*Journal of Mechanical Engineering* *Vol 18(2), 111-124, 2021*

# Comparative Investigation of Worm Positions for Worm Gearbox Performance under No-Load Condition

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## ABSTRACT

*The Worm Gear drive is a gear arrangement where the worm shaft meshes with a worm wheel (gear). The worm shaft plays an important role in reduction ratio & efficiency. This worm shaft can be used at the top and the bottom in the gearbox. This technical research paper provides a comprehensive comparative evaluation of Input torque analysis & heating rate of lubricant inside the gearbox for two positions of the worm shaft in the worm gearbox under no-load condition. Worm shaft at the top and worm shaft at the bottom were assessed at variable speed (1000-1400 rpm), the different splashed volume of lubricant (1.5-2.7 liter), and variable temperature of lubricant (30-50 ºC). Input torque was measured with the help of a direct torque measurement technique. Similarly, the heating rate of the lubricant was also measured with a temperature sensor for both orientations of the worm shaft. Full factorial experiments were performed on a specially designed and fabricated worm gear test rig. The experiments showed that the input torque requirement for the worm at the bottom position is 20 -25% higher than the worm at the top position at an*

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ISSN 1823-5514, eISSN 2550-164X
Received for review: 2020-03-18
Accepted for publication: 2020-10-16
Published: 2021-01-15

*average speed. The heating rate remains almost the same for both orientations. This study aimed to find the suitable orientation of the worm shaft which reduces the power losses and increases efficiency.*

**Keywords:** *Worm gear; Torque analysis; Worm orientation; Heating rate; Power loss*

## Introduction

Worm Gear is used to transmit the motion and power from one shaft to another non-intersecting non-parallel shaft. The worm gear is used for limited space and a high reduction ratio. Worm gear consists of the main two parts, worm shaft, and worm wheel. The worm drives by its threads sliding into contact with the teeth of the worm wheel (gear). This constant sliding action generates heat due to friction and therefore adequate cooling and superior lubrication must be provided for gears [1].

Muminovic et al. [2] presented the results of an experimental method for determining the efficiency of worm gears. They also investigated the influence of lubricant type on the efficiency of worm gear. Mautner et al. [3] investigated the efficiency of worm gear by considering different gear ratios, worm wheel materials, lubricants, and contact patterns on efficiency and load-carrying capacity. They suggested that harden steel and copper-tin–bronze are the best material for worm shaft and worm wheel respectively to increase the efficiency. Magyar and Sauer [4] presented the calculation method to determine the efficiency of worm gear drives. This study showed how to increase the efficiency of worm gear drive by reducing the tooth friction power loss and reducing bearing power loss. Turci et al. [5] investigated the influence of center distance and reduction ratio on the efficiency of worm gear. They also showed the comparison of calculation of efficiency by various standards. Blaza et al. [6] worked on the influence of lubricant viscosity on the efficiency of worm gear. They concluded that the degree of efficiency is always higher for the high viscosity of the lubricant. Fontanari et al. [7] investigated the lubricated wear behavior of worm gear material. Many authors worked on the modification of worm gear geometry to increase the efficiency by increasing output [8]–[11].

The main aim of this work is to increase the efficiency of worm gear by considering various factors. Efficiency can be increased by increasing output power/torque or reducing input power/torque. Output power can be increased by reducing load-dependent losses while input power can be reduced by reducing non-load dependent losses. The non-load dependent losses are primarily related to viscous effects. These losses can be further subdivided into oil churning and windage losses that are the result of the interaction between the oil/air and the moving/rotating elements like gears and shafts, into pocketing/squeezing losses due to the pumping effect of the mating gears. Oil seal loss and bearing losses are part of non-load dependent losses. The non-load dependent losses are mainly dependent on input torque. The input torque may be reduced by considering various parameters such as lubricant type, lubricant viscosity, lubricant temperature tribological geometry, worm shaft position, and types of the worm shaft. The position of the worm shaft plays important role in worm gearbox performance [12]–[16].

Worm gears have an interesting property that no other gear set has: the worm shaft can easily turn the gear, but the gear cannot turn the worm shaft. This is because of the angle on the worm shaft. This feature is very important where a self-locking phenomenon is required. According to the orientation of worm shaft, it can be classified in mainly three categories that worm shaft at the top position, worm shaft at the bottom position, and worm shaft at the side position as shown in Figure 1. Similarly, according to the direction of rotation, it can be classified into the right-hand worm and the left-hand worm as shown in Figure 1. Among these, the worm shaft at the bottom and the worm shaft at the top were selected for the experiment. The aim was to investigate the effect of the orientation of the worm shaft on the input torque and heating rate of lubricant.

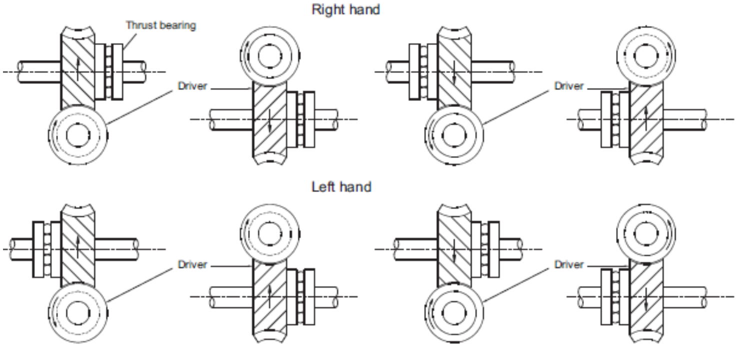


Figure 1: Classification of worm gear drive according to the position of worm shaft [17].

## Material and Methodology

The experimental studies were performed on a specially designed torque measurement test machine. The schematic representation of this developed test machine is given in Figure 2. The test machine is composed of a motor, torque sensor, temperature sensor, variable frequency drive (VFD), shaft, Bearings, couplings, testbed, and data collector.

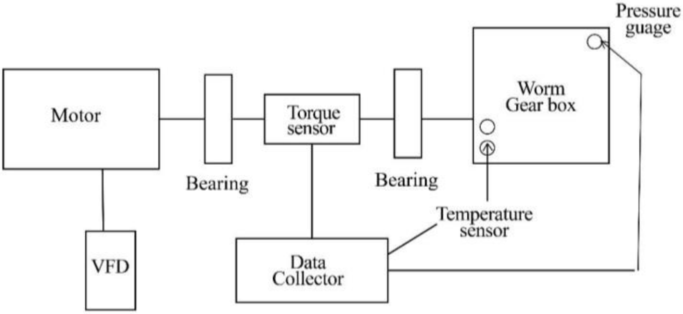
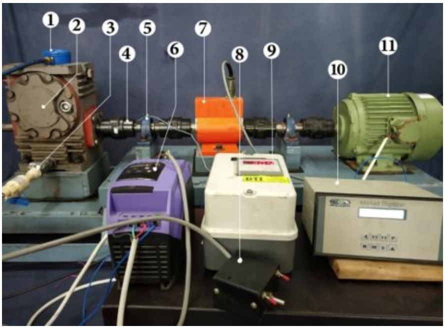


Figure 2: Schematic representation of the test machine for worm gear [18].

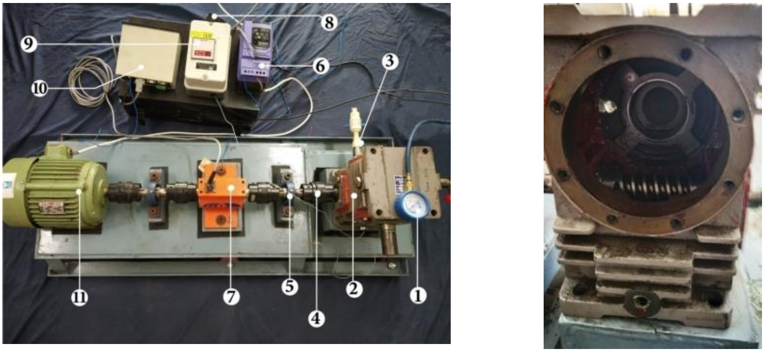
The test stand is built with an electric motor controlled by the variable frequency drive to enable the variation in rotational speed. The gearbox containing the test gear pair is connected to the motor through the shaft, torque sensor, and couplings. The gearbox is rigidly mounted at the end of the test-bed and similarly, the motor is mounted on the other end of the test-bed. The input torque of the test gear is measured with the torque sensor. The temperature of oil inside the gearbox and pressure of the air inside the gearbox can be measured with the help of a temperature sensor and pressure gauge respectively. This test rig is designed to perform the experiment based on the direct torque measurement technique. The same test rig is used for both orientations of the worm gearbox. The complete test rig with different views are shown in Figure 3(a) and (b). The selected test worm gearbox is shown in Figure 3(c) and its inside volume of the gearbox was kept constant (180 mm×180 mm×280 mm). In the same gearbox, the worm shaft can be used at the top and bottom positions.

The purpose of this study was to analyze the influence of the worm shaft of non-throated worm gearbox on input torque and heating rate of lubricant under the different speed, and different oil conditions. The range for control factors for various experiments was selected through various pilot experiments. The test matrix is given in Table 1.



(a)

1-Pressure Gauge,
2-Worm gearbox,
3-Provision for oil level indicator,
4-Jaw type coupling,
5-Foot mounted bearing,
6-Variable frequency drive (VFD),
7-Torque sensor,
8-VFD regulator,
9-Temperature indicator,
10-Digital controller for Torque sensor
11-AC motor



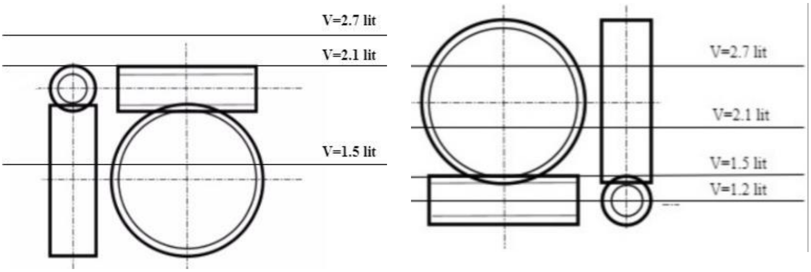
(b) (c)

Figure 3: Test machine to measure the input torque and heating rate of worm gearbox. (a) Front view of the test rig, (b) Top view of test rig (c) Detailed arrangement of test gearbox.

Table 1: Test matrix

| Control factors | Unit | Values |
|---|---|---|
| Speed of worm | rpm | 1000, 1200, 1400 |
| Oil volume | liter | 1.5, 2.1, 2.7 |
| Temperature | ºC | 30, 40, 50 |
| Orientation of worm | - | The worm at the top, worm at the bottom |

The speed of the driving shaft was selected as 1000 rpm minimum speed and 1400 rpm maximum speed [18]. Static oil levels were selected based on the capacity of the gearbox and worm gear manufacturer report [19]. The gearbox was operated at various lubricant volumes which are shown in Figure 4. The experiments were tested at three temperature levels of 30 ºC, 40 ºC and 50 ºC [18].



(a) Worm shaft at the top (b) Worm shaft at the bottom

Figure 4: Lubricant level of worm gearbox for the various position of the worm shaft.

When worm gear operated at a 1.5-liter volume only the worm is fully immersed in lubricant and it operated at 2.7-liter volume both worm shaft and worm wheel are almost immersed in lubricant for worm at the bottom position as shown in Figure 4(b). For the worm at the top position, Volume 2.1 liter immersed both gears fully in lubricant as shown in Figure 4(a). For this experiment as a test gearbox, a single start worm gearbox was selected. The details of the selected worm gearbox are given in Table 2.

Table 2: Worm gear geometric properties

| Gear | No. of teeth | Material | Module (mm) | Pressure angle | Center distance (mm) | Outer diameter (mm) | Reduction ratio |
|---|---|---|---|---|---|---|---|
| Worm Wheel | 30 | CuSn12 | 3 | 20 | 75 | 132 | 30:1 |
| Worm Shaft | Single start | 16MnCr5 | | | | 40 | |

The most commonly used lubricant for worm gears is compounded mineral oils and synthetics oil. The synthetic lubricant was select for this experiment, detailed properties of the lubricant are given in Table 3.

Table 3: Lubricant properties

| Sr. No | Name of oil | Kinematic Viscosity (cSt) @ 40 ºC | Kinematic Viscosity (cSt) @ 100 ºC | Viscosity Index | Density (Kg/m3) @ 15 ºC |
|---|---|---|---|---|---|
| 1 | Synthetic oil | 330 | 35.50 | 162 | 790 |

Before any test, the machine was operated for at least 30 minutes with heated lubricant in circulation to bring the entire gearbox up to the steady-state test temperature. The experiments were operated from 2 ºC to 5 ºC before the starting temperature to avoid the previous experiment effect. The test machine was operated with different positions of the worm shaft at various controlling factors as per the test matrix. The input torque and temperature of the lubricant were measured at every interval of time.

## Results and Discussion

According to the orientation of a worm, it can be classified in mainly three categories: worm on the top, worm on the bottom, and worm on the side. Among these three categories, two categories were tested on the designed test rig, worm at the bottom and worm at the top. The experiment test was conducted for at least a prior 5 ºC temperature of the basic starting temperature of the test. Time was not bounded for the test but the test was going on till the desired temperature was reached. This test was designed to describe the influence of the orientation of the worm shaft on multiple responses: 1) influence of Position of worm shaft on input torque, and 2) influence of position of worm shaft on lubricant heating rate.

### Influence of worm orientation on input torque

The input torque at various operating conditions was recorded in the digital controller of the torque sensor. To investigate the effect of the position of the worm shaft on input torque, the input torque obtained from the experiments was plotted in the form of a graph. The influence of worm position on input torque at different volume for speed 1000 and temperature 40 ºC is shown in Figure 5. At 1.5-liter volume, there is no dragging of lubricant for worm at the top position therefore the input torque was very small. For the worm shaft at the bottom position at 1.5-liter volume, the worm shaft was fully immersed so there is dragging of lubricant therefore comparatively large input torque was noted [18]. Once the volume of lubricant increased to the next level, dragging of lubricant faced by the worm shaft at the top position so the gap in input torque between both positions was reduced. The worm shaft at the top position is better at the lower level of lubricant. The input torque for the worm shaft at the bottom is 24%, 8%, and 7% higher than the worm shaft at the top for lubricant volume 1.5 liter, 2.1 liter, and 2.7 liter respectively as shown in Figure 5. It shows that the lubricant volume/static head significantly affects the non-load-dependent losses, however, it hardly affects the load-dependent losses [21].

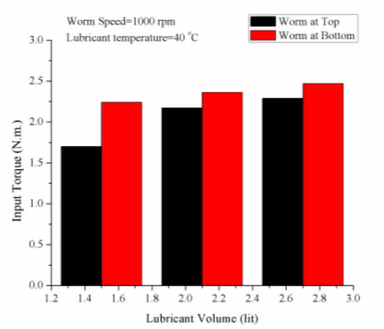


Figure 5: Influence of worm positions on input torque at different volume.

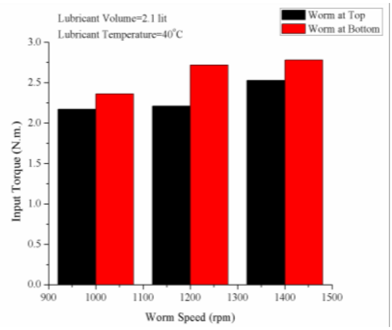
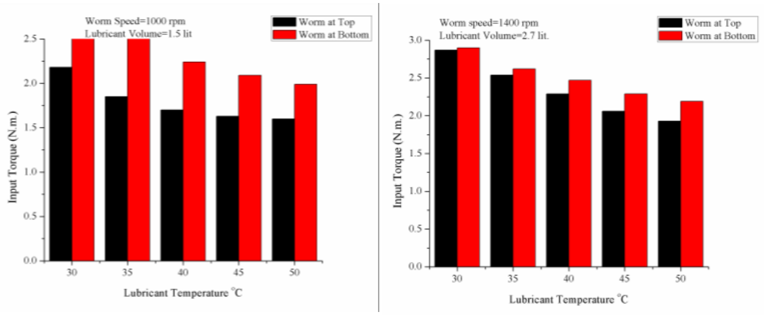


Figure 6: Influence of worm positions on input torque at a different speed.

The influence of worm position at various speeds is shown in Figure 6. As speed increases the input torque always increases for both positions, however, the difference is higher for worm at the bottom position due to higher dragging force comparatively at worm at the top position. At lower speed, the gap between input torques for both positions of the worm shaft is very small. As speed increases the gap of input torque for the worm at the top and the bottom position increased however, after a certain speed this gap again reduces. The input torque for the worm at the bottom position is 0.2 Nm, 0.5 Nm, and 0.25 Nm higher than the worm at the top position for worm speed 1000, 1200, and 1400 respectively. The theoretical reason behind it, When the worm shaft at the top, the least amount of oil is likely to be forced compared to the worm at the bottom [14]. It reduces the churning power loss.

Figure 7 shows the influence of worm position on input torque at different lubricant temperature. The temperature range is selected from 30 to 50 ºC. As temperature increases viscosity of lubricant goes down, this reduces the dragging force of lubricant [14]. Due to static head, dragging forces are high for worm shaft at the bottom and less for worm at the top so input torque for worm at top position is less for every temperature condition [18]. Input torque required for the bottom position of the worm shaft reduces as temperature increases, however, the gap was remained almost the same for temperature range from 30 ºC to 50 ºC. The constant gap suggests that there is no influence of the worm shaft position on input torque based on lubricant temperature.



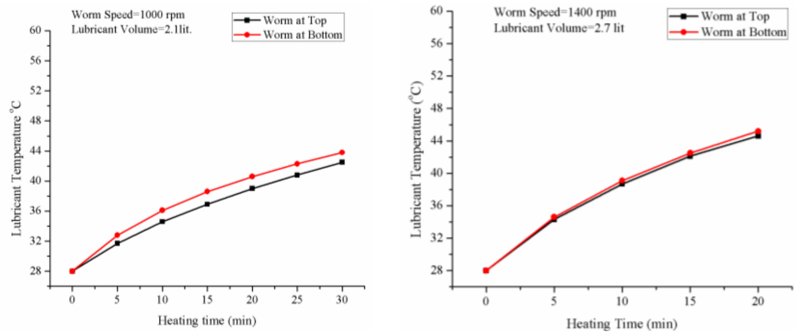
(a) 1.5 litre volume and 1000 rpm

(b) 2.7 litre volume and 1400 rpm

Figure 7: Influence of worm position on input torque at different temperature.

## Influence of worm orientation on heating rate of lubricant

Lubricant is not essential only for the friction of gear and bearing but it is also useful to dissipate the heat during the operating condition [18]. Figure 8(a) shows the heating rate of lubricant for both operating conditions at volume 2.1 liter and speed of worm 1000 rpm. The lubricant heating rate was observed based on time. The experiment was started at room temperature. This work aimed to compare the position of the worm shaft so only one lubricant was used as mentioned in Table 2.Theoretically if the lubricant is not sufficient, the heat generated due to friction and if lubricant is excessive, the heat generated due to dragging [20]. However, the aim was to select the best position of the worm shaft by considering the heating rate of lubricant and input torque. Figure 8(a) shows that there were good agreements for the heating rate between the orientations of the worm shaft. The average heating rate at 1000 rpm and 2.1-liter oil volume for the worm shaft at the bottom position is only 3% higher than the heating rate for the worm shaft at the top position. As speed and immersion depth increases, this gap is negligible as shown in Figure 8(b). The gap/difference of input torque or heating rate between both orientations shows the comparison and helps to select the better one. If the gap is minimum, it does not have much effect on power loss, in this situation anyone (either top position or bottom position) can be selected.



(a) (b)

Figure 8: Influence of heating rate at (a) Volume 2.1-liter and 1000 rpm (b) Volume 2.7-liter and 1400 rpm.

## Conclusion

The research tries to analyze the best position of the worm shaft in the worm gearbox at different speeds, lubricant level conditions, and lubricant temperature under no-load conditions. The experimental setup was specially developed for the research study. Various experiments were conducted with the worm shaft at the top position and the worm shaft at the bottom position. Input torque and heating rate of lubricant were noted and plotted to understand the variations concerning worm positions. With the increase in the volume of lubricant, gear gets more dragged which increases the input torque. At 1.5 liter volume, 23.31% higher input torque is required for the worm at the bottom position, similarly, 10.9% and 7.9% higher input torque is required at 2.1 liter and 2.7 liter volume for the worm at the bottom position compares to the worm at the top position. As volume increases the gap between input torque for both positions reduces. The worm at the top condition for lower volume is quite preferable. With the increase in the temperature of the lubricant, input torque reduces. As volume increases at the same speed heating rate of lubricant reduce and as speed increases at the same volume heating rate of lubricant increases. However, it was applicable for both conditions of the shaft so the Influence of the position of the worm shaft cannot be evaluated based on lubricant temperature only. With the increase in speed, higher input torque was noted for both positions of the worm shaft however increasing input rate is quite higher for the worm at the bottom position. For worm at bottom position at 1000 rpm 12% input torque is more compare to worm at the top position. Based on the speed, the worm shaft at the top position required less input torque compare to the worm at the bottom position. It is concluded that the worm shaft at the top position is more preferable to the bottom position for non-load dependent losses.

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