Mechanical Product Design Term Project (Autumn, 2021)
Title: Reverse Engineering Final Report
Team number: 6
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1. Introduction

We chose an “Impact Wrench” for the term project. An impact wrench delivers high torque output with minimal exertion by storing energy in a rotating mass, followed by a sudden delivery of energy to the output shaft. We have disassembled the product, which let us delve into the electrical circuit and mechanical structure. It is planned to model the product using CAD program to simulate its action and utilize computational model for theoretical kinematic analysis and fatigue analysis. Detail product specifications can be found in Bosch website, a very useful resource for researching the product’s circumstantial structure and mechanism.

1.1. Description of the Selected Product

From several candidates, “Cordless Impact Driver Wrench GDX18V-180, BOSCH” is chosen for the budget issue. (**Fig. 1.1**) Adjustable impact intensity of the product is 180Nm.

1.2. Reasons of Selection

First, unlike other ordinary drivers, an impact wrench delivers not only rotational force, but also a forward thrust on the area. It is very interesting that one unified mechanism delivers such a strong force and torque in a short time.

Second, the machine does not apply force consistently like ordinary electrical drills or drivers. It applies force twice in one revolution with special mechanism (**Fig. 1.2**), so it can drive stronger force. It is intriguing to scrutinize the torque output compared to ordinary electrical drills or drivers powered by same power source.

Third, the machine impacts directly, and the impact frequency is measurable. Therefore, we can analyze the fatigue of the machine, and estimate the life expectancy of the impact wrench in theory.

Moreover, we are wondering how the changes in rotational variables, such as making 3~4 impact at a single rotation, or utilizing smaller output shaft, will change the property of the wrench, such as the maximum torque or life expectancy.

1.3. Comparison with Two Similar Products

There are many similar tools used in the industrial field, like electrical drivers and non-electrical drivers.

1.3.1. Electrical Driver, GBM 6 RE (Fig. 1.3): Electrical drills are also used for similar purposes, but electrical drills deliver constant torque, by rotational motion, so it cannot drive very strong torque in a short period. Electrical energy actuates the motor.

1.3.2. Hydraulic Impact Wrench (Fig. 1.4): The function of this tool is same as the product we chose, but the biggest difference between the two machines is the power source. Adjustable impact intensity of hydraulic impact wrenches is about 680~3400Nm. It is much larger than the electrical impact wrench we chose. Hydraulic impact wrenches can be used with long hose sets keeping the wrench away from the pump or other power sources. It is commonly used by the power utility industry for drilling, tightening and loosening hardware on hardwood poles. (**Fig. 1.5**) Furthermore, some hydraulic impact wrenches can be operated underwater. We thought electrical impact wrench is more suitable for reverse engineering project this semester than hydraulic impact wrench for several reasons. First, hydraulic impact wrench requires hydraulic power source, but we thought it seems difficult to handle it. Next, hydraulic wrench is quite expensive in general. For the last, we thought electrical impact wrench is safer to investigate with, since it applies smaller torque.

2. Description of Product Function and Properties

The function of impact wrench is very simple, applying torque to a shaft by certain mechanism. The product can be roughly divided into two big parts, The machine and battery pack. For the machine part, it can be worked at 0~2800 rpm without load and apply impact at 0~3600 bpm. Its maximum torque is 180Nm. The weight of the product is about 1.45 kg. The battery works at rated voltage, 5V. Unlike other ordinary drivers, an impact wrench delivers not only rotational force, but also forward thrust on the area. It is very interesting that one unified mechanism delivers strong force and torque in short time.

We found a detail product specification from Bosch website (**Fig. 2.1**, **Fig. 2.2**), which is very useful for researching the product's circumstantial structure and mechanism.

3.A. Process of Disassembly

Our team started disassembling the impact wrench in purpose to investigate the principle of the motion of the wrench. We started by removing bolts that can be observed from outside. Two kinds of bolts were used to assemble this wrench. 4 bolts are used to assemble the front part of the wrench with the back part of the wrench, which sizes are relatively big compared to the other bolts. We'll name these bolts as bolt A, denoted with 4 green squares (**Fig. 3.1**). 9 bolts are used to assemble the left and right parts of the back part of wrench, and these are smaller than bolt A. We'll denote these bolts as bolt B, denoted with 9 orange circles (**Fig. 3.2**). 2 more bolts are positioned at the back of the wrench to fasten the cover, which protects the electric part of the wrench, with the back part of the wrench. Bolt B are used, and these bolts are denoted with orange circles (**Fig. 3.3**). No bolts were shown from the left of the wrench (**Fig. 3.4**).

By disassembling bolt A, we could separate the front part and the back part of the wrench. Rotation parts were lubricated in large amounts (**Fig. 3.5**, **Fig. 3.6**). We could also observe two teeth at the rotation parts, both at the front and the back of the wrench. Variation of relative position of these teeth make the special movement of the wrench. The wrench stops rotating and gains energy when these teeth interlock each other. Then, when these teeth overcome reaction between each other with stored energy, they burst out releasing high energy.

Our team also disassembled 11 of bolt B. However, we found difficulty separating the left and right parts of the wrench. Since it was strongly connected (**Fig. 3.7**), we worried that it would be impossible to reassemble the parts, which is necessary because we are planning to analyze the motion of the wrench. Also, we couldn't apply maximum force to split apart because of the lubricant. We also revealed the cover at the back, but not much observation was possible without disassembling the left and right parts (**Fig. 3.8**). As a result, we decided to reassemble the parts, do some experiments regarding the rotation first when the idea factory is available, and then return to disassembling the wrench.

3.B. Process of Disassembly 2

Our product can be disassembled by unscrewing every screws. After unscrewing, we removed grease(lubricant) with cotton swabs. The body part and bit sleeve part are also assembled with screws. **Fig 3.9** is the overall structure of the body part. Part A takes role of supplying power to the motor, connected to battery pack. Part B is switch. With this switch, user can modify rotational direction (**Fig. 3.10**). The trigger of part B controls rotational speed i.e., input torque of the motor (**Fig. 3.11**). Part C is the motor part. Rotor is a form in which copper wires are wound around a metal core. One end of the rotor is a contact connected to an electricity, which is called a commutator (**Fig 3.12**). The motor brush (**Fig 3.13**) is contacting commutator and power source. This prevents sparks when rotor rotates in high rotational speed. As shown in the picture, the commutator has pieces of copper insulated from each other in a circular shape. The two pieces of copper facing each other are connected by winding, so when current flows through this winding, it forms an electromagnetic field. A stator, which is a permanent magnet, is placed around the rotor. Part D is the hammer part which transfers torque to the bit-sleeve part. The hammer part can be further disassembled to the gearbox (**Fig. 3.14**), and the hammer-spring system (**Fig. 3.15**). There is a washer with lubricant to minimize the friction. The gearbox contains two small gears with shaft (**Fig. 5.4.9**), and the surrounding gear (**Fig. 3.16**). These gears organize the gear system **(Fig. 5.3.4)**. The rotor rotates central gear. The small gear rotates, but the surrounding gear is fixed to the body **(Fig. 3.17, Fig 3.18)**, so the hammer rotates. **Fig. 3.19** is bit sleeve part. There is water-proof rubber band between the body and the bit sleeve part. **Fig. 3.20** is bit sleeve-anvil. It was unable to disassemble the anvil and the plastic case holding it, so we cut the body with saw to disassemble the anvil. **Fig. 3.21** is the anvil.

4. Areas of Analysis

By disassembling the impact wrench, our team figured out that the impact wrench was composed with 3 main parts: battery-motor system, torque transmission system, and bit-holder system. We have chosen 3 areas for analysis, crossing out other non-mechanical elements.

The mechanism of delivering impact to bit-holder system, which distinguishes from other driver devices, is the key to the impact wrench. The objective of analyzing this area is to know the conditions of the impact and the effect to the performance. As we progressed some simple experiments using slow video motion, our team recognized that the rotation speed of the bit is constant rather than discontinuous. This movement is different from what we've expected since the discontinuous movement of the bit is the most distinguishable feature from other normal drilling instruments. Referring that impact wrench is used when high torque is needed, extreme conditions are needed for impact to happen. So, the basis of analysis of this area will start from configuring the critical condition when impact happens. After the manipulation of the condition, it is planned to see the contribution to output performance of the impact.

In addition to the impact mechanism, the gearbox to create high torque from the motor is crucial to the impact wrench. Unlike other drills or drivers that run in low torque conditions, the impact wrench is more desirable in high torque conditions as we discussed earlier. To make high torque from limited resources, additional gears should be used to increase the torque from the motor. Here, the analysis focuses on how the gears are arranged and the gear ratio of the torque transmission system.

Last but not least, the bit sleeve mechanism is also an interesting part to analyze. A bit sleeve is a clever mechanism to hold the bit without any additional fastening. In conventional electronic drivers or drills, the user fastens the bit to the holder by rotating the holder clockwise before any operations. On the other hand, BOSCH GDX 18V-180 fastens the bit by the following steps: pulling out the bit sleeve, placing the bit inside the bit sleeve, letting go of the sleeve. Despite the simple steps, the bit of the impact wrench can withstand high rotation speed (up to 2800RPM) and high torque (up to 180Nm) without any slips or dislocations. The objective is to figure out the mechanism embedded in the bit sleeve.

5. Analysis

5.1. Rotating Speed

At the start of our project, we expected our impact wrench to rotate in irregular angular velocity because of the impact system. The rotating hammer gets stuck by the anvil connected to the bit and the spring mechanism applies the force on the hammer, consequently making higher rotating speed periodically.

To find out if we made a right assumption, we prepared a conventional electric driver for a comparison, and measured the angular velocity and the aspect of rotation on each machine. A marker was attached on the end of each head of the tools and placed on fixed horizontal desk. Then we activated both machines in maximum power (power source in two machines are same). We recorded two motions in slow motion and used a tracker program to analyze their motions (**Fig. 5.1.1**). Knowing the ability of our slow video camera, we were able to calculate their angular velocity and graphically visualize their rotating motions.

First, we checked for the accuracy of the tracker analysis. The maximum speed data given by Bosch site was 1300RPM and 2800RPM each for driver and wrench. The average rpm data from the tracker was 1059.538RPM and 2231.055RPM each for driver and impact wrench. The gap between the values from site and measurement were brought about by lack of charge in battery, problem in tracker tracking the marker, and unstable camera hold.

Our main interest, whether the impact wrench has an inconstant angular velocity with periodic interchange between phases, was clearly identified. The wrench was rotating in almost constant angular velocity without any up and down movements as shown in the graph (**Fig. 5.1.2**). Later while disassembling, we found out that the mechanism of hammer hitting the amble does not work in ordinary conditions. Obviously, if the head is in such condition, it just rotates solely by the torque from the motor, not by the impact. So, our team decided to create a harsh condition, by increasing the torque needed using a hardened wood plate and check the rotational and axial motion of hammer and the spring.

5.2. Screwing Mechanism

After disassembling and reassembling the wrench, first, the screwing experiment was done to see the mechanism of the impact wrench. 2 kinds of wood boards were screwed by the impact driver wrench as a driver. It was because it is easier to make a tough condition while screwing than fastening or loosening bolts and nuts. The deeper it screws, more the friction is applied to the screw, which makes more torque to screw it. Therefore, 2 boards were overlapped and screwed at once. However, it was hard to see the 'impact' motion – the hammer rotates separately with the anvil, and then hits the anvil after a revolution with high speed – while screwing. The 'impact' was only recorded when almost the whole screw was screwed. When the screw was stuck, because the head reached to the board, high friction force was applied to the screw that made the anvil rotate slower than the rotor. It can be explained with the equation below why the rotational speed of the anvil decreased.

$$F_{friction}v_{screw} = T_{friction}\omega_{screw} = P_{driver}$$

With full-power operation, P_{driver} is constant. So as the friction force (or the torque needed) increases, screwing speed (or the rotational speed) decreases.

This made the hammer to rotate slower too because it was pushing the anvil while in contact. Since the hammer is connected to the rotor with a (torsional) spring, the spring was compressed as the rotation continued. (**Fig. 5.2.1**; The red line is the increasing gap in level between the hammer and the anvil. The images are captured with a term of 1 revolution.) After a small rotation – where the rotor rotates faster than the anvil – the spring was compressed enough to lift the hammer from the anvil. When the hammer was lifted, there were no resistance to the hammer, so it started to rotate fast. On the other hand, there were nothing pushing the anvil, so the screw was stable. After the speed of the hammer become same with the rotor, the spring was stretched, and it pushed the hammer to the same level with the anvil to hit it. (**Fig. 5.2.2**; The red line indicates the rotation of screw from when the hammer was lifted to when it hit the anvil. While the hammer was lifted (1~3), the screw is stable but after hitting the anvil (4), the screw rotated.) After hitting the anvil once, the screw was no more screwed.

The ‘impact’ motion could not be seen while unscrewing (rotating CCW) because there were no obstacle or resistance strong enough as the screwing condition. However, impacting mechanism is used in both situation of screwing/fastening and loosening bolts and nuts.

5.3. Gear Ratios

In the gear box, which connects the rotor (which is directly connected to motor) and the end sleeve, there were 4 gears. The first gear is the rotor gear (gear I, **Fig. 5.3.1**), which has same rotational velocity with motor. Other two gears (gear II, **Fig. 5.3.2**) are the gear connected to the spring structure that applies the converted angular velocity to the outer sleeve. The last gear (gear III, **Fig. 5.3.3**) is the gear race (attached to the outer cover of wrench) for two gears in spring structure to rotate in stabilized condition. The overall mechanism in the gear box is as shown (**Fig. 5.3.4**).

Since the product we are analyzing is an impact wrench which mainly deals with rotary motion and rotational speed, we thought it is crucial to calculate the gear ratios. A gear ratio is the ratio of the number of rotations of a driver gear to the number of rotations of a driven gear. In our case the driver gear is the gear I, and the driven gears are gear II. Additionally, the design of a gear set in our product is a non-reversing design (**Fig. 5.3.5**), which has main purpose of maintaining the rotating direction of a driven gears same with the direction of driver gear.

From the definition of gear ratio, its value can be easily driven by simple calculation. Knowing that each tooth of gear contacting has the same velocity, and its value can be calculated with $r(Radius) \times \omega(Angular\ Velocity)$, the ratio of angular velocity of gear I and gear II is same with the reversed ratio of each gear’s radius. By measuring the geometric value of gears with vernier calipers, we found out the radius of gear I is 2.5mm, and the radius of gear II is 7.5mm. This means one rotation in gear I gives 1/3 rotation of gear II. As a result, since gear II is attached to the outer sleeve with stabled shafts, we found out that the sleeves are rotating in the one thirds of the rotational speed of the motor. Of course, this is an analysis neglecting all the other interferences including gear friction, we are planning to analyze it deeply using stress analysis with modeling in Solidworks.

5.4. 3D Modeling

After disassembling, we could divide the parts into 5 big areas: the cover parts, electrical parts (including switches, wires, power source), motor parts, gearbox, and bit-sleeve parts. For our project, we focused on the gearbox and the bit-sleeve parts. For our project, we decided to focus on the gearbox (**Fig. 5.4.1**) and the bit-sleeve parts (**Fig. 5.4.4**). This is because these parts are consisted of various parts that we can disassemble and analyze using the knowledge that we learned throughout the semester. Throughout the disassembly process, we could disassemble gearbox into several small and basic parts such as gears, cylinders, and other associated parts such as retaining rings. For further analysis such as stress concentration or simulation on the change of design of the anvil and hammer, such as the numbers or dimensions of the anvil, making 3D modeling of the parts was necessary.

We divided the gearbox into 10 fundamental parts, such as basic gears or cylinders that cannot be disassembled. We neglected other associated parts (**Fig. 5.4.5**) since the functions of those parts were out of our interest. However, we couldn’t disassemble the bit-sleeve any further, so we regarded it as a single rigid body and made a 3D model of it. Modelling with precise dimensions, including fillet, was important since stress vary with bigger range, especially with the press-fit parts. Utilizing vernier calipers (**Fig. 5.4.6**), we could precisely measure the dimensions of the parts. We also measured the length using image analysis (**Fig. 5.4.7**) with some parts that cannot be measured with vernier calipers because of its geometry. All modeling process were done using Solidworks.

Again, the parts at gearbox could be divided into 2 big sections. The first section is the part connecting the motor and the gear (**Fig. 5.4.3**). We divided this section into 4 parts and modeled each part (**Fig. 5.4.8**). The other part is the gear-spring structure consisted of planetary gears and torsion spring (**Fig. 5.4.2**). This part was press-fitted with gear and cylinders (**Fig. 5.4.9**). We divided this part with 6 parts and modeled each part (**Fig. 5.4.10**). There was also an outer gear that surrounded the inner gearbox (**Fig. 5.4.11**), which was also modeled (**Fig. 5.4.12**). By assembling these parts, we could construct the full structure of the gear box (**Fig. 5.4.13**). The bit-sleeve parts were also modeled by Solidworks (**Fig. 5.4.14**), regarded as a single rigid body.

Fig. 1. 1 Impact Wrench

Fig. 1. 2 Impact Mechanism

Fig. 1. 3 Electrical Drill

Fig. 1. 4 Hydraulic impact wrench

Fig. 1. 5 Hydraulic impact usage

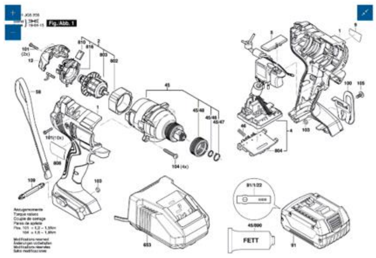

Fig. 2. 1 Product detail 1

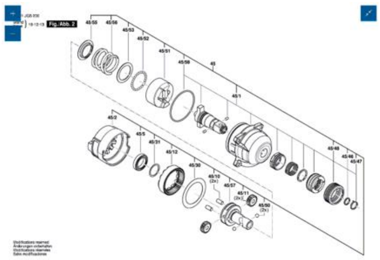

Fig. 2. 2 Product detail 2

Fig. 3. 1 Front View

Fig. 3. 2 Right View

Fig. 3. 3 Back View

Fig. 3. 4 Left View

Fig. 3. 5 Hammer Part


Fig. 3. 6 Anvil Part

Fig. 3. 7 Disassembly Process


Fig. 3. 8 Electric Parts of the Wrench


Fig. 3. 9 Overall Structure


Fig. 3. 10 Rotational Direction Switch

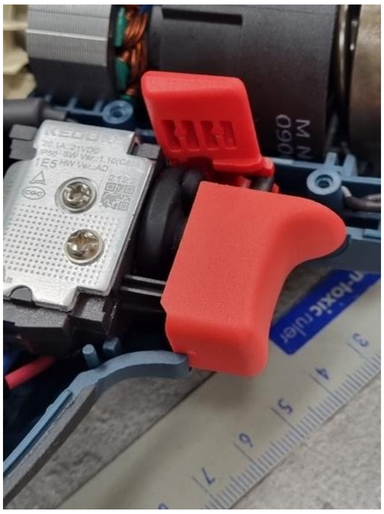
Fig. 3. 11 Trigger


Fig. 3. 12 Commutator


Fig. 3. 13 Motor Brush


Fig. 3. 14 Gearbox


Fig. 3. 15 Hammer-Spring System

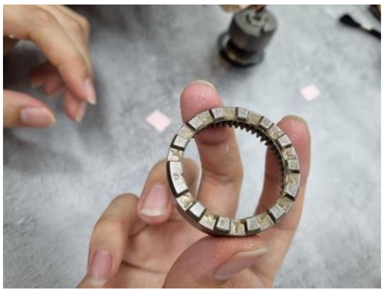
Fig. 3. 16 Surrounding Gear


Fig. 3. 17 Wrench Body

Fig. 3. 18 Gear Fixed to Wrench Body

Fig. 3. 19 Bit-Sleeve

Fig. 3. 20 Anvil with Bit-Sleeve

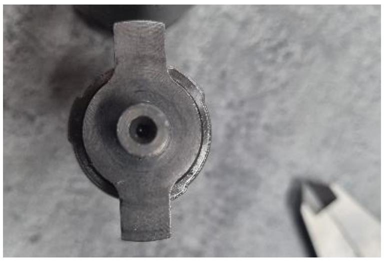

Fig. 3. 21 Anvil

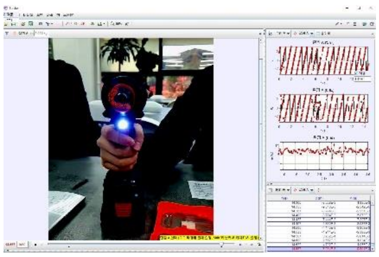

Fig. 5. 1. 1 Using Tracker for Analyzing the Rotation

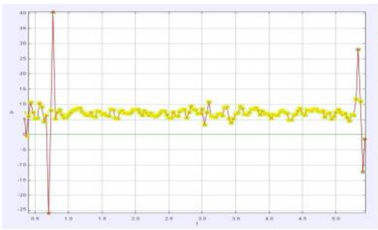

Fig. 5. 1. 2 Angular Velocity of Impact Wrench Rotating in Free Condition

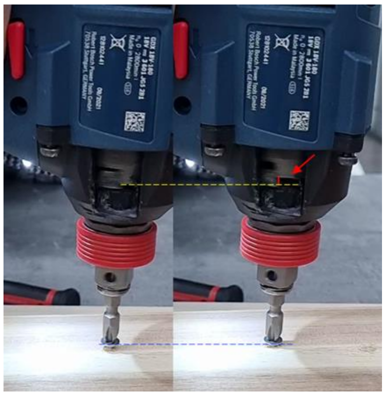

Fig. 5. 2. 1 Increasing Gap Between Hammer and Anvil

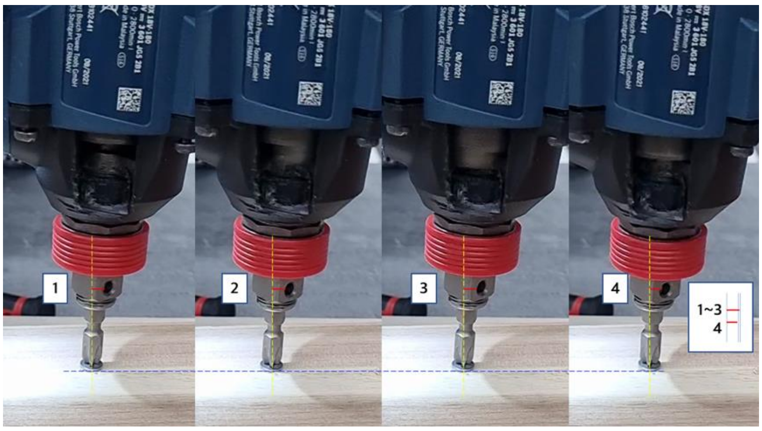

Fig. 5. 2. 2 The Rotation of Screw while the Hammer is Lifted to Hit the Anvil

Fig. 5. 3. 1 Gear I

Fig. 5. 3. 2 Gear II

Fig. 5. 3. 3 Gear III

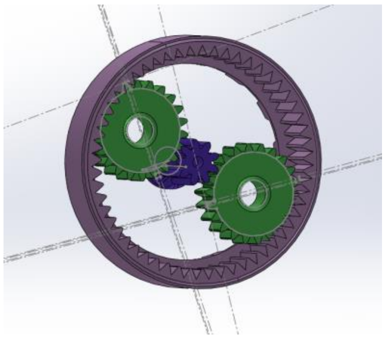

Fig. 5. 3. 4 Overall View of Gearbox

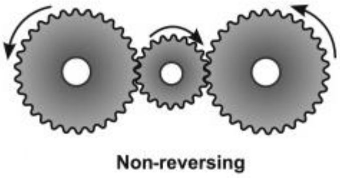

Fig. 5. 3. 5 Non-reversing Gear Set

Fig. 5. 4. 1 Gearbox

Fig. 5. 4. 2 Gear-Spring Structure

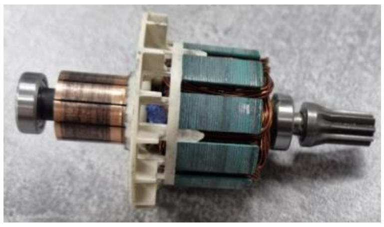

Fig. 5. 4. 3 Parts Connecting the Motor and Gears

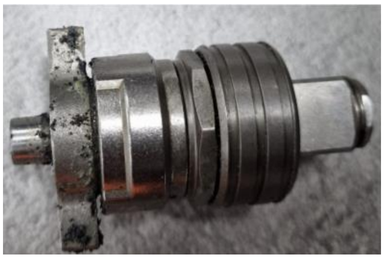

Fig. 5. 4. 4 Bit-Sleeve

Fig. 5. 4. 5 Coverings and Associated Parts

Fig. 5. 4. 6 Measuring Dimensions Using Vernier Calipers

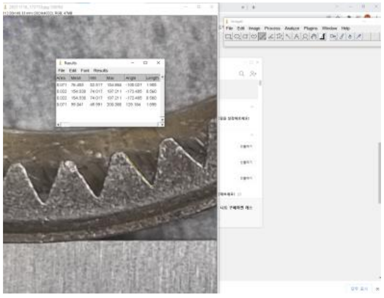
Fig. 5. 4. 7 Image Analysis

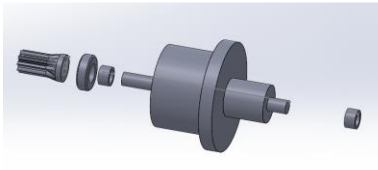
Fig. 5. 4. 8 Modeling of Motor-Gear


Fig. 5. 4. 9 Gear and Cylinder Assembled in Press-Fit

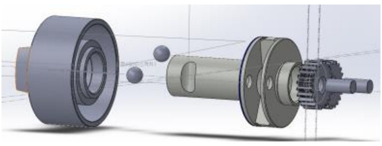
Fig. 5. 4. 10 Modeling of Gear-Spring

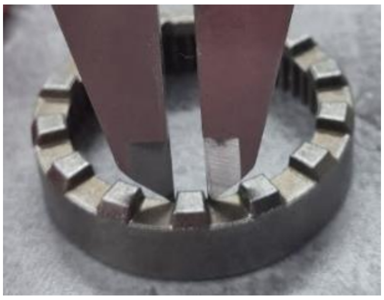
Fig. 5. 4. 11 Outer Gear

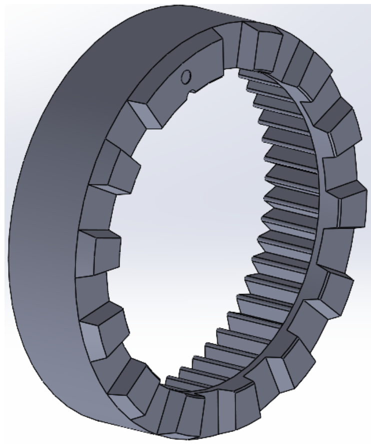
Fig. 5. 4. 12 Modeling of Outer Gear

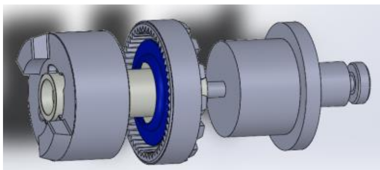
Fig. 5. 4. 13 Full Assembly of Gearbox

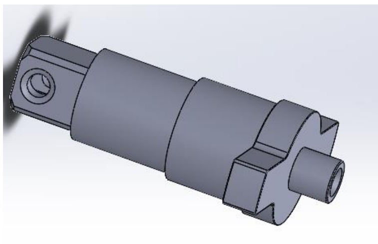
Fig. 5. 4. 14 Modeling of Bit-Sleeve