A Bidirectional Rotary Actuator Using Shape Memory Alloy Wires

The University of Tokyo Donghyun Hwang, Shinya Hattori, Toshiro Higuchi

A bidirectional rotary actuator using shape memory alloy (SMA) wires is proposed. To achieve more multifunctional and wider applicability in comparison with previously reported various types of SMA rotary actuators, a cycloidal driving mechanism is devised and applied to the proposed rotary actuator. The cycloidal driving mechanism which consists of a rotor gear, a wobbling annular gear with rollers, and three crankshafts can effectively convert the expansion and contraction of the SMA wires to the bidirectional rotary motion. And, with this mechanism, the proposed actuator quietly and smoothly generates bidirectional high torque motion without interference. In this work, a conceptually designed actuator is fabricated as a functional prototype, and driving characterization and working performance verification are experimentally conducted. Due to its structural simplicity, scalability, modularity, and bidirectional capability with high torque and low speed, the proposed actuator is expected to apply to diverse scientific and industrial fields.

1. Introduction

Various types of SMA actuators have been practically used in many fields due to its attractive working characteristics as follows: high power density, silent operation with smooth motion, simple driving mechanism, compatibility with corrosive environment, and so on [1]. Generally, the SMA actuators consist of SMA actuating elements, parts for biasing force, driving mechanism, and electrical control units to electrically activate the SMA elements by Joule heating. In the case of the rotary actuators using the SMA, the rotational driving mechanism, which can convert the motion of SMA to rotary motion, is essentially required.

In this work, a cycloidal driving mechanism based SMA actuator which can generate bidirectional rotary motion is proposed. With its unique driving characteristic, the cycloidal driving mechanism is widely used for high-torque rotary actuators or motors. To generate bidirectional motion with relatively high torque using SMA wires, this driving mechanism is adopted to the proposed actuator. The actuator is conceptually designed and fabricated as a functional prototype. And, driving characterization and working performance verification are experimentally carried out.

2. Configuration and operating principle of the actuator

The proposed actuator, as shown in Figure 1, consists of a central cycloidal driving mechanism and radially symmetrically placed SMA wires which are linked in series with bias springs. As the cycloidal driving mechanism, a rotor gear is rotationally fixed on the center of actuator, and an annular gear supported by three crankshafts is eccentrically engaged with the rotor gear. In this configuration, by adjustment of the preloads on the SMA wires and the springs, the tensional forces can be balanced. And, the resultant force on the driving mechanism is minimized. It means that small external force is needed to rotate the rotor gear.

Figure 2 schematically shows operating principle of the proposed rotary actuator. Due to the sequentially applied external forces F_1, F_2, and F_3 which are generated by contraction of SMA wires S(1), S(2), and S(3), respectively, the annular gear is wobbled. This wobbling motion is guided as curvilinear motion, by triple parallel-crank-mechanism formed by radially equally placed three crankshafts. Thus, the eccentrical engagement between two gears is kept during the wobbling motion, and the rotor gear is rotated. In this principle, the function of the cycloidal driving mechanism is to convert expansion and contraction of the SMA wires to the rotary motion. The proposed actuator generates bidirectional rotary motion. The rotational direction is given by activation sequence of the three SMA wires, i.e., clockwise rotation and counterclockwise rotation for the S(1)–S(2)–S(3) activation sequence and S(1)–S(3)–S(2) activation sequence, respectively.

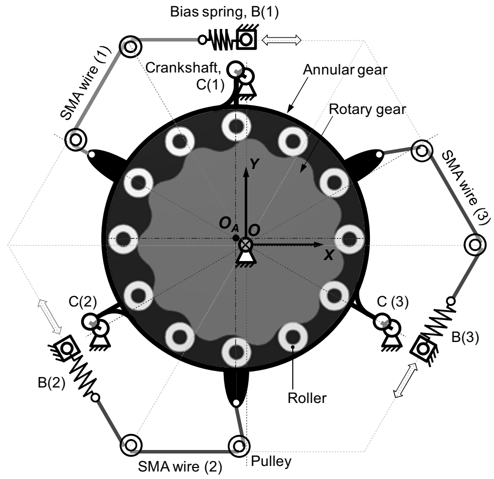

Fig. 1. Configuration of the bidirectional rotary actuator which consists of a rotational driving mechanism and three SMA wires with bias springs

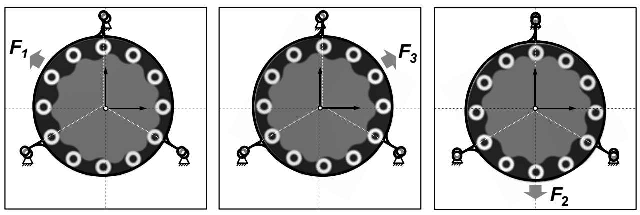

Fig. 2. Operating schematics of the rotational driving mechanism

The transmission ratio, R, of this mechanism may be expressed as

$$R = (P - L)/L \tag{1}$$

where P and L are the number of pins of the annular gear and the number of lobes of the rotor gear, respectively. Therefore, the transmission ratio of the actuator is 11 with 12 pins and 11 lobes.

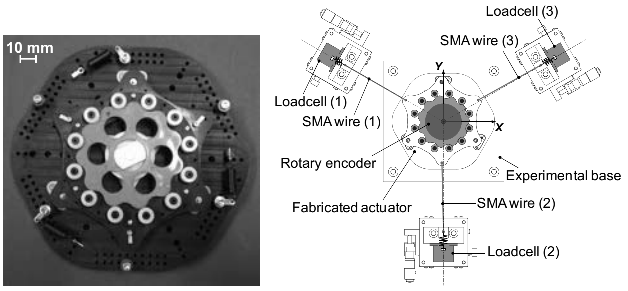

Fig. 3. A fabricated functional prototype of 160×150×25 mm with three SMA wires of 0.1 mm diameter and 50 mm length (left) and planar schematics of experimental setup (right)

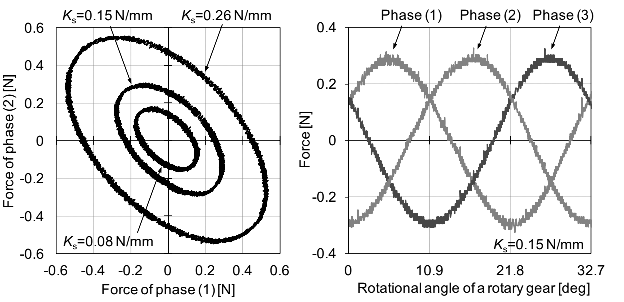

Fig. 4. Balanced tensional forces in SMA wires and springs when the rotor gear is rotated by an external force

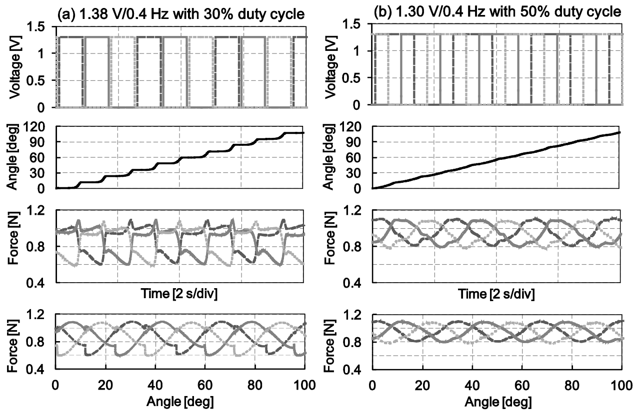

Fig. 5. Measured tensional forces and rotational displacement with different amplitudes of applied voltage and pulse duty cycles

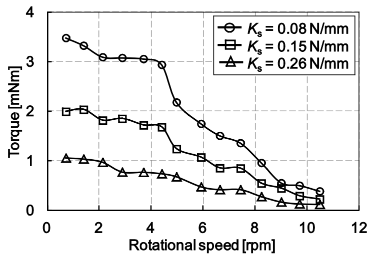

Fig. 6. Pull out torque vs. speed for different stiffness of the bias springs

3. Fabrication and experimental setup

For experimental verification of working performances, a functional prototype is fabricated. The used cycloidal gear set with rollers is disassembled from a polymeric prototype which is made to verify the cycloidal driving principle. And, three NiTiCu SMA wires of 0.1 mm diameter and 50 mm length are utilized [2]. In the proposed actuator, these SMA wires are electrically heated up, and cooled down by natural convection. The fabricated actuator is assembled on the experimental bench, as shown in Figure. 3. To measure the tensional forces in SMA wires and springs, all SMA wires are straightly arranged without pulley. In this experimental setup, the rotational displacement and the tensional forces are measured using optical rotary encoder (K-1, *Canon*) and three loadcells (LVS-1KA, *Kyowa*) set up on manual linear stages, respectively. The tensional forces in the SMA wires and the springs are balanced by adjusting the positions of the loadcells. Figure 4 shows balanced tensional forces, when the rotor is rotated by an external force. Under this condition, driving characterization test and working performance verification are conducted.

4. Performance verification

To drive the actuator, three-phase pulsed voltage is applied to the three SMA wires. With consideration for generating forces affected by voltage amplitude, activation frequency, and pulse duty cycle (PDC), various driving tests are carried out to characterize the performance. Figure 5 shows results of the measured tensional forces and the rotational displacement with different amplitudes of applied voltage and pulse duty cycles at the same frequency. When 1.38 V/0.4 Hz with 30% PDC is applied, the SMA wires are activated one by one. And, the actuator generates rotational stepping motion. Incremental step size is 10.9º approximately. This step size can be theoretically expected with the transmission ratio of the actuator. As compared with this motion, when 1.30 V/0.4 Hz with 50% PDC is applied to the actuator, the rotor gear is rotated relatively smoothly by overlapping pulses. Also, peak-to-peak amplitudes of measured tensional forces are reduced.

Experimental result of output torque versus speed characteristic with the bias springs with different stiffness is shown in Figure 6. The graph shows the deterioration of torque capability with rotational speed. And, with relatively high spring stiffness, more high torque can be achieved at the same rotational speed.

5. Conclusion

In this work, the bidirectional SMA rotary actuator based on the cycloidal driving mechanism, which converts the expansion and contraction of the SMA wires to the bidirectional rotary motion, is proposed. A conceptually designed actuator is fabricated, and driving characterization and working performance verification are experimentally conducted. Experimental results show that the proposed SMA rotary actuator generates relatively high torque with low speed. The proposed actuator is expected to apply to diverse scientific and industrial fields, as a high-torque low-speed actuator, with its structural simplicity, scalability, modularity, and operational easiness for bidirectional rotary motion.

References

[1] W. Huang, “On the selection of shape memory alloys for actuators,” *Materials and Design*, Vol. 23, pp. 11–19, Feb. 2002.
[2] NT-H7-TTR, Furukawa NT Alloys, Furukawa Techno Material, www.furukawa-ftm.com