# Design and Technological Features of 3D-Printing Usage in Agricultural Machines Gearings Repair

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***Abstract*—The repair of agricultural machines and its gearing drives is a an important challenge. Normally, a wide range of machine tools are required for gear replacement manufacturing, which is hard to provide at repair shops of farm garages. The way to temporary replace broken metal gear for 3d printed polymeric one is proposed. The usage of Novikov gearings and arch-tooth gearing instead of traditional involute cylindrical gears is offered. Estimation of accuracy of such a gearing is offered and results of experimental evaluation are given.**

***Index Terms*—gearing, drive, 3d printing, agricultural machines, repair, gear ratio, Novikov gear**

## I. INTRODUCTION

One of the main elements of most types of machines is a gear drive. The drive serves to transfer kinetic energy from its source — the engine — to the consumer — the actuator. It is known that during the operation of gears, their instantaneous or gradual destruction is possible, caused by various external environmental factors or properties of structural materials.

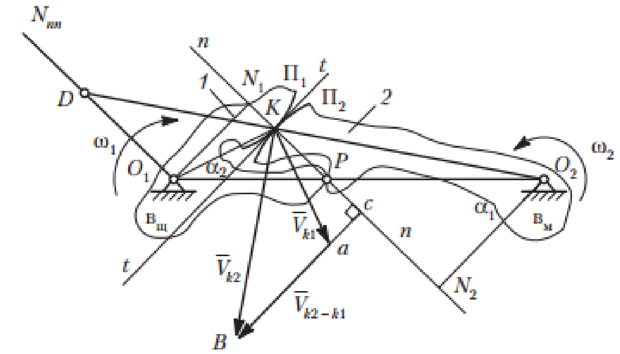


Figure 1. Abrasion from slip profiles

Gear drives are mechanisms with higher kinematic pairs. It is known that with relative movement of the teeth of the wheels there is a mutual slippage of the profiles, which leads to wear of the teeth from abrasion (Fig. 1). The speed of the relative movement of the teeth is proportional to the distance to the pole of the engagement, which leads to characteristic wear (Fig. 2). From the works [1-2] it is known that such a change in the shape of the teeth leads to a deviation of the actual gear ratio of the gear from the required value, which can lead to a violation of the kinematics of the mechanisms [3-4].

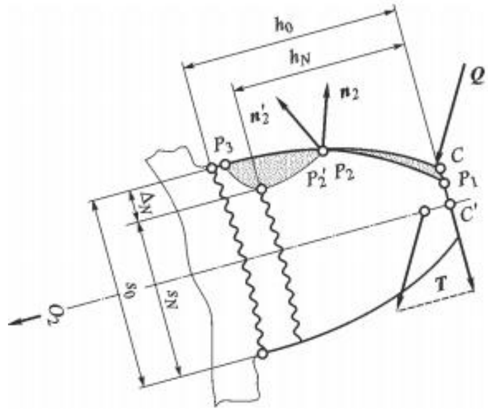


Figure 2. Characteristic tooth profile wear

On the other hand, a change in the profile of the gearing can be caused by chipping of the teeth due to high contact stresses. To eliminate such phenomena, optimization of the shape of the tooth is required.

The most difficult cases of the functioning of gears are associated with their work with an open installation scheme, when the transmission is possible the action of external environmental factors of physical and chemical nature. Such transmissions are subject, on the one hand, to increased corrosion due to the influence of climatic factors, and, on the other hand, to rapid abrasive wear caused by particles entering between the engaging surfaces.

All of the above defects are very characteristic of agricultural machinery drives. Such machines operate in harsh climatic conditions, and, as a rule, have an open design in order to reduce metal consumption and lower energy consumption. At the same time, the frames of machines of similar designs have a sufficiently low rigidity, which leads to the possibility of small deformations, disruption of the geometry of the machines and, accordingly, the appearance of excessive bonds, which, in turn, lead to additional deformations of machine parts.

These reasons lead to frequent failure of agricultural machinery mechanisms, and lead to the need for repair work [5-9].

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## II. Maintanability of Gear Drives

Maintaining maintainability of gear drives of agricultural machines requires the maintenance of an extensive fleet of machine tools [10] So, even for rough machining of the surfaces of gears, at least the presence of lathes, screw-cutting and milling groups, as well as a wide range of shaped disk and finger mills, is required. In the event that requirements are imposed on the accuracy of the gears, it is necessary to carry out the cutting of the teeth by the centroid generative method, which also requires the presence of machine tools of the gear group.

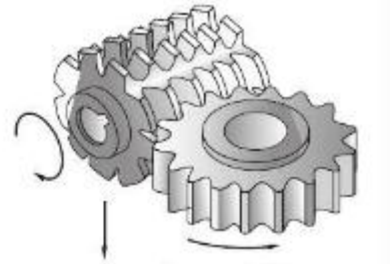

Figure 3. Generative method of gear cutting

The maintenance of a wide range of equipment requires high material and technical costs, and also increases the requirements for the qualification of workers. A possible replacement for the traditional methods of producing gear elements in the repair industry may be the use of three-dimensional printing methods, including the use of polymeric materials. However, due to the lower strength of polymers in comparison with metallic materials, a change in the design of the drives is necessary.

To increase the strength of the elements of gear drives, it is necessary to increase their module (or, for equipment manufactured in countries with an imperial system of measuring values, reduce the pitch). An increase in the module, in turn, leads to an increase in the overall dimensions of the transmission. Considering that the drive's center distance is rigidly set by the machine design, while increasing the dimensions, it is necessary to simultaneously strive to reduce the number of gear teeth.

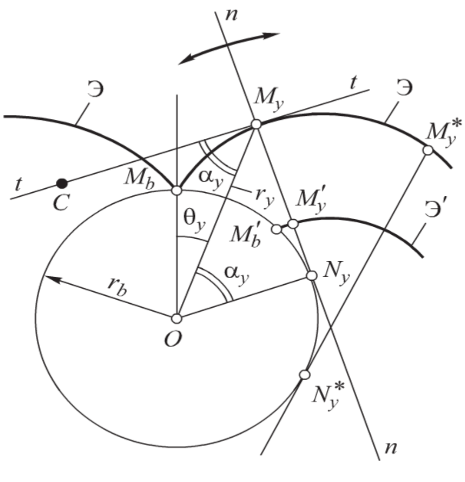


Figure 4. Involute profile of gear

Most gears used in industry have an involute tooth profile. One of the main limitations imposed on the design of involute gears is the need to avoid undercut of the tooth leg - a defect leading to a decrease in the bending strength of the teeth. To eliminate this phenomenon, gears cut by a tool with a standard initial producing contour must have at least 18 teeth.

The second serious drawback of involute gears characteristic of external gears is the contact of two convex tooth surfaces, which leads to an increase in contact stresses and chipping of the teeth.

## III. Design Improvement of Agricultural Machines Gears

In order to improve the design and operating conditions, which will allow us to build a workable transmission from polymeric materials, the tooth profile of the gears can be replaced from involute to round-screw (Novikov profile[11-12]) (Fig. 2).

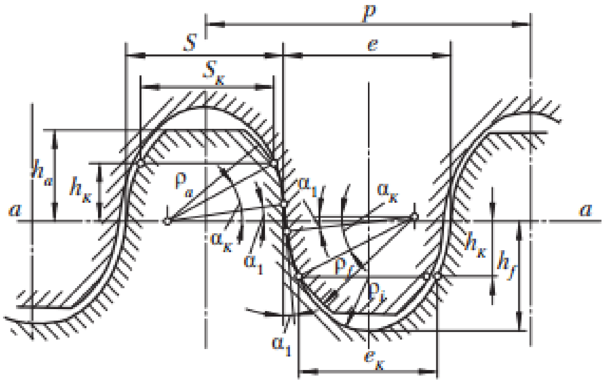


Figure 5. Profile of Novikovs gear

Novikov meshing is characterized by reduced contact stresses, which is achieved due to the contact profiles made in the form of arcs of circles of close diameter. In addition, the use of such profiles allows you to cut a smaller number of teeth without defects.

On the other hand, tooth profiles outlined by circular arcs do not provide optimal meshing conditions for a non-rigid machine frame. To eliminate this drawback, it is necessary to synthesize self-aligning gear mechanisms, which can be achieved by using gears with arched teeth, the generatrix of which is not straightforward. Such teeth provide a linear contact of the tooth profiles with a possible relative rotation of the axes in one plane caused by deformation of the frame. This solution allows you to eliminate redundant bonds and rationally place the engagement zone, avoiding edge contact.

Wheels with arched teeth are not common in agricultural engineering due to the complexity of their manufacture and the impossibility of repair in the conditions of repair sites, since their cutting requires five-coordinate machines with numerical control. Using 3D printing methods eliminates this limitation. [13-19] The gearings made by means of 3d printing are shown below.

Figure 6. 3d printed gears, top to bottom: 1-contact line Novikov, 2-contact line Novikov, arched tooth involute.

To study the possibility of replacing the gears of the drives with polymeric ones, prototype gears were made, the kinematic accuracy of which was estimated by varying the instantaneous gear ratio. [20-21]

## IV. Experimental Evaluation of Accuracy

As part of the testing of the project, an experiment was conducted with use of an intercenter to calculate instantaneous gear ratios of the manufactured specimen of the transmissions (Fig. 7-9).

The following models were tested (Tables I-III):

TABLE I. Characteristics of Gearing Pair#1

| | | |
|---|---|---|
| Gearing type | | Novikov |
| Parameter | | Value |
| The number of teeth: | z1 | 11 |
| | z2 | 17 |
| Module, m | | 4.5 mm |
| Center distance, aw | | 70.09 mm |
| Tooth angle β | | 26 ° |

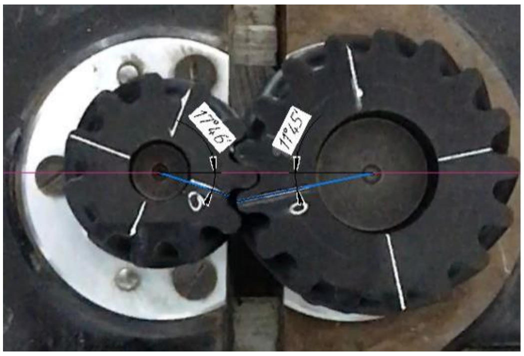

Figure 7. Measurement of instantaneous gear ratios for 1st pair of gears

TABLE II. Characteristics of Gearing pair#2

| | | |
|---|---|---|
| Gearing type | | Novikov |
| Parameter | | Value |
| The number of teeth: | z1 | 14 |
| | z2 | 21 |
| Module, m | | 4 mm |
| Center distance, aw | | 74.03 mm |
| Tooth angle β | | 19 ° |

TABLE III. Characteristics of Gearing pair#3

| | | |
|---|---|---|
| Gearing type | | Involute with arched teeth |
| Parameter | | Value |
| The number of teeth: | z1 | 22 |
| | z2 | 22 |
| Module, m | | 4 mm |
| Center distance, aw | | 88 mm |
| Tooth angle β | | variable |

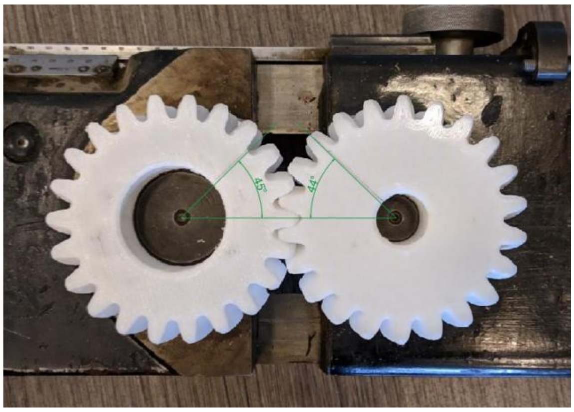

Figure 8. Measurement of instantaneous gear ratios for 3rd pair of gears

After the measurement of the instantaneous gear ratios the following results were acquired.

The results of measurements (Tables IV-VI)shows, that the fluctuation of the instantaneous gear ratio is about 5%, that is accurate enough for usage in agricultural machines. It means that 3d printing of machines parts may be used as a technology in repair production without deterioration of the kinematic characteristics of the machines.

TABLE IV. Instantaneous Gear Ratios for 1st Pair

| 1st wheel angle | 2nd wheel angle | Center distance | Gear ratio |
|---|---|---|---|
| 3°52' | 3°15' | 70.12 | 1.491 |
| 9°34' | 6°21' | 70.14 | 1.507 |
| 12°32' | 8°42' | 70.02 | 1.441 |
| 17°46' | 11°45' | 70.08 | 1.512 |
| 21°32' | 14°11' | 70.10 | 1.518 |
| 26°28' | 18°1' | 70.06 | 1.469 |
| 30°15' | 20°1' | 70.10 | 1.511 |
| 33°1' | 21°51' | 70.06 | 1.511 |
| 35°58' | 24°1' | 70.02 | 1.498 |
| 40°21' | 27°2' | 70.00 | 1.493 |

TABLE V. Instantaneous Gear Ratios for 2nd Pair

| 1st wheel angle | 2nd wheel angle | Center distance | Gear ratio |
|---|---|---|---|
| 2°56' | 1°56' | 74.06 | 1.518 |
| 4°04' | 2°41' | 74.04 | 1.509 |
| 7°29' | 4°58' | 74.02 | 1.507 |
| 10°40' | 7°03' | 74.08 | 1.513 |
| 15°20' | 10°19' | 74.14 | 1.486 |
| 20°19' | 13°22' | 74.06 | 1.520 |
| 24°01' | 15°55' | 74.02 | 1.509 |
| 28°11' | 18°34' | 74.04 | 1.518 |
| 31°27' | 21°09' | 73.96 | 1.487 |
| 36°05' | 24°11' | 73.98 | 1.492 |
| 40°22' | 26°47' | 74.02 | 1.506 |
| 43°40' | 28°54' | 74.04 | 1.511 |
| 47°29' | 31°22' | 74.08 | 1.514 |
| 51°50' | 34°09' | 74.06 | 1.518 |
| 55°19' | 36°41' | 74.02 | 1.508 |

| | | | |
|---|---|---|---|
| 58°47' | 39°13' | 74.00 | 1.499 |
| 63°31' | 42°36' | 73.98 | 1.491 |
| 66°56' | 45°08' | 73.96 | 1.483 |
| 71°39' | 47°52' | 74.00 | 1.497 |
| 76°29' | 50°17' | 74.06 | 1.521 |
| 80°50' | 53°24' | 74.02 | 1.514 |
| 84°20' | 55°43' | 74.04 | 1.516 |
| 87°44' | 58°51' | 74.12 | 1.498 |
| 93°52' | 62°15' | 74.10 | 1.508 |

TABLE VI. INSTANTANEOUS GEAR RATIOS FOR 3RD PAIR

| 1st wheel angle | 2nd wheel angle | Gear ratio |
|---|---|---|
| 0°57′ | 0°59′ | 1.02 |
| 6°16′ | 5°58′ | 0.95 |
| 15°22′ | 14°54′ | 0.97 |
| 19°15′ | 18°57′ | 0.98 |
| 24°48′ | 25°12′ | 1.02 |
| 31°5′ | 30°49′ | 0.99 |
| 36°13′ | 36°58′ | 1.02 |
| 45°4′ | 44°56′ | 0.99 |
| 50°34′ | 51°9′ | 1.01 |

Measurements of the transmitions ratios of 3d-printed gearings shows, that values obtained is close to the theoretical gear ratios.

To assess the quality of the transmission, in addition to determining the average value of the gear ratio, it is necessary to evaluate its fluctuations.

To assess the admissibility of the influence of fluctuations in the gear ratio, you can use the technique based on the use of Shewhart control charts.

It is necessary to calculate the mean value, standard deviation σ, build a plot of measured value of gear ratio, mean, and upper and lower ranges of u+3σ and u-3σ.

The control cards for three gears are given on Figs. 9 - 11.

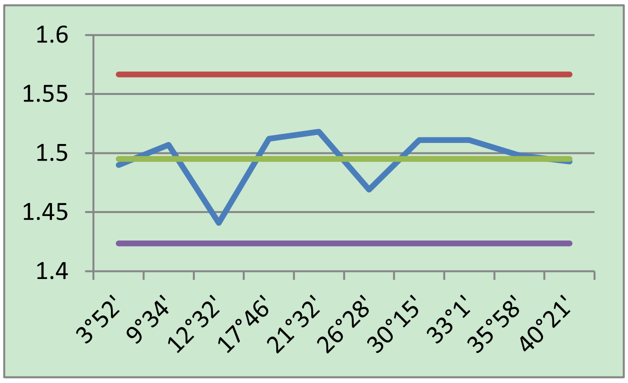


Figure 9. Control card for 1st pair

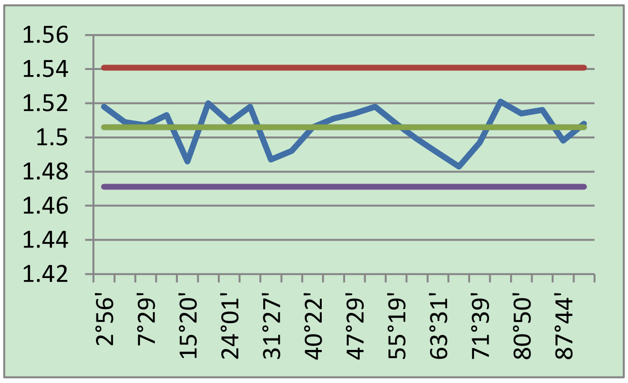


Figure 10. Control card for 2nd pair

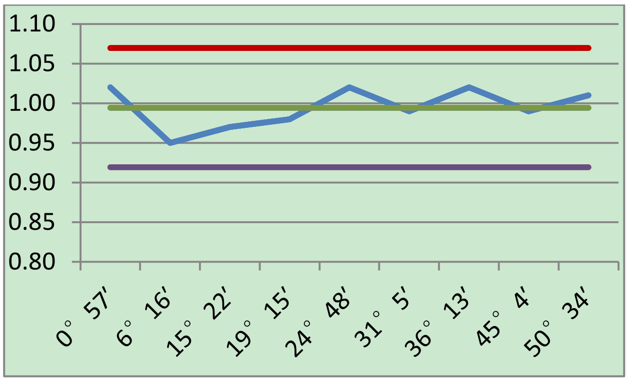


Figure 11. Control card for 3rd pair

The signs of unstable work of gearings on Shewhart charts are:

1. Exit of points beyond the upper or lower boundaries of the control card
2. 7 or more points in a row lie on one side of the midline
3. More than 6 points monotonically increase or decrease

It is evident, that lines being built does not show the signs. It means that all 3 gearings are valid for usage.

The transmission quality in the case of using Novikov gearing is also determined by the sensitivity of the gear ratio to a change in the center distance. When calculating the influence, the results of experimental data are taken into account.

An example of the definition of such an effect for transmission under number 2 is given in Fig. 12.

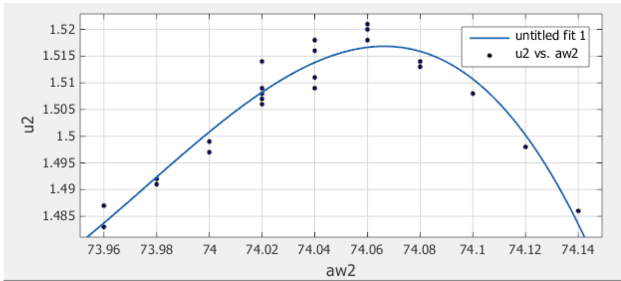


Figure 12. Influences of the interaxial distance of Novikov transmission on the gear ratio

The resulting function of the sensitivity of the gear ratio to a change in the center distance is described with following polynomial function:

f(x) = p1*x^3 + p2*x^2 + p3*x + p4

where x is normalized by mean 74.04 and std 0.04656

Coefficients (with 95% confidence bounds):

p1 = -0.001807 (-0.00287, -0.0007442)

p2 = -0.007108 (-0.00835, -0.005866)

p3 = 0.0109 (0.007991, 0.0138)

p4 = 1.513 (1.512, 1.515)

## V. OPTIMIZATION OF GEARING CONTROL

Measurement process of gearing ratio may be described with four dimentionless criteria, which show process stabilizing with each next measure. This criteria are [22-33]:

- criteria of variation of average value

$$T_1(n) = \frac{x(i)_{av} - x(n+1)_{av}}{x(n)_{av}}$$

where n is the current number of measurements, x(i) is the current value of measurable;

- criteria of variation of average value increment

$$T_2(n) = T_1(n) + T_1(n+1);$$

- criteria of variation of standard deviation

$$\mathrm{T}_3(n) = \frac{S(n) - S(n+1)}{S(n)},$$

where S(n) is standard deviation;

- criteria of variation of standard deviation increment

$$T_4(n) = \frac{D(n) - D(n+1)}{D(n)}$$

where D(n) is dispersion.

The rational number of measurements in control process may be determined when all the criteria is lower than 0.1. The results of criteria calculation on each measurement are given on Figs. 13-16.

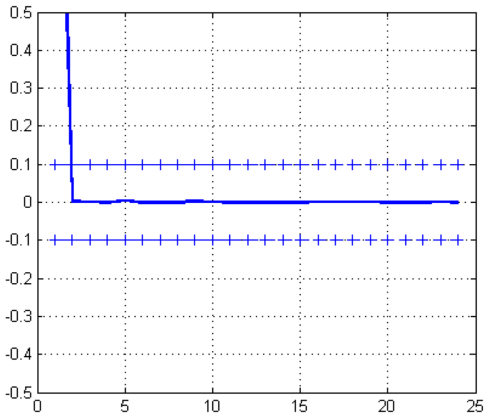


Figure 13. the result of stabilizing of gear ratio measurement stabilizing by 1st criteria

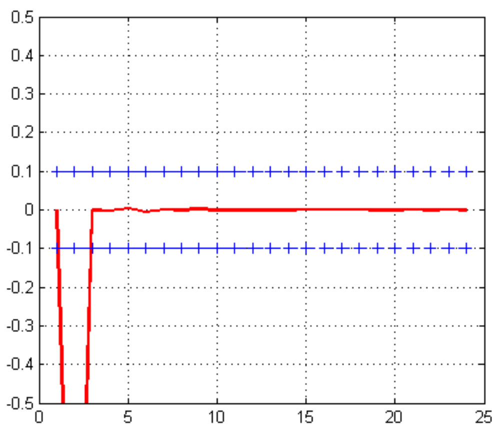


Figure 14. the result of stabilizing of gear ratio measurement stabilizing by 2nd criteria

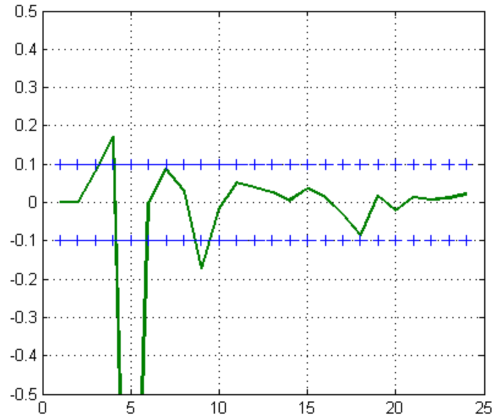


Figure 15. the result of stabilizing of gear ratio measurement stabilizing by 3rd criteria

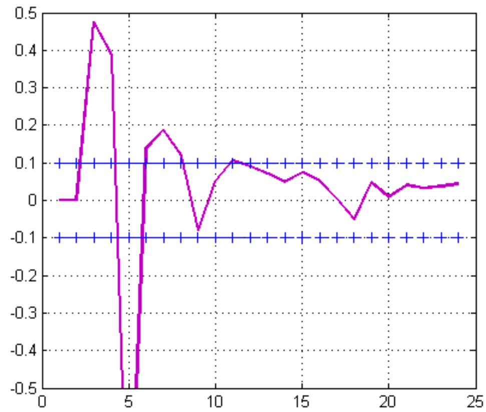


Figure 16. the result of stabilizing of gear ratio measurement stabilizing by 4th criteria

The calculation shows that number of measurement required for determination of mean gear ratio does not exceed the number of 12.

## VI. Conclusion

The research being held has shown the following results:

1. Replacing metal parts of the drive with polymer parts requires a change in its design.
2. As a replacement for metal gears with an involute tooth profile, there may be polymer round-helical wheels (Novikov gears) of a smaller number of teeth
3. To compensate for the deformative errors of the base, the tooth generatrix can be replaced by an arc, which will lead to the possibility of self-alignment of the wheels relative to each other
4. 3D-printed gears are accurate enough to work in agricultural machines drives.
5. The variation of gear ratio of gearing lies within 3σ range, which means that it is stable enough
6. The absence of signs of desynchronization on the Shewhart charts shows the possibility of using these gears in agricultural vehicles

7. The rational number of measurements for 3d printed gears control is determined as 12.

## Conflict of Interest

Author declares no conflict of interest.

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