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Experimental Evaluation of a Quasi-direct-drive Actuator with a 3D-printed Planetary Gear Reducer

Takateru Yoshida[1], Gen Endo[1], Akifumi Okubo[1] and Hiroyuki Nabae[1]

Abstract— **When electromagnetic motors are used as actuators for robots, the reduction gear is an essential component in most cases. The mechanical design choices increase if we can fabricate the custom-made reduction gear. The performance of the robot also increases because of the optimized reduction ratio. Moreover, the rapid progress of the 3D printing technology allows us to develop the reduction gear at a low cost agilely. However, most of the previous development remains at the proof-of-concept level, and quantitative evaluation of the 3D printed reduction gear is insufficient.**

In this paper, we fabricated a quasi-direct-drive actuator with a 3D-printed planetary gear reducer. The planetary gear reducer consists of resin molded parts by Fused Filament fabrication. We quantitatively measured its performances such as 1) transmission efficiency of static torque, 2) joint stiffness, 3) the effect of temperature on stiffness, 4) the influence of the 3D printing parameters on stiffness and strength, and 5) durability against a continuous operation. The prototype actuator unit demonstrated a sinusoidal joint movement for 46 hours, where its maximum output torque and frequency were 19.6 Nm and 0.1 Hz, respectively.

I. INTRODUCTION

When electromagnetic motors are used as actuators for robots, the reduction gear is an essential component in most cases. No matter how high the output of the electromagnetic motor is, the reduction gear performance is crucial because the maximum output power and torque are governed by the transmission efficiency and maximum allowable torque of the reduction gear. On the other hand, high-performance reduction gears are generally expensive, and highly rigid reduction gears tend to have a higher mass. In the prototyping of the robot, the selection of the reduction gears has traditionally been based on size, mass, maximum torque, reduction ratio, price, and delivery time, all of which satisfy the individual design specifications.

If we fabricate the reduction gear from scratch, it would increase the design choices, and the robot achieves higher performance thanks to the optimum reduction ratio. For example, Fujimoto et al. demonstrated that the forward- and backward-driving efficiencies of a 3K planetary reduction gearbox can be improved by optimizing the number of teeth and the profile shift coefficients in a prototype [1]. Yamato et al. have developed a thin and lightweight cycloidal reduction gear and conducted detailed evaluations of torque transmission efficiency, no-load running torque, durability under overload conditions, and temperature under overspeed conditions [2]. As a result, they have reported that the reducer has higher design freedom and sufficient durability by operating experiments on a mobile robot.

In the meantime, 3D printing technology for resin materials, represented by the FFF method, has been dramatically developed in recent years. The strength of resin materials was significantly insufficient that they could only be used to confirm the shape of parts 20 years ago. However, material strength has gradually improved in recent years, allowing us to make functional parts that transmit force through a mechanism. If a reduction gear can be constructed using 3D printed parts, it will enable low-cost and rapid agile development. Also, it would allow for a higher degree of design freedom, for example, by integrating the structural parts and the reduction gear output into a single unit. Also, weight reduction through the use of resin is highly desirable.

Takesue et al. fabricated a prototype of a quasi-direct-drive actuator that combines a DD motor and a 3D printer-made reduction gear with a reduction ratio of 10:1 [3]. This actuator, combined with a spring-cam type gravity compensation mechanism, demonstrated enhancement of the position controllability of the manipulator. Kim et al. have developed a prototype actuator unit that combines an actuator

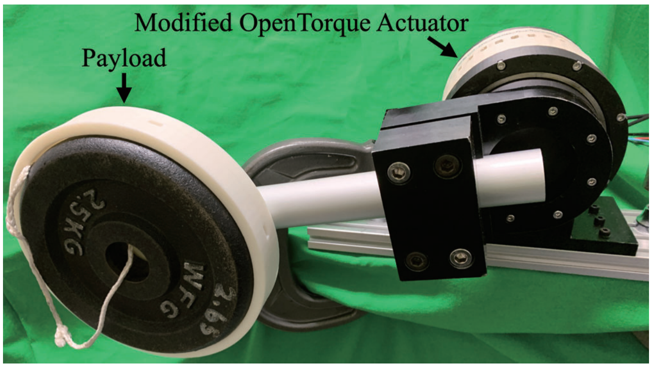

Fig. 1. Overall image of Modified OpenTorque Actuator

TABLE I
SPECIFICATIONS OF MODIFIED OPENTORQUE ACTUATOR

Size	114 mm in diameter, 116.5 mm in height
Weight	1381 g
Actuator output	1433 W
Raito	8 : 1
Number of Teeth (Sun, Planetary, Ring)	9, 27, 63
Rated Torque	37.6 Nm (theoretical value)
Max Torque	80 Nm (theoretical value)

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for a drone with a 3D printed epicycle planetary gearbox and a cycloid gearbox, aiming at a cost reduction of the collaborative robot [4]. Tough PLA is used as the material. There is also an open source project to realize a quasi-direct-drive actuator with a similar configuration, but higher output power[5]. However, the purpose of these prototypes is proof of concept, and concrete performance evaluation, as in the study by [2] has not been sufficiently conducted.

This paper aims to develop an actuator unit with a higher output reduction gear using resin molded parts by FFF type 3D printer and to clarify its various performances. Fig. 1 shows an overview of the developed quasi-direct-drive actuator unit and Table. I shows specifications. In particular, we tested two types of high-strength fiber-reinforced nylon resin materials to achieve a high strength instead of the conventional ABS and PLA materials. In addition, various characteristic tests will be conducted to evaluate the performance of the actuator unit. Specifically, detailed measurements were made of 1) efficiency at static torque output, 2) servo stiffness of the output shaft, 3) effect of temperature on stiffness, 4) effect of 3D printing parameters on strength and stiffness, and 5) durability against a continuous operation.

II. Development of a Quasi-Direct-Drive Actuator Unit using 3D-printed parts

Although there are various reduction mechanisms, this paper uses a single-stage planetary reduction mechanism. This reduction gear is the most straightforward coaxial reduction mechanism, and its basic characteristics are easy to understand. In addition, since the mechanical strength of plastic parts is much lower than that of metal parts, it is desirable to mesh multiple teeth and reduce the tooth surface pressure. Furthermore, thanks to sufficient backdriverbility, damage can be prevented by passive compliance with electromagnetic forces or active compliance with control, even if a large load, such as an impulsive force, acts on the output shaft. For these reasons, we will start with a quasi-direct-drive actuator unit as a first study, aiming at the highest performance that can be achieved with this unit.

As an example of a 3D printed actuator that satisfies the above conditions, the OpenTorque Actuator [5] was selected for this paper, and a prototype actuator unit was fabricated by modifying [5]. The improvements from the original are as follows.

- From the viewpoint of availability, the large cross roller bearings on the output shaft were replaced with two deep groove ball bearings.
- To suppress the tilt of the rotating shaft, the planetary gear was supported by two ball bearings.
- To suppress the generation of axial loads, the planetary gears were changed from helical gears to spur gears.

All parts shown in Fig. 2 were fabricated by a 3D printer except the bearing, planetary gear shaft, and screw insert. A brushless DC motor for drones with high torque density (ZHUHAI Owl Eagle motor. ltd: X8318S, rated voltage: 48 V, rated torque: approx. 4.7 Nm, torque density: 6.76 [Nm/kg]) is used as the actuator. A sun gear with 9 teeth is

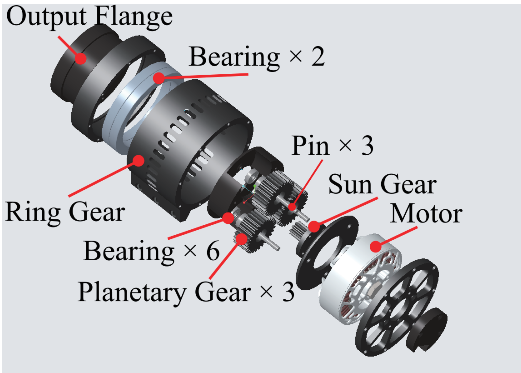

Fig. 2. Exploded view of Modified OpenTorque Actuator

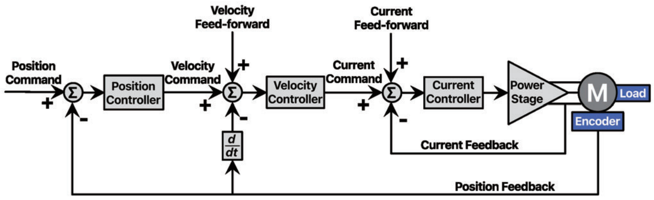

Fig. 3. Block diagram of motor control (ODrive)

fastened to the output shaft of this actuator via a flange to serve as the input to the reduction gear. The output of the reduction gear is the rotation of a planetary gear carrier with 27 teeth, and since the internal gear has 63 teeth, its reduction ratio is 8:1. The tooth geometry is a spur gear with a module of 1.5, a pressure angle of 20° , and an involute tooth profile. The specifications are shown in TABLE I. The rated output of this actuator is 1433 W, which is approximately 24 to 34 times higher than the rated output of the actuator in Reference [4].

The actuator is controlled by sending commands to the motor driver (ODrive Robotics, Inc. ODrive) from a PC via USB. The rotation angle of the actuator, i.e., the sun gear, is measured by a magnetic encoder (ams AG: AS5047D-TS EK AB). The feedback control system is a cascade control system as shown in Fig. 3. The position control, speed control, and current control loops are P, PI, and PI control, respectively. Feedforward control is also incorporated to reduce trajectory tracking errors.

III. Materials

Onyx from MarkForged and a potassium titanate fiber-reinforced material from Otsuka Chemical Corporation called POTICON were used as materials for the FFF 3D printer. The mechanical properties are shown in TABLE II [6] [7]. It can be seen that POTICON is superior in terms of strength. Both of these resins are superior to conventional PLA and ABS resins in terms of mechanical strength. In particular, POTICON is widely applied to watch gear because of its high abrasion resistance [8]. Moreover, FFF with short fiber reinforcement is superior to injection molding in bending stress thanks to the fiber orientation going through the nozzle in the FFF process [9]. Therefore we investigate the possibility of applying Onyx and POTICON to a planetary gear reducer.

TABLE II

MECHANICAL PROPERTIES OF THE MATERIALS

Material	Onyx	POTICON	ABS	PLA
Tensile strength [MPa]	37	100	38	45
Bending strength [MPa]	71	167	61	92
Flexural Modulus [GPa]	3.0	6.3	1.4	2.9
Heat deflection temp. [°C] @0.45 MPa	145	120	87	58

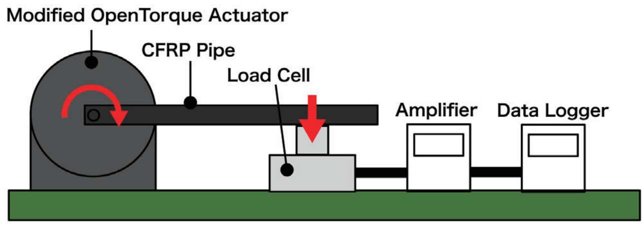

Fig. 4. Experimental apparatus for static torque measurement

IV. EVALUATION OF CHARACTERISTICS

To evaluate the basic performance of OTA, we investigated 1) static torque transmission efficiency, 2) joint stiffness, 3) relationship between temperature and stiffness, 4) relationship between parameters for the 3D printing and stiffness, and 5) durability against a continuous operation. These characteristics depend on the gear material. Three types of planetary gears are used: sun gear, ring gear, and planetary gear, and each material is combined as shown in Table II for comparison through experiments. Onyx and POTICON parameters for the 3D printing are shown in TABLE IV. The sun gears of A7075 and POM were fabricated by machining from a solid material.

A. Static torque measurement

In this section, we measure the torque transmission efficiency during a stall. In particular, we quantitatively clarify how the transmission efficiency is affected by the gear material. As shown in Fig. 4, a pipe made of CFRP material was attached to the output shaft of the OTA, and a load cell was installed so that the CFRP pipe was horizontal to the ground and in contact with the load cell. Type 1, Type 2, and Type 3 in TABLE III were used for the measurements in this section.

The results are shown in Fig. 5. The horizontal axis shows the commanded torque multiplied by the reduction ratio, and the vertical axis shows the efficiency, which is the measured value of static torque divided by the commanded value multiplied by the reduction ratio. Although the reduction gear with A7075 sun gear showed a decrease in efficiency when the stall torque increased, the decrease was smaller, and the efficiency was higher than that of the Onyx and POTICON reduction gears. Both Onyx and POTICON gear reducers showed more than 80% efficiency at 20Nm or less, but the efficiency decreased as the stall torque increased in the range of 20Nm or more. No significant differences were observed when Onyx and POTICON gear reducers were compared. In addition, no gear component breakage was observed within the experimental measurement range.

TABLE III

COMBINATION OF MATERIALS

Type	Sun	Planetary	Ring
1	Onyx	Onyx	Onyx
2	POTICON	POTICON	POTICON
3	A7075	POTICON	POTICON
4	POM	POTICON	POTICON

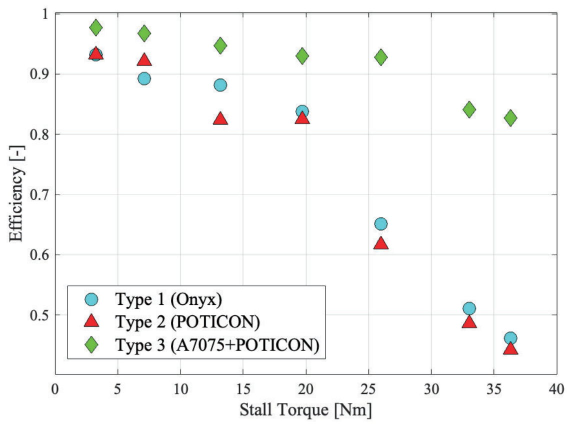

Fig. 5. Transmission efficiency of static torque

The reason why the reduction gears with all gear parts made of Onyx and those made of POTICON showed significantly lower efficiency than those with only sun gears made of A7075 was due to the rigidity of the sun gears. The resin sun gears deformed during the measurement, and the mechanical resistance, such as gear meshing, increased, resulting in less torque generated at the output shaft. The reason for the slight difference between POTICON and Onyx, which are more than two times different in terms of strength and stiffness as shown in TABLE II, is considered to be that the stiffness varies depending on the lamination pattern because different 3D printers were used to fabricate the materials even though the parameters for the 3D printing are the same. The details are described in section D.

B. Joint stiffness measurement

This section measures joint stiffness when the joint angle keeps the horizontal position. In particular, the relationship between gear material and joint stiffness will be clarified. A carbon fiber reinforced plastic (CFRP) pipe was fixed to the output shaft of the actuator unit to investigate joint stiffness, as shown in Fig. 6, and a load was applied by suspending a weight on the pipe. A marker for motion capture was attached to the CFRP pipe to measure the displacement angle. The experiment was conducted on Type 1, Type 2, Type 3, and Type 4 in TABLE III. The results are shown in Fig.7. $\Delta\theta$ is the amount of gear deformation. $\Delta\theta$ is calculated by the output shaft rotation, the input shaft rotation, and the reduction ratio.

The results for A7075 and POM were close to each other. Onyx and POTICON also showed a similar tendency. The larger the load torque, the larger $\Delta\theta$ becomes. Although POTICON has higher strength and stiffness properties than POM [10], POTICON showed a larger rotation angle than

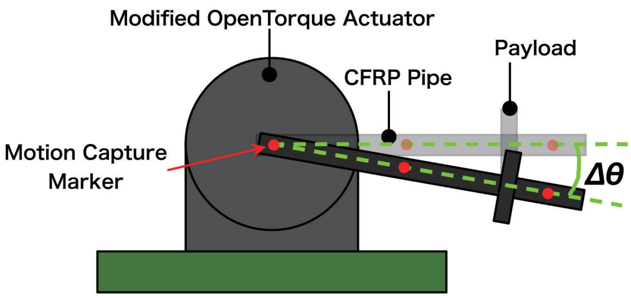

Fig. 6. Experimental apparatus for joint stiffness measurement

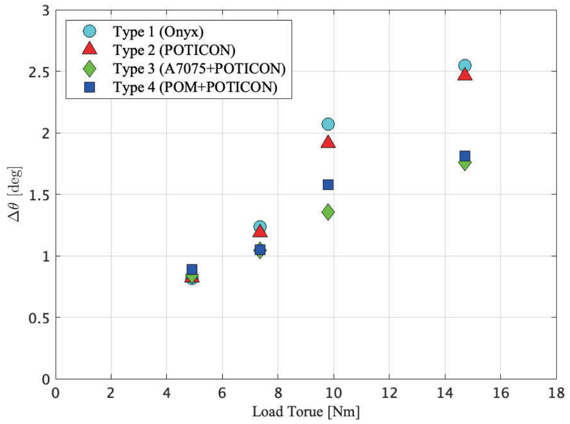

Fig. 7. Joint Stiffness of Modified OpenTorque Actuator

POM. The reasons would be a backlash caused by the modeling accuracy and the stiffness reduction by the layering of the 3D printer, as mentioned in Section IV-A.

C. Effect of temperature on stiffness

Because FFF 3D-printed parts are made of thermoplastic resin, we need to avoid overheating above the load deflection temperature. We measured the temperature of the reducer and the time history of the rotation angle of the output shaft using motion capture when a static load was continuously applied while the actuator unit kept the horizontal position. This measurement investigates the relationships between temperature and stiffness of the gear reducer. The magnitude of the load torque was 14.7 Nm, which is less than the rated torque of the output shaft. Temperatures were measured using a thermal imaging camera to measure the surface temperature of the ring gear and winding coils of the motor. Experiments were conducted on Type 2 and Type 3 in TABLE III.

Fig. 8 shows the time histories of the temperature of the ring gear surface and the motor coil, and Fig. 9 shows the time history of the joint angle. The surface temperature of the ring gear was slightly higher in the case of the POTICON than in the case of the A7075 at the same elapsed time, but it was not as high as the difference in the motor coil temperature, confirming that the temperature rising rate of the 3D printer modeling part due to motor heat is not proportional. After 45 minutes, we removed the

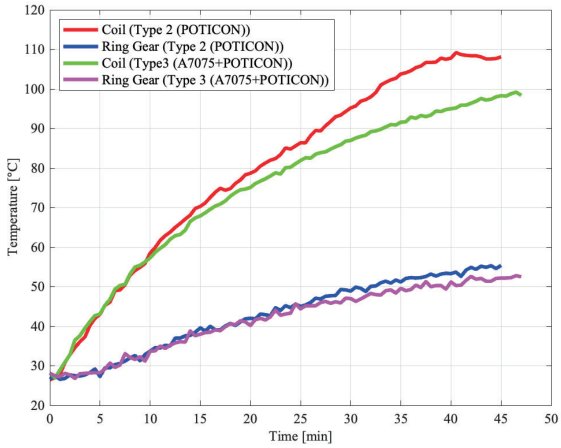

Fig. 8. Time history of the temperature

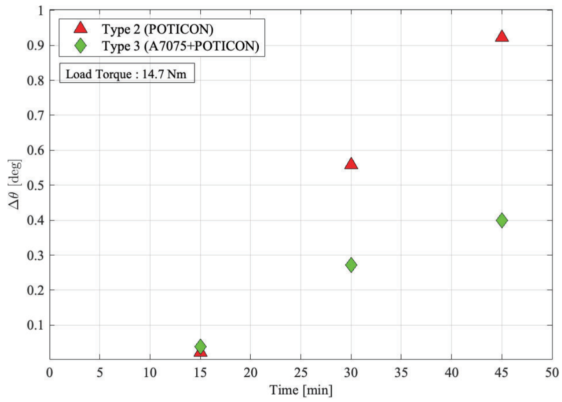

Fig. 9. Time history of the deviation of the output joint angle

motor, and measured the temperature inside the reducer. The temperatures of both the POTICON and A7075 were about 55 ° C, below the heat deflection temperature.

As shown in Fig. 9, the rotation angles of the output shafts were similar after 15 minutes of measurement. However, the displacement angle difference between the POTICON and A7075 increased as time passed after 30 and 45 minutes. Considering that there was no significant change in the rotation angle of the input shaft during the measurement, the change in the rotation angle of the output shaft was due to the creep deformation of the resin gear and was influenced by temperature. In summary, under the conditions of this experiment, the resin components remained below the heat deflection temperature, suggesting that no significant deformation of the gears occurred but that the rigidity of the gears decreased in a temperature-dependent manner.

D. Stiffness and strength effects by the parameters for the 3D printing

When the motor rotated with a load attached to the gear reducer, the sun gears manufactured by the 3D printer often broke at the boundary between the flange and the teeth, as shown in Fig. 10. In addition, comparing the Onyx and the POTICON, the POTICON sun gear was weaker than the Onyx. This result contradicts the material strength in Table II.

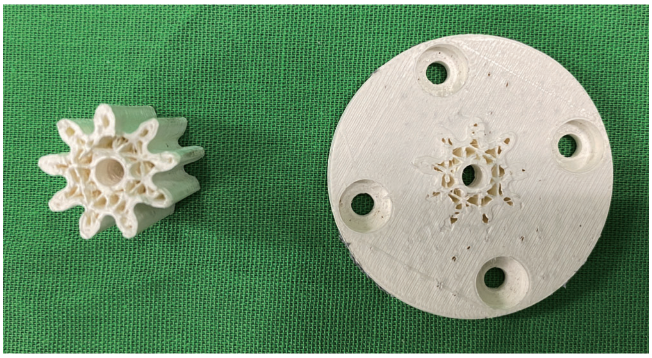

Fig. 10. Break of sun gear

TABLE IV
PARAMETERS FOR THE 3D PRINTING

Material	Onyx	POTICON
3DPrinter	MarkTwo	Raise3D Pro2
Slicer	Eiger	ideaMaker
Nozzle diameter [mm]	0.4	0.4
Extruder temperature [$^\circ$ C]	270	270
Pitch [mm]	0.1	0.1
Number of shells	2	2
Number of solid layers (top / bottom)	4 / 4	4 / 4
Fill Density / shape	37% / Triangle	37% / Triangle

Therefore, we examined the modeling patterns of the slicing software.

Table IV shows the parameters for the 3D printing. We set the same printing parameters for the Onyx and the POTICON. However, 3D printers and the slicer software that automatically generates the modeling path from the 3D CAD data are different. Fig. 11 shows the internal structure of an Onyx sun gear fabricated with MarkTwo and a POTICON sun gear fabricated with Raise3D Pro2. The lamination plane shown is the boundary plane between the flange and the teeth of the sun gear. The lamination pitch, the number of shells, the filling ratio, the filling shape, and the number of solid layers are the same. Since the number of solid layers is 4, the top surface of the flange area is 100% filled. However, both Eiger, MarkTwo's slicer software, and ideaMaker, Raise3D Pro2's slicer software, generate a sparse internal structure for the teeth depicted in the area circled in red. Although the filling shapes of Eiger and ideaMaker are both triangles, their paths are different. The reason for the difference in the strength between Onyx and POTICON can be explained by the difference in the adhesiveness of each layer due to the difference in lamination paths. Measures such as adding fillets at the border between the flange and the teeth, where stress is concentrated, and increasing the number of shells and filling them to the teeth were taken to improve strength, however these measures did not have a significant effect.

E. Durability against continuous operation

As shown in Fig. 12, a CFRP pipe was fixed to the output shaft of the modified OpenTorque Actuator, and a 5 kg weight was attached at a distance of 0.4 m from the

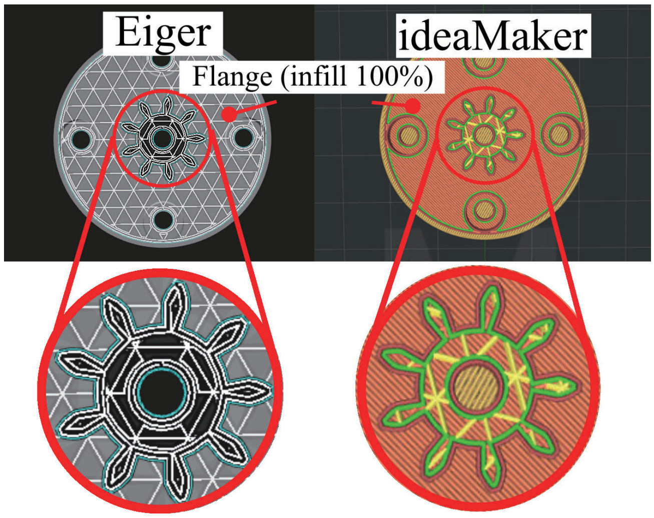

Fig. 11. Internal structure of the sun gear with different slicer softwares

output shaft. Thus, the applied maximum torque was 19.6 Nm, which was approximately 50 % of the theoretical rated torque. The motion was performed with a sinusoidal wave with a period of 10 seconds over a movement range of $\pm$90[deg.] While cooling the motor with an air blower, the experiment was conducted with Type 2 and Type 4 in Table III.

Fig. 13 shows an example of the measured joint angle and motor current when the target joint angle was given as a sine wave. It shows sufficient trajectory tracking accuracy. On the other hand, actuator current exhibits fluctuation with high frequency. When the reducer was driven for a long time under these conditions, the sun gear of POTICON broke in about 2 hours as shown in Fig. 10. For the sun gear of POM, the ring gear broke in about 46 hours as shown in Fig. 14. Although the filling ratio of the internal gear was 37%, Fig. 14 shows that the teeth were very sparse and hardly filled. On the contrary, no damage was observed in the sun and planetary gear. This result indicates that for FFF 3D printer parts, the molding path generated by the slicer software and the internal filling structure are more dominant factors for durability than the physical properties of the filaments themselves.

The output of 19.6Nm is, to our knowledge, the highest among resin reduction gears made by 3D printer fabrication.

V. CONCLUSIONS

In this paper, a quasi-direct-drive actuator with a 3D-printed planetary gear reducer was fabricated and evaluated as an example to investigate the performance of a 3D printer fabricated plastic reduction gear. The findings are summarized as follows.

- In the static torque measurement, the reducer with all parts made of resin showed an efficiency of more than 80% under 20 Nm, and the efficiency decreased as the static torque increased.

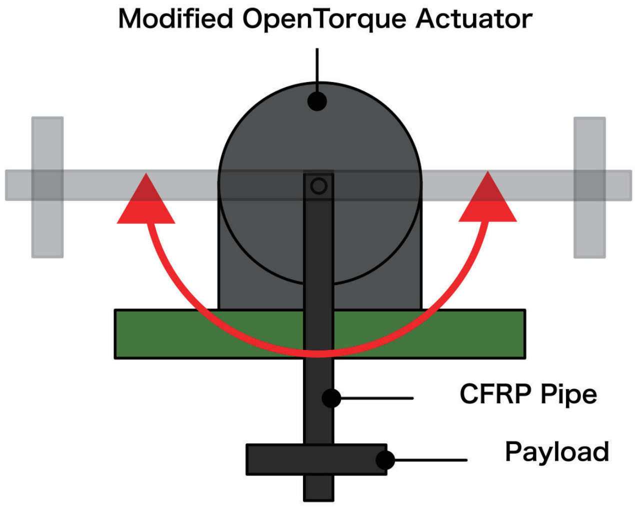

Fig. 12. Experimental apparatus for the continuous operation test

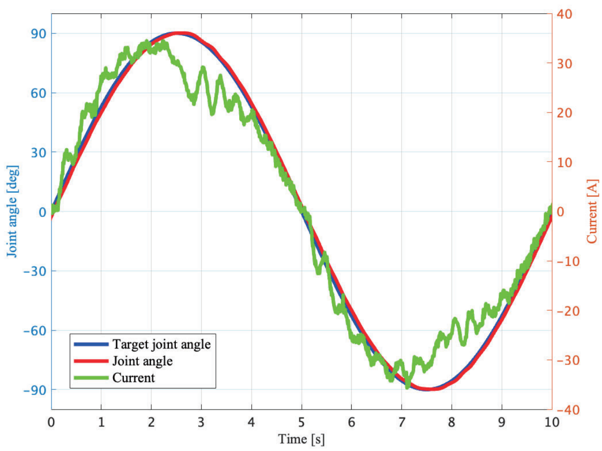

Fig. 13. Joint angle and current

- In the measurement of joint stiffness, the 3D printed resin sun gear had lower joint stiffness than the sun gear made of A7075 or POM, with no significant difference between the Onyx and POTICON gear, respectively.
- The effect of the heat generated by the motor on the resin gear was examined, and the heat generated by the motor decreased in stiffness, although the temperature was below the heat deflection temperature.
- The strength and stiffness of 3D printer parts are highly dependent on the lamination path and the filling structure generated by the slicer software rather than the strength and stiffness of the material.
- The durability was improved by machined solid POM sun gear instead of the 3D printed sun gear.

The results of this study quantitatively reveal some of the performance of the 3D-printed reduction gears. On the other hand, there are still many issues to be solved in terms of efficiency, rigidity, and durability in the high-torque range. It is also clear that the output path of the slicer software is

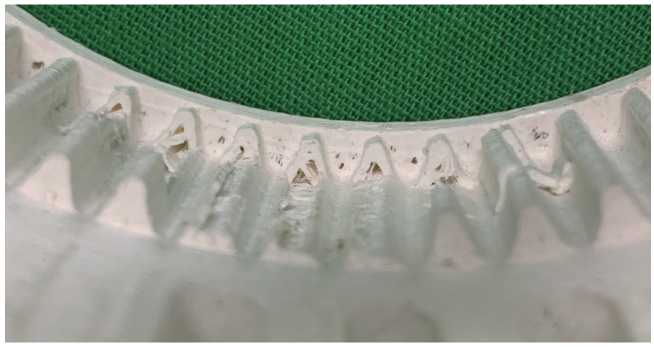

Fig. 14. Teeth break of the ring gear

extremely important for the strength of the 3D printed parts. The ability to create a high filling rate in a specific location is one of the most important issues to be addressed in the future.

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