the lubricant to call down. Since lubricant collects all the wear materials from teeth action, it needs to be replaced at a regular interval. In general, wear due to rolling action is much less than that for sliding action.

Lubricant viscosity is very important to create a non-separating or sticky oil film in the tooth contact areas. On the other hand, too much viscous lubricant creates higher friction. A balance has to be drawn for optimum performance. The primary purpose is to cool the gear and reduce sliding friction to minimize long-term wear of the set. The lubricant must have fatty additive content to be a good lubricant for the gear set. For worm gears, mineral based and with EP additives to withstand high contact pressure. Anti-wear oil is very suitable for such gears. From time to time, oil in the gearbox must be tested for contents and cleanliness. ISO 460 and 480 are commonly used industrial lubricants for worm gears.



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#### Worm Gear Nomenclature

A = addendum; C = throat thickness

d = Nominal pitch diameter

d<sub>R</sub> = Root Diameter of worm

D<sub>O</sub> = Outside Diameter of gear

F<sub>O</sub> = Effective Face width of gear

h<sub>k</sub> = Working Depth; h<sub>a</sub> = addendum

L = Lead of Worm;

n<sub>w</sub> = Number of Threads of worm

p<sub>x</sub> = Axial Pitch of worm, p<sub>n</sub> = Normal Pitch of worm

φ = Normal Pressure Angle

#### Calculation of Worm Gears and Worm: (See Fig. 1 also)

$$\text{Lead } L = n_w * p_x$$

$$\text{Root Diameter } d_R = d_o - 2 * h_t$$

$$\text{Outside Diameter } d_o = d + 2 * a$$

$$\text{Minimum Face width } f = 2 * ((0.5 * D_t^2) - (0.5 * D - a)^2)^{0.5}$$

$$\text{Lead Angle } \lambda = L / (3.14 * d)$$

$$\text{Normal Pitch } p_n = p_x * \text{Cos } \lambda$$

$$\text{Normal Pitch Diameter of Gear } D = 2 * C - d \text{ or } N_g * (p_x / 3.1416)$$