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Roller Screw and Threaded Chain Speed Reducer: An Experimental Evaluation

Filiberto Gutiérrez

Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico City, Mexico
Email: FGutierrezM@iingen.unam.mx

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Abstract

We are developing a speed reducer that can be considered a transformation of a worm gear reducer: the worm is replaced by an inverted roller screw, and the gear is replaced by a threaded chain drive. This configuration lessens wear, increases load capacity, and improves efficiency. The threaded chain consists of nut-shaped links. This paper presents the results of tests carried out on a prototype with a reduction ratio of 46.

Keywords

Speed Reducer, Inverted Roller Screw, Chain Drive, Threaded Chain Drive

1. Introduction

It is well known that the worm gear reducer has been improved by increasing the contact area between the worm and the gear. For this purpose, the worm was made concave to increase the number of its teeth in contact with the gear [1], and the width of the gear teeth was increased. The gear teeth were also made concave so that the worm and the gear partially wrap each other. Nevertheless, the number of teeth of both parts contacting each other is still limited. Furthermore, other improvements have been implemented to increase efficiency by replacing the sliding friction of the classical worm gear mechanism with the rolling friction of spherical balls [2] [3], or rollers [4] [5]. This research was conducted to evaluate the efficiency of a prototype based on a new concept of speed reducer using an inverted roller screw and a threaded chain. The innovative mechanism makes it possible to increase the contact area and, additionally, enables force transmission through rolling motion.

2. Description of the Roller Screw and Threaded Chain Speed Reducer

Compared to a worm gear reducer, the threaded chain has a larger contact surface with the inverted roller screw, Figure 1, which reduces the contact pressure between them, thus increasing load capacity and reducing wear. Using the inverted roller screw, Figure 2, as the drive screw means that the input power is transmitted to the threaded chain with minimal friction. The rolling contact increases efficiency and allows the unit to work in reverse as a speed amplifier. All of these are according to the concept described in Patent US 9,927,012 [6].

The threaded chain, Figure 3, is a power transmission chain consisting of two parallel endless roller chains with extended pins and a set of threaded bodies supported by these pins.

A threaded body, Figure 4, includes a threaded hole and four cylindrical grooves to accommodate the extended pins of the supporting roller chains. The threaded hole has a cut to prevent interference of the threaded body with the

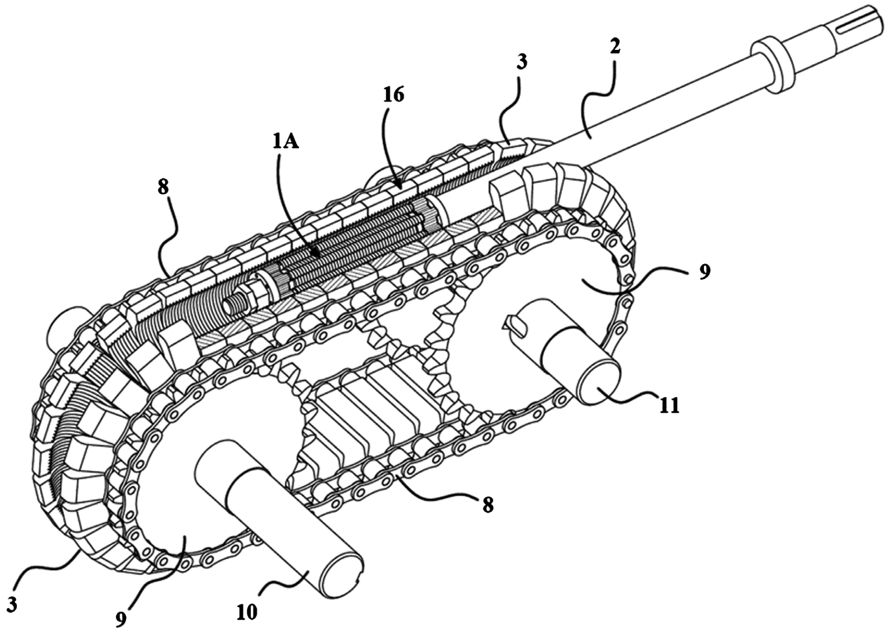

Figure 1. Schematic arrangement of the roller screw and threaded chain speed reducer, with a cutaway view to show the inverted roller screw.

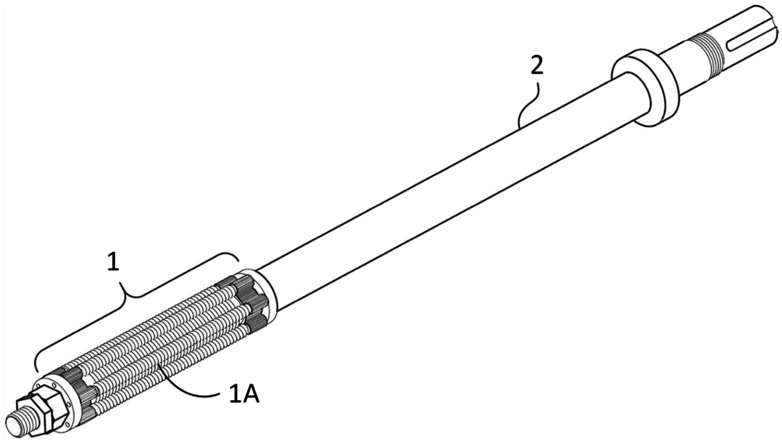

Figure 2. Inverted roller screw used to drive the threaded chain.

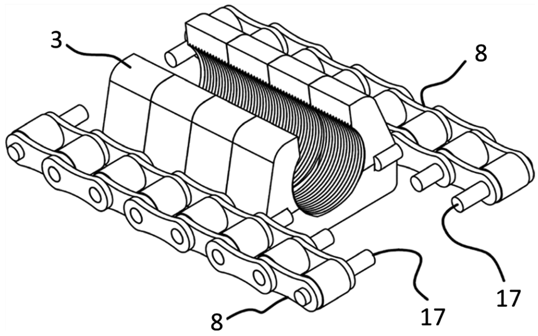

Figure 3. Threaded chain.

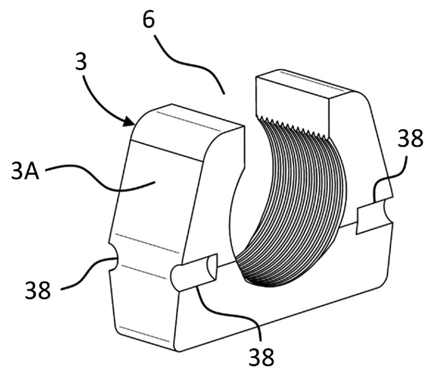

Figure 4. Threaded body.

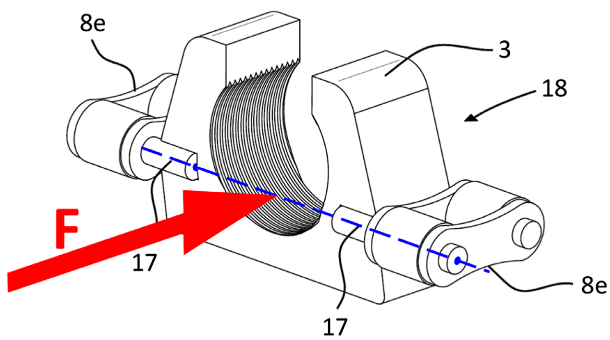

Figure 5. Link of the threaded chain.

shaft of the inverted roller screw.

Figure 5 shows a threaded chain link comprising a threaded body and two roller chain links provided with extended pins. These pins fit into the grooves of the threaded body and are positioned at the centroidal height of the threaded hole to avoid any tilting torque that could cause jamming when the roller screw applies force F. The extended pins support the threaded bodies and serve as pivots for these bodies when they lightly turn while entering and leaving the circular path imposed by the sprockets.

3. Working Prototype

In order to evaluate the practical behavior of a speed reducer designed according to the new reduction concept described above, a prototype with a reduction ratio of 46 was built and tested, **Figure 6**. The prototype comprises the following main parts:

- An inverted roller screw with 40.8 mm diameter, 12.7 mm lead, and ten threaded rollers 38.1 mm long; the roller screw shaft diameter is 25 mm.
- An endless threaded chain consisting of:

Two 80/ANSI endless roller chains (25.4 mm pitch) with extended pins; forty-two threaded bodies, 25.4 mm width, 39.7 mm threaded hole diameter, 12.7 mm lead, and six-start thread. Each threaded body weighs 0.412 kg.

The total weight of the threaded chain is 23.4 kg.

- Four sprockets with 23 teeth each and 25.4 mm pitch.
- Two sprocket shafts, 44.5 mm diameter.
- Four pillow block-bearing units for the sprocket shafts.
- Two angular contact thrust bearings for the inverted roller screw shaft.

The threaded rollers of the drive screw could be as long as the straight part of the threaded chain. However, a short commercial inverted roller screw was used in our prototype because it was readily available commercially. Such a roller screw has an efficiency of about 85% and is used in electromechanical linear actuators [7].

4. Tests Carried Out

Tests performed with the prototype operating as a speed reducer are described in the following. However, the device can also work as a speed amplifier, with an amplification ratio of 46. Because the threaded rollers of the drive screw used are much shorter than the straight portion of the threaded chain, no attempt was made to apply such a high input torque that would demonstrate the high torque

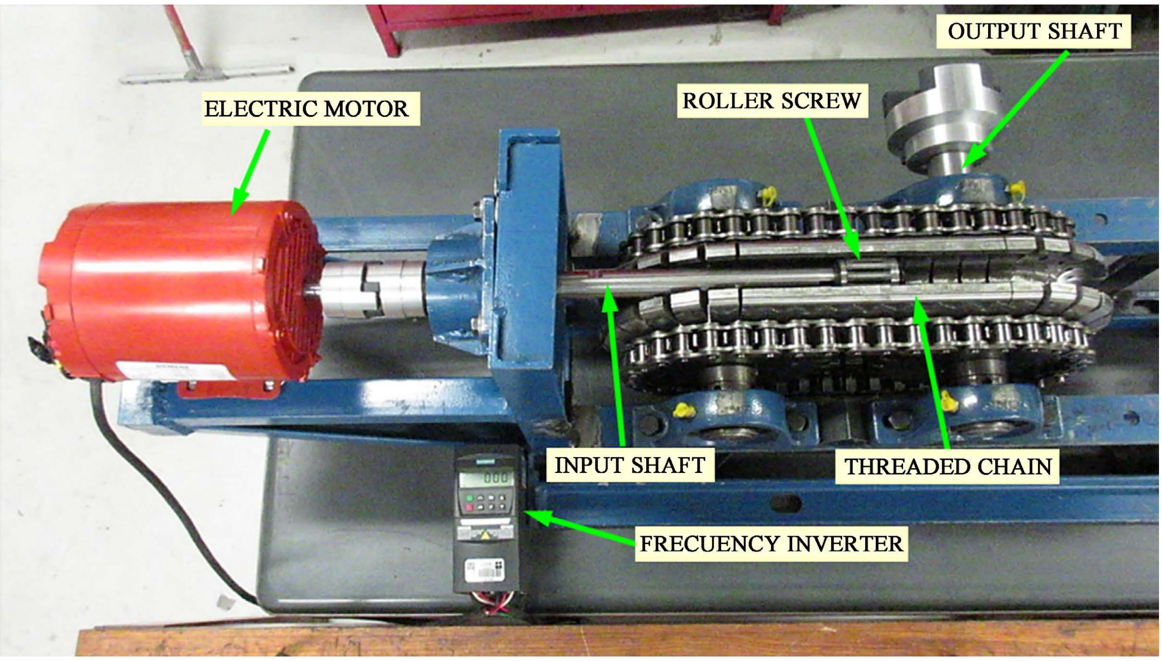

Figure 6. Prototype of the roller screw and threaded chain speed reducer.

capacity of the reducer. Only one-sixth of the straight portion of the threaded chain was used to transmit the input power.

Since we did not have an appropriate dynamometer to test the prototype at high output torque and low speed, we used a simple hoist to lift weights (Figure 7). The hoisting cable is wound around a drum whose shaft is supported by ball bearings and is driven directly by the output shaft of the speed reducer. The hoisting drum has a ratchet gear system to prevent the weight from falling when the motor stops. During testing, weights of 31, 63, 110, and 158 kg were hoisted. Lubrication was applied manually. The prototype was powered by an AC electric motor controlled by a frequency inverter.

The roller screw shaft is driven by an electric motor whose stator is floating, *i.e.*, it is mounted on bearings, but the stator rotation is impeded by an arm that presses a force transducer. The measured force is used to calculate the input torque. The output torque is calculated from the hoisted weight, the radius of the lifting drum, and the hoist efficiency. The rotational speed of the motor is measured

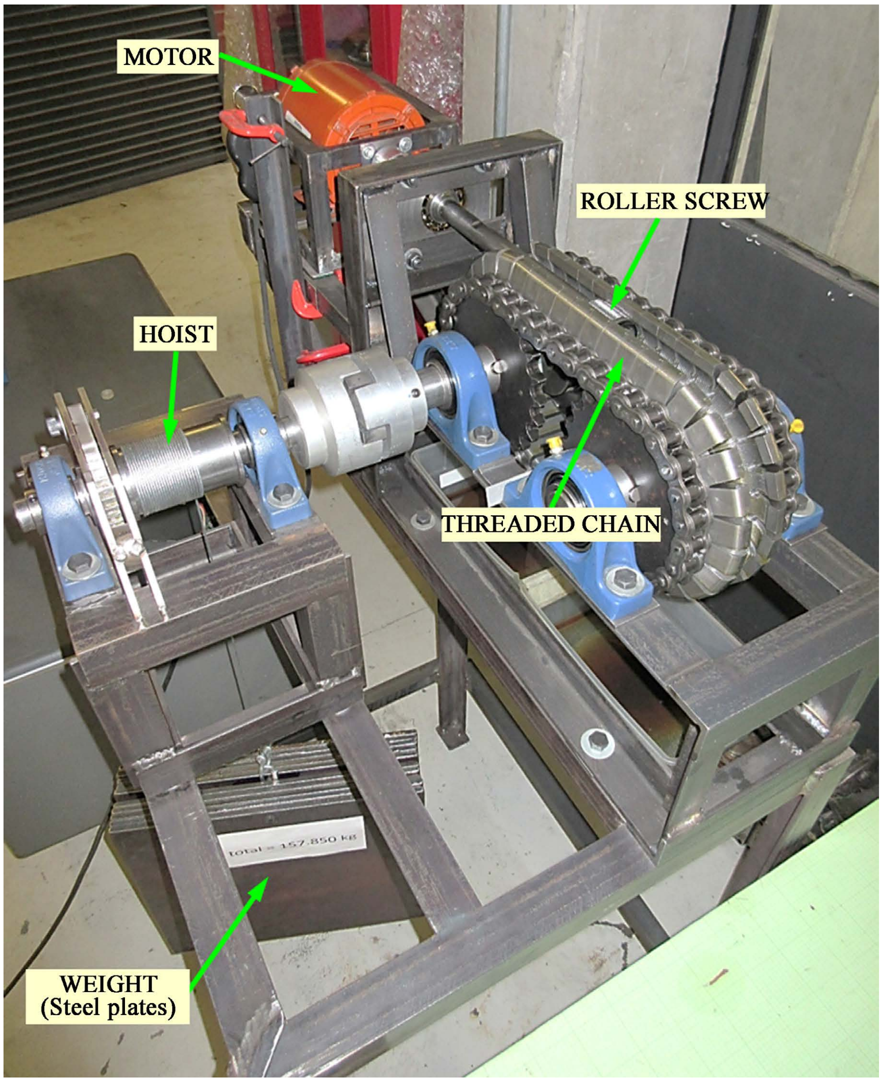

Figure 7. Experimental setup.

with an optical device.

During testing, the maximum input speed was restricted to 450 rpm due to the difficulty of starting to hoist the heavier weight while attempting to achieve higher rates. Such a limit was also established to avoid excessive noise and vibration levels.

5. Results

The results of the tests were analyzed according to the following considerations:

N—Rotational speed, (RPM);

r_{hoist}—Hoist drum radius, (meter);

R—Reduction ratio, (---);

T—Torque, (N-m);

W—Hoisted weight, (Newton);

η—Efficiency, (---).

The reduction ratio R of our speed reducer is determined by considering the lead of the roller screw, as well as the pitch and number of teeth of the output sprocket, as follows:

$$R = \frac{N_{\text{input}}}{N_{\text{output}}} = \frac{\left[\text{Number of teeth} \cdot \text{Pitch}\right]_{\textit{output sprocket}}}{\text{Lead of the roller screw}} = \frac{23 \times 25.4}{12.7} = 46 \tag{1}$$

The output torque of the reducer is obtained from the weight being lifted, the hoist drum radius, and the hoist efficiency:

$$T_{\text{output}} = \frac{W \cdot r_{\text{hoist}}}{\eta_{\text{hoist}}} \tag{2}$$

The mechanical efficiency of the reducer is calculated from the output power and the input power [8]:

$$\eta = \frac{\text{Power}_{\text{output}}}{\text{Power}_{\text{input}}} = \frac{T_{\text{output}} N_{\text{output}}}{T_{\text{input}} N_{\text{input}}} = \frac{1}{R} \frac{W \cdot r_{\text{hoist}}}{T_{\text{input}} \cdot \eta_{\text{hoist}}} \tag{3}$$

Figures 8-11 illustrate the test results; the plotted points show the average values of each variable. The speed reducer efficiency shown in the graphs was calculated based on an experimental efficiency of 97% for the simple hoist utilized.

6. Discussion

Although some drawbacks of the prototype had already been identified before testing, input speeds close to 1000 rpm were expected to be reached. However, initiating hoisting of the heaviest load (158 kg) was problematic when trying to attain input speeds above 450 rpm due to limitations in the electric drive system. Another problem related to the operating rate was the noise caused by hammering between the threaded bodies, which became louder as that speed increased. For these reasons, the maximum input speed was limited to 450 rpm to avoid damaging the delicate threads of the roller screw and threaded chain. As that

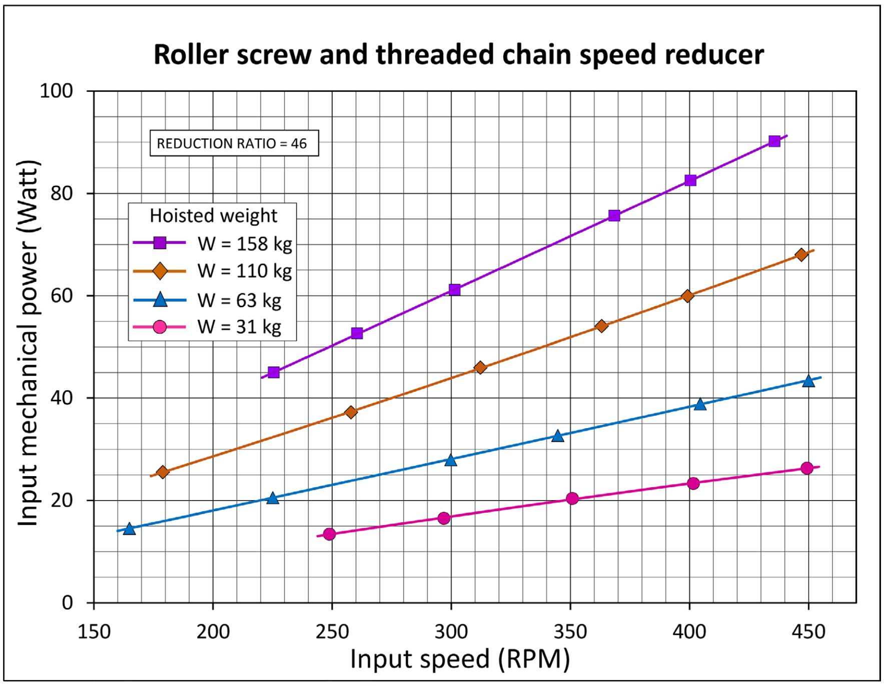

Figure 8. Input mechanical power as a function of input speed. The speed reducer was used to drive a hoist, lifting weights of 31, 63, 110, and 158 kg.

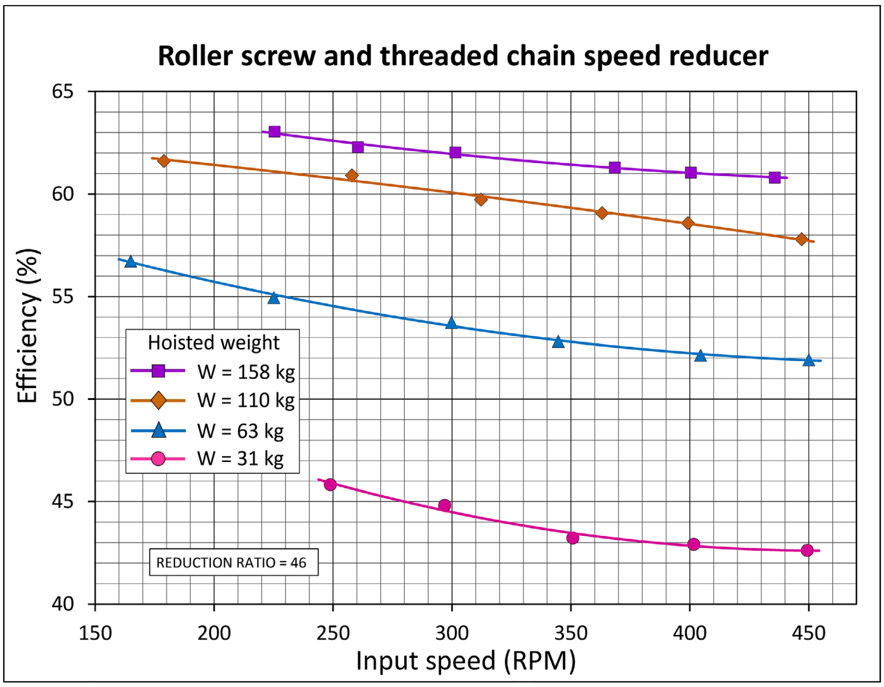

Figure 9. Speed reducer efficiency as a function of input speed. The reducer was used to drive a hoist, lifting weights of 31, 63, 110, and 158 kg.

speed was exceeded, there was a growing concern about noise and vibration levels.

According to the test results, the efficiency of the prototype decreases with increasing input speed, while it improves when hoisting heavier weights (**Figure 9**). Otherwise, efficiency improves with increasing either input mechanical power

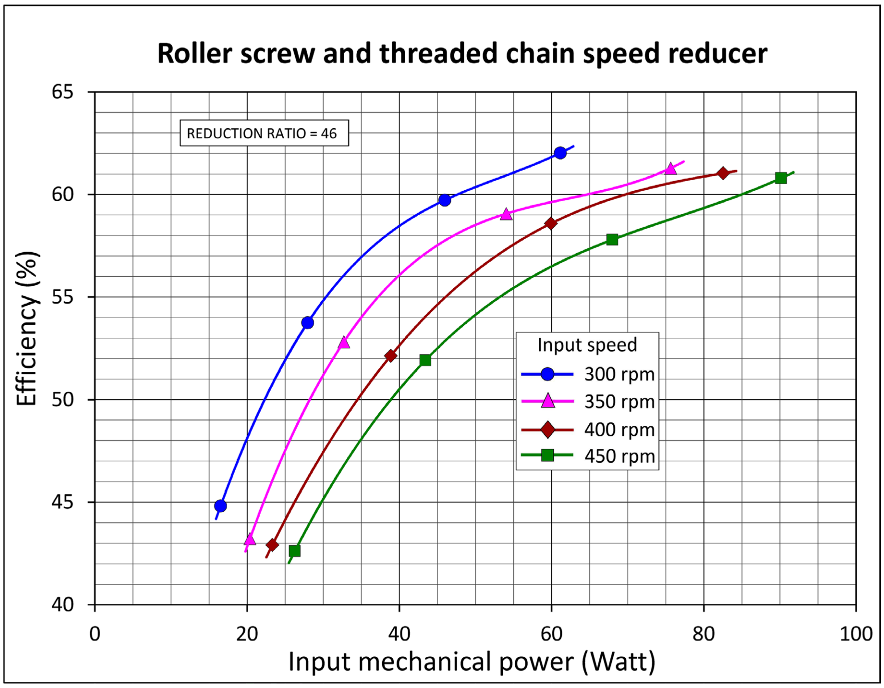

Figure 10. Speed reducer efficiency as a function of input mechanical power, according to four constant input speed rates: 300, 350, 400, and 450 rpm.

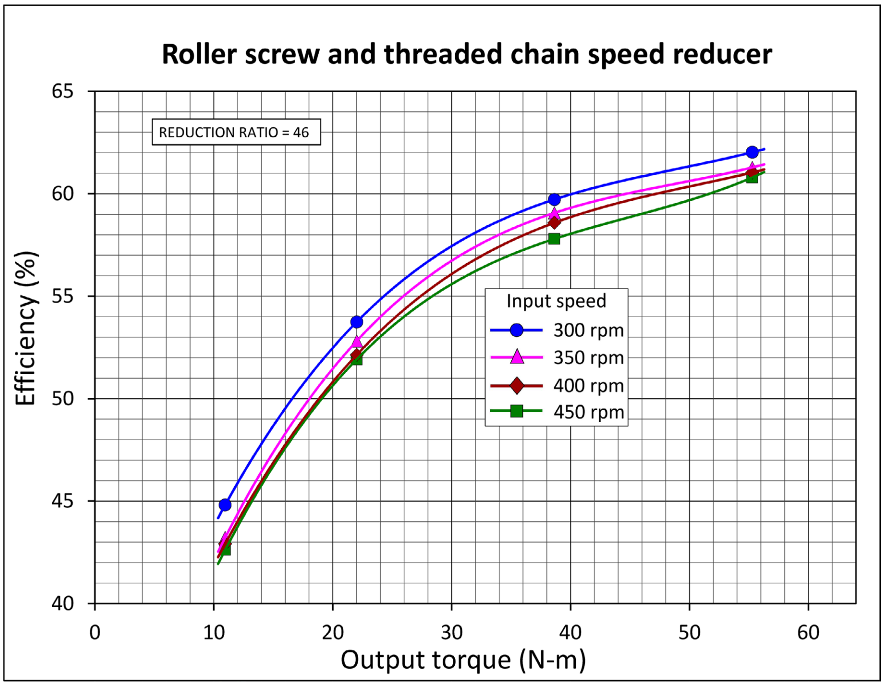

Figure 11. Speed reducer efficiency as a function of output torque, corresponding to four constant input speed rates: 300, 350, 400, and 450 rpm.

(**Figure 10**) or output torque (**Figure 11**). However, these last two figures also indicate that efficiency declines with increasing input speed. This unfavorable behavior occurred even though the prototype was operated at a relatively low input speed, no higher than 450 rpm. The maximum efficiency achieved during the tests was 63% when hoisting the heaviest of the four weights (158 kg), applying an input speed of 225 rpm and an output torque of 56 N-m.

Comparing the efficiency curves, shown in **Figure 11**, with those of another speed reducer that also uses rolling contact to transmit power, such as the roller enveloping worm face speed reducer [9], it is found that when both reducers operate at a constant input speed of 300 rpm and the same output torques, our reducer is slightly more efficient than the cylindrical roller version of the referred reducer, but less efficient than its conical roller version.

The effectiveness of the prototype is limited by several adverse characteristics associated with its innovative design. These features include the following:

1) The chordal action of the roller chains induces considerable vibration because they support the heavy-weight threaded bodies, causing them to move up and down repeatedly. In addition, the vertical displacement of said bodies is transmitted to the cantilevered end of the roller screw shaft, causing a slight and repetitive bending of the shaft. Both of these problems worsen as the input speed increases.

2) When a threaded body leaves the circular path imposed by the sprockets, it collides with the threaded body in front of it, which has already acquired a straight-line path. This issue becomes more severe as the input speed rises, resulting in a gradually increasing noise level.

3) Since the threaded chain of the prototype is heavy, weighing 23.4 kg, a significant collision occurs between the teeth of the sprockets and the rollers of the two roller chains that comprise the threaded chain. The intensity of that collision is more significant as the input speed increases.

4) The threaded rollers of the drive screw do not work optimally inside the threaded holes because these holes have a wide cut that removes a portion of their thread. As the rollers pass through the cut, they lose contact with the hole thread and are affected by centrifugal force, causing them to become slightly misaligned and increase friction as they re-engage the thread. This problem becomes more pronounced as the input speed increases.

5) The width of the cut in the threaded holes is sufficient to admit three threaded rollers. When these rollers pass through the cut, they lose contact with the threads of the threaded holes and do not transmit axial force. Since only seven of the ten rollers apply axial force to the threaded holes, an imbalance of radial forces occurs inside these holes. As a result, the rollers and roller screw shaft move slightly towards the inside of the cut, off-center concerning the hole, causing the rollers to become slightly misaligned before re-engaging the hole thread, increasing friction. This condition worsens as more axial force is applied as the input torque increases.

6) The input torque applied by the roller screw to the threaded bodies causes the twisting of the two roller chains supporting these bodies. This condition results in a misalignment between said chains and the teeth of the corresponding sprockets, increasing frictional losses. This drawback becomes worse as the input

torque increases.

7. Conclusions

The roller screw and threaded chain speed reducer has been described. Also, the experimental behavior of a prototype with a reduction ratio of 46 has been presented. The results indicate that the efficiency of the speed reducer improves with an increase in output torque, provided that the input speed remains constant. The highest efficiency of 62% is achieved at an output torque of 56 N-m and an input speed of 300 rpm.

However, the efficiency of the prototype declines as the input speed rises due to the unfavorable characteristics inherent to its innovative design. Future work could be done to mitigate some of the problems encountered, either:

1) Using silent chains to minimize the harmful chordal effect.

2) Reducing the weight of the threaded bodies.

3) Reducing the cut width in the threaded bodies.

4) Adding a device to prevent the torque applied by the roller screw from twisting the roller chains.

Nevertheless, our reducer has other serious disadvantages: it requires elaborate machining and is bulky and heavy. The drawbacks are so numerous and substantial that it is doubtful whether it is worth attempting to overcome them.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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