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RESEARCH ARTICLE

Optimal Design of a Compound Planetary Reducer Using a Nonlinear Optimization Method

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ABSTRACT The growth of the robotics industry has led to rising demand for reducers that increase torque efficiently while reducing motor speed. Among them, compound planetary reducers can be effectively used in robots because they can achieve high gear ratios with smaller volume. The design of conventional reducers comprises the method of setting a gear ratio to design the gear dimensions and calculating efficiency through dynamic analysis. However, this method suffers from repeated designing and analysis, which makes it very time-consuming. Therefore, this study defines the problem of reducer design as the problem of optimization by setting an objective function, constraints, and boundary conditions, and proposes to obtain the results in a short period of time using the Sequential Least Squares Programming(SLSQP) method. Using the SLSQP method, optimization results can be obtained as real numbers, making it suitable for use in compound planetary friction reducers with no constraints on the selection of gear dimension. For the design problem of the conventional compound planetary gear reducer in which the module value exists, an additional optimal design method considering the module is proposed. To compare the optimal results, we have made a 30:1 compound planetary friction reducer and a 50:1 compound planetary gear reducer using 3D printing. A gear ratio evaluation experiment was conducted to evaluate the performance of the actual manufactured prototype reducers.

INDEX TERMS Design automation, gears, optimization methods, quadratic programming.

I. INTRODUCTION

The growth of the robotics industry fueled by Industry 4.0 has led to rising demand for reducers that reduce motor speed while increasing torque efficiently. Reducers commonly used in robots include planetary gear reducers, such as the one used in Massachusetts Institute of Technology(MIT)'s Mini cheetah [1], harmonic drive reducers, such as the one used in Korea Advanced Institute of Science and Technology(KAIST)'s DRC-HUBO+ [2], and cycloid drive reducers [3] used in industrial robots.

Among these, planetary gear reducers are used for a wide range of robotic applications since they can transmit higher torque with a simple structure and smaller volume [4]. In particular, compound planetary gear reducers can achieve higher gear ratios than single stage gears and provide high backdrive efficiency and high transmission efficiency [5]. Conventional reducer design suffers from the problem of having to repeat dynamic analysis after designing based on constraints, making it time-consuming.

Existing reducer design problems focused on gear trains weight optimization. Savsani et al. described the optimization of gear trains weight using particle swarm optimization and simulated annealing algorithms [6]. Yokota et al. described the optimization of gear using genetic algorithm [7]. Thompson et al. presented the optimization of multi-stage spur gear reduction units taking into account minimum volume and surface fatigue life, as objective functions, employing quasi-Newton method [8]. In addition, for studies related to compound planetary reducer, Zhang et al. described dynamic modeling and vibration characteristics of a two-stage closed-form planetary gear train [9], Ericson and Parker studied

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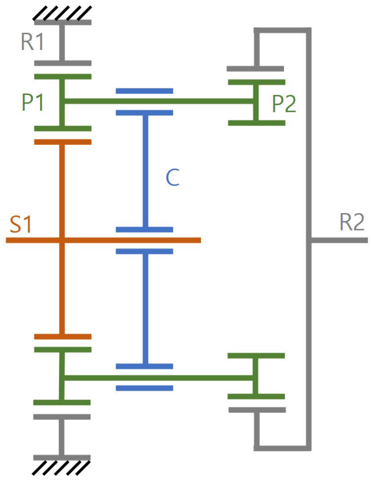

FIGURE 1. Structure of 3K type compound gear.

planetary gear modal vibration experiments and correlation against lumped-parameter and finite element models [10]. As such, existing reducer gear design problems are studied mainly on optimization of reducer weight and dynamic models of compound planetary reducer, and research on gear ratio optimization of compound planetary reducer is rare.

The previous study conducted at this lab [11] transformed the problem of reducer design into the problem of conventional optimization in which optimal solutions to the objective functions were found using many variables. The study proposed a solution to the problem of designing an optimal gear ratio by applying the Sequential Quadratic Programming(SQP) method. However, while friction drive reducers could benefit from this solution, it was difficult to apply it to gear drive reducers because it failed to take modules into consideration. Therefore, in this study, modules were additionally defined as constraints to propose a module-based optimal gear ratio design. Furthermore, in this study, optimal design was carried out based on the above-described optimal design method and a prototype reducer was manufactured using 3D printing to evaluate the performance of an actual reducer through an experiment.

II. COMPOUND PLANETARY REDUCER

A. REDUCER STRUCTURE

A planetary gear reducer comprises the central sun gear, a peripheral ring gear, multiple planet gears in between the sun and ring gears, and a carrier holding the planet gears in place. Planetary reducers are classified according to the combination of shafts. The shaft of the sun and ring gears is expressed as K, the shaft of the carrier H, and the shaft of the planet gears V. According to the combination of these, the reducers are divided into 2K-H and 3K types [12]. This study uses a 3K compound planetary reducer as shown in Fig. 1.

The 3K compound planetary reducer used in this study comprises the first gear featuring sun gear S1, planetary gear P1, and ring gear R1 and the second gear featuring sun gear S2, planetary gear P2, and ring gear R2, having a structure in which S1 is used as an input shaft and R2 as an output shaft. The 1^{st} and 2^{nd} gears are coupled to comprise a compound gear through the coupling of P1 and P2 [13].

A compound planetary gear reducer can overcome the ratio limitations of single stage gears, achieve total ratio up to 1000:1, and accommodate thin structures. Moreover, the large diameter of the sun gear benefits gears with center hollow, and the multiple planet gears help increase torque effectively.

B. GEAR RATIO ANALYSIS

Gear ratios for the 3K compound planetary gear reducer can be found as shown in (1). In determining a gear ratio, when the I_2 in the denominator gets closer to 1, the denominator gets closer to 0, achieving a higher gear ratio. It means that higher gear ratios can be achieved as the gear ratios of P_1 and P_2 and the gear ratios of R_1 and R_2 get closer to 1. The forward efficiency and the backdrive efficiency of the reducer can be calculated using (2) and (3), respectively [13].

$$Gr = \frac{\omega_{S_1}}{\omega_{R_2}} = \frac{1+I_1}{1-I_2} = \frac{1+\frac{R_1}{S_1}}{1-\frac{R_1}{R_2}\cdot\frac{P_2}{P_1}} \left(I_1 = \frac{R_1}{S_1}, I_2 = \frac{R_1}{R_2}\cdot\frac{P_2}{P_1}\right) \tag{1}$$

where, Gr is gear ratio, ω_{S1} is angular velocity of S1, ω_{R2} is angular velocity of R2, S_1 is pitch radius of the 1^{st} sun gear, P_1 is pitch radius of the 1^{st} planetary gear, R_1 is pitch radius of the 1^{st} ring gear, S_2 is pitch radius of the 2^{nd} sun gear, P_2 is Pitch radius of the 2^{nd} planetary gear and R_2 is pitch radius of the 2^{nd} ring gear.

$$\eta_{for} = \frac{(1+\eta_a\eta_b I_1)(1-I_2)}{(1+I_1)(1-\eta_b\eta_c I_2)} \tag{2}$$

where, η_{for} is forward efficiency, η_a is efficiency between the 1^{st} sun gear and the 1^{st} planetary gear, η_b is efficiency between the 1^{st} planetary gear and the 1^{st} ring gear and η_c is efficiency between the 2^{nd} planetary gear and the 2^{nd} ring gear.

$$\eta_{back} = \frac{(1+I_1)\eta_a(\eta_b\eta_c - I_2)}{\eta_c(\eta_a\eta_b + I_1)(1-I_2)} \tag{3}$$

where, η_{back} is backdrive efficiency.

III. DEFINING THE PROBLEM OF OPTIMIZATION

To design an optimal gear ratio for the reducer, the problem of optimization was defined as shown in Table 1 [14]. The objective function was designed to maximize the forward efficiency, and the problem consists of five constraints. Constraint 1 was defined so that the optimal backdrive efficiency was a higher value than the target backdrive efficiency. Constraint 2 was defined so that the optimal gear ratio was equal to the target gear ratio. Constraints 3 and 4 were defined so that, based on the kinematics of the planet gears, the pitch radius of the sun gear and the pitch diameters of the planet gears were added up to equal the pitch radius of the ring gear [15]. Constraint 5 was defined based on the premise

TABLE 1. Problem definition of optimal design.

$min \frac{1}{\eta_{for}}$	Objective function: Maximizing forward efficiency
$\eta_{back} \geq \eta_{target}$	Constraint 1: Making backdrive efficiency greater than target efficiency
$\frac{1+I_1}{1-I_2} = Gr$	Constraint 2: Gear ratio is given as Gr
$R_1 = S_1 + 2P_1$	Constraint 3: Kinematics condition of 1^{st} planet gear
$R_2 = S_2 + 2P_2$	Constraint 4: Kinematics condition of 2^{nd} planet gear
$S_1 + P_1 = S_2 + P_2$	Constraint 5: Condition that central distances of compound planetary gears are identical
$S_{min} \leq S \leq S_{max}$ $P_{min} \leq P \leq P_{max}$ $R_{min} \leq R \leq R_{max}$	Boundary condition: Defining ranges of pitch radius of sun gear, planet gears, and ring gear
$x_0 = (S_1, P_1, R_1, S_2, P_2, R_2)$	Defining initial values

that P1 and P2 were coupled together as long as the center distances of the compound planetary gears were identical, and that the center distances of the 1^{st} planet gear and the 2^{nd} planet gear were also in agreement. Constraint 1 was set as an inequality condition while constraints 2 to 5 were set as equality conditions. The boundary conditions could be set according to the motor size or user preferences, and the initial value could be selected within the boundary condition.

IV. SQP OPTIMIZATION SOFTWARE

An SQP optimization method is a repetitive method aimed at nonlinear optimization under constraints. There are a variety of SQP methods, such as Space Nonlinear OPTimizer(SNOPT), Sequential Least SQuares Programming(SLSQP), Non-Linear Programming by Quadratic Lagrangian(NLPQL), and Feasible Sequential Quadratic Programming(FSQP) and supported in a variety of environments, including MATLAB, GNU Octave, and Python. Among these, one can benefit from using SLSPQ since it is simple in obtaining an optimal solution to an objective function that has received multivariable inputs using SciPy library [16] in a Python environment. Therefore, this study utilized SLSQP as a method for solving the problem of optimization as defined in Section III.

A. GEAR OPTIMIZATION PSEUDO CODE BASED ON GEAR DIMENSIONS

To carry out optimization, the calculations were made based on the gear ratio using Python, as well as the scipy optimize package. Since the optimal values are long decimals when the SLSQP method is used, it results in limitations for the manufacturing of an actual compound planetary reducer. Therefore, an optimal value found using the SLSQP method was rounded to the desired decimal place and then the constraints were taken into consideration to produce the software program for optimal design. Fig. 2 represents the flowchart of optimization based on gear dimension.

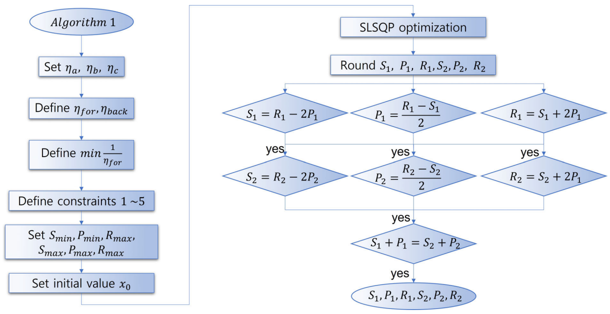

FIGURE 2. Flowchart of optimization based on gear dimension.

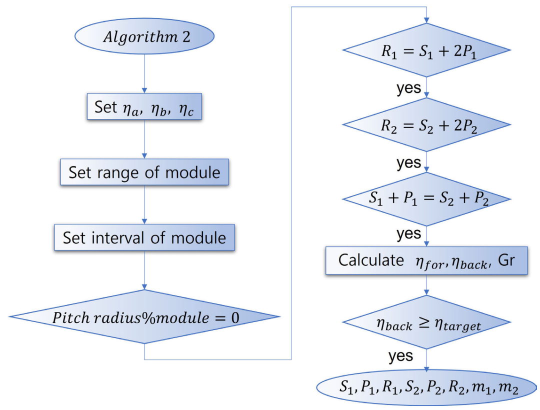

FIGURE 3. Flowchart of optimization based on module.

B. GEAR OPTIMIZATION PSEUDO CODE BASED ON MODULE

As described in Section IV-A, the SLSQP method is aimed at nonlinear optimization with constraints, it is useful for the optimal design of a compound planetary friction reducer. However, module-based composite planetary gear reducers have limitations in using SLSQP because the boundary conditions are discontinuous when applying the module. The module-based optimization program is designed by using module values to specify boundary conditions as discontinuous data, creating a list of data that meets constraints 2 and 3, and then re-creating a list that meets constraint 4. Fig. 3 represents the flowchart of optimization based on module.

C. GUI (GRAPHICAL USER INTERFACE)

A GUI was created using the PyQt5 package [17] to make it easier to use the optimization program. Qt is a C++-based cross platform framework commonly used in the development of GUI programs, and PyQt refers to the package that can be used in Python. The UI was made using Qt Designer of PyQt5, and PyQt5 was used to set the function for buttons. Also, to import the UI to Python, pyuic5 was used to convert it into a py file. To use the optimization program in a Windows environment, instead of a Linux environment, the Pyinstaller library [18] was used to create an executable file.

TABLE 2. Optimal result.

Optimal design based on gear dimension		
Goal Gr:30	Gr	30.04
	Gr error	0.04
	$\eta_{for}(\%)$	91.51
	$\eta_{back}(\%)$	90.93
	S_1, P_1, R_1(mm)	30.0, 8.5, 47.0
	S_2, P_2, R_2(mm)	30.87, 7.63, 46.13
Optimal design based on module		
Goal Gr:50	Gr	50.29
	Gr error	0.29
	$\eta_{for}(\%)$	91.11
	$\eta_{back}(\%)$	90.53
	S_1, P_1, R_1(mm)	7.0, 8.0, 28.0
	S_2, P_2, R_2(mm)	8.0, 7.0, 22.0
	m1(mm)	1.0
	m2(mm)	1.0

1) OPTIMIZATION SOFTWARE BASED ON GEAR DIMENSION

Based on the conditions defined in TABLE 1, the boundary conditions, default values, target gear ratios, and target backdrive efficiency are set. Then, the desired decimal place is selected to obtain the optimal parameters and constraint validation is conducted.

2) OPTIMIZATION SOFTWARE BASED ON MODULE

The target gear ratios, module and boundary conditions were set for optimization, and the GUI was created so that all the results could be produced in the order in which ones with greater forward efficiency and smaller gear ratio errors.

V. OPTIMAL GEAR DESIGN

Each optimal design was carried out based on the gear dimensions and module, respectively. To test the performance of an actual compound planetary reducer in regards to the optimal design, 3D printing was used to manufacture a reducer.

A. OPTIMAL DESIGN BASED ON GEAR DIMENSIONS

The optimal design of a 30:1 compound friction reducer was conducted based on gear dimensions. In the optimal design, the boundary condition was designed within the radius range of S = (30, 40), P = (5, 15), and R = (40, 47). The efficiencies between the gears were assumed to be $\eta_a = 0.977$, $\eta_b = 0.996$, and $\eta_c = 0.997$, and the target gear ratio was set to 30:1 and the target backdrive efficiency to 80% to carry out the optimal design.

Under the above conditions, the gear dimensions for the optimal design were optimized to the second decimal places. The optimization results are shown in Table 2, with the resulting gear ratio of 30.04:1 and the backdrive efficiency of 90.93%.

B. OPTIMAL DESIGN BASED ON MODULE

The module-based optimal design of the 50:1 reducer was conducted. In the optimal design, the boundary conditions for the gears were designed within the radius ranges of S = (5, 15), P = (5, 10), and R = (20, 30). The efficiencies between the gears were assumed to be $\eta_a = 0.977$, $\eta_b = 0.996$, and $\eta_c = 0.997$, the target gear ratio was set to 50:1 and the target backdrive efficiency to 80% to carry out the optimal design.

Table 2 shows the optimization design results under the above conditions, with the gear ratio of 50.29:1 and backdrive efficiency 90.53%, and the result of 1.0 mm was obtained for modules 1 and 2.

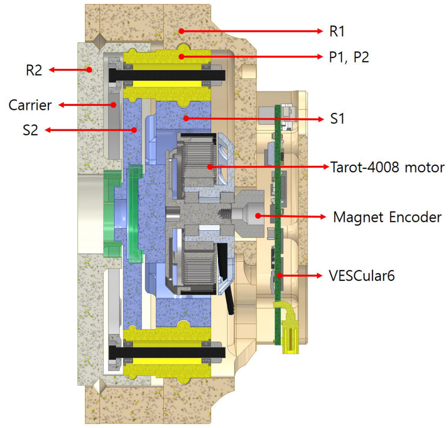

FIGURE 4. 30:1 compound planetary friction reducer.

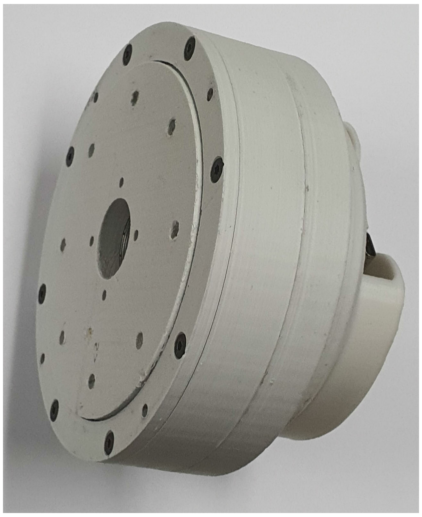

FIGURE 5. Manufactured 30:1 compound planetary friction reducer using 3D printing.

C. 30:1 COMPOUND PLANETARY FRICTION REDUCER

The 30:1 compound planetary friction reducer was manufactured using 3D printing based on the gear dimensions-based optimal design. The friction of the compound planetary friction was increased by applying a urethane coating to the 3D print. As for the motor, Tarot-4008 was used; as for the motor drive, VESCular6 [19], [20] was used and four planetary friction wheels were used.

To reduce the friction of R1 and R2, iron beads were used to serve as ball bearings. Fig. 4 represents the design for the 30:1 compound planetary friction reducer. Fig. 5

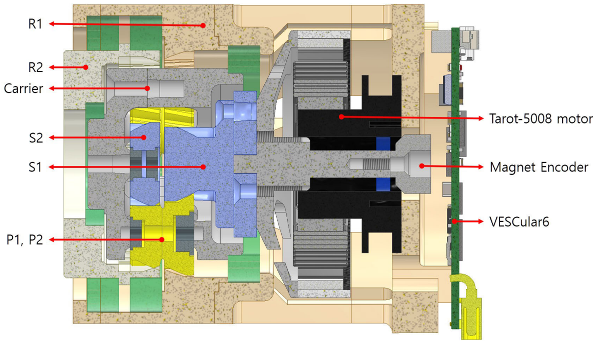

FIGURE 6. 50:1 compound planetary gear reducer.

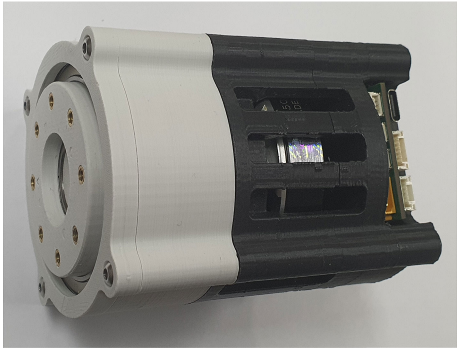

FIGURE 7. Manufactured 50:1 compound planetary gear reducer using 3D printing.

represents manufactured 30:1 compound planetary friction reducer using 3D printing.

D. 50:1 COMPOUND PLANETARY GEAR REDUCER

The 50:1 compound planetary gear reducer was manufactured using 3D printing based on the module-based optimal design. As for the motor, Tarot-5008 was used; for the motor drive, VESCular6 was used. Three compound planetary gears were used. Fig. 6 shows the design of the 50:1 compound planetary gear reducer. Fig. 7 represents manufactured 50:1 compound planetary gear reducer using 3D printing.

VI. EXPERIMENT AND RESULTS

Based on the optimal gear design described in Section V, the 30:1 compound planetary friction reducer and the 50:1 compound planetary gear reducer were manufactured using 3D printing. The experimental apparatus was developed to compare the optimal values and actual values by using the aluminum profiles, Tarot-4008 motor, Tarot-5008 motor, Maxon EC-4pole motor, the VESC driver, and VESCular6 as shown in Fig. 8.

A. CONSTANT-SPEED DRIVE GEAR RATIO EXPERIMENT

An experiment was conducted for the measurement of gear ratios using the ratio of an output velocity to an input velocity during continuous rotation at constant velocity.

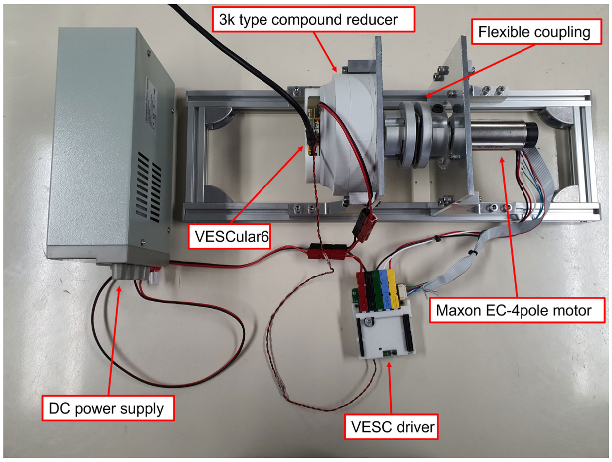

FIGURE 8. Experimental system.

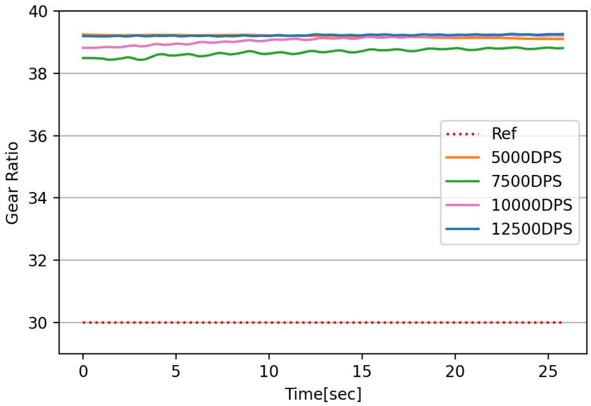

FIGURE 9. Experimental result of gear ratio error of 30:1 compound planetary friction reducer.

Four measurements were taken for about 25 seconds at the input velocities of 5000DPS, 7500DPS, 10000DPS, and 12500DPS.

B. EXPERIMENTAL RESULT

Fig. 9 shows the measurement results of the 30:1 compound planetary friction reducer, while Fig. 10 shows the measurement results of the 50:1 compound planetary gear reducer. The experimental results of gear ratio measurements during continuous rotation at constant velocity showed that 39.04:1 was obtained for the gear ratio of the manufactured compound planetary friction reducer and 50.31:1 for the gear ratio of the compound planetary gear reducer. There was a 0.02 difference from the 9.0 gear ratio tolerance of the optimal design. TABLE 3 represents the detailed experimental results.

As for the compound planetary friction reducer, there was a relatively big tolerance due to a dimensions error caused by 3D printing, and an error caused by the slip of the friction wheels. However, the time-series representation of the compound planetary gear reducer found that, although the fluctuations in gear ratio seemed great, they were caused by

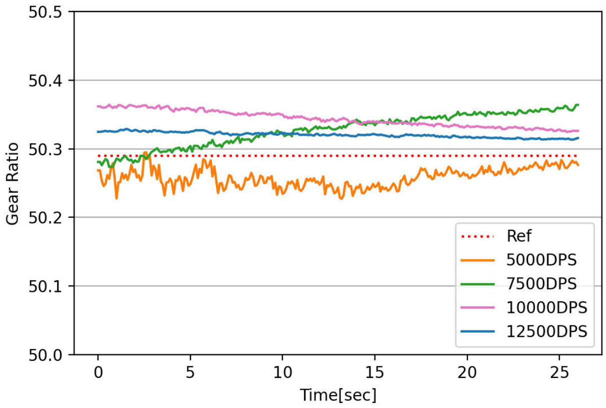

FIGURE 10. Experimental result of gear ratio error of 50:1 compound planetary gear reducer.

TABLE 3. Experiment result.

		Gear ratio
30:1 compound planetary friction reducer	Optimal design	30.04
	2500DPS	39.18
	5000DPS	38.67
	10000DPS	39.08
	125000DPS	39.22
	Experiment average	39.04
	Gear ratio error	9.0
50:1 compound planetary gear reducer	Optimal design	50.29
	2500DPS	50.26
	5000DPS	50.33
	10000DPS	50.34
	125000DPS	50.32
	Experiment average	50.31
	Gear ratio error	0.02

the speed changes to keep the speed constant and thus actually small differences on average. In other words, the results show that there was no significant difference between the optimal design and the actual reducer. Moreover, the errors seem to have been caused by the use of theoretical values for the efficiencies between gears, instead of actual measurements.

VII. CONCLUSION

The study solved the problem of optimal gear ratio design by transforming it into a general problem of optimization with constraints. Furthermore, it proposed a solution for the optimal design of a compound planetary gear reducer by taking into account the modules of compound planetary gear reducers and adding modules as constraints.

To make the proposed optimal design method easy to use in practice, a GUI was created and programmed [21]. To compare the optimal design and an actual reducer, a reducer was manufactured using 3D printing. Using the manufactured reducer, a gear ratio measurement experiment was conducted based on changes in gear ratio and revolutions with time.

Since the proposed optimal design method has been programmed, it is easy to use in actual settings and provides high accuracy. Therefore, it can be effectively applied to a wide range of robots or actuators that utilize actual reducers.

The gear parameter design method proposed in this paper has a limitation in that it may not accurately match the value specified by the user in terms of gear ratio. In some cases, the target gear ratio may not be physically achieved at a size specified by the user. Therefore, we designed to find a value as close as possible to the gear ratio specified by the user. However, this is not a big issue because when applied to an actual robot, it is controlled based on the result gear ratio.

In this paper, we propose an optimization method using only SLSQP, but in future studies, we will study the optimal design of gear parameters through more various optimization techniques.

In addition, to compare performance more accurately, we will include torque efficiency measurements using a torque gauge and performance tests will be carried out by adding a preload system that can apply more pressure as necessary to reduce slip and increase grip of the compound planetary friction reducer.

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