MICRO PLANETARY REDUCTION GEAR USING SURFACE-MICROMACHINING

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Abstract

A micro planetary gear mechanism featuring a high gear reduction ratio with compactness in size is presented in this paper. SUMMiT V is employed for the fabrication method so that the redundancy of assembling parts is eliminated. The design rules of which has also been checked. To make full use of the benefits of the surface-micromachining, the planetary reduction gear is designed toward using the on-chip micro-engine. The expected gear reduction ratio is calculated and compared with the conventional chain gear mechanism. The microplanetary gear mechanism presented in this paper is expected to have 162:1 reduction ratio utilizing less space consumption. This is an order of magnitude higher than the previously reported design in a single reduction gear train.

Keywords: MEMS, planetary gear, reduction gear, surface-micromachining, SUMMiT V process

Nomenclature

- a sun gear
- b planet gears
- c internal gear (fixed)
- d internal gear (rotary)
- n the number of units of gear train
- D diameter of the pitch circle
- N number of teeth
- P number of planets
- ω angular velocity

Introduction

The gear mechanisms in microelectromechanical systems (MEMS) are commonly expected to generate high torque in the confined micro-size systems. However, it is generally difficult for the micro-scale systems to have such a high torque without having multiple reduction systems.

The design of the reduction gear drive based on a planetary paradox gear mechanism can increase the torque within a compact area, since the micro planetary gear system has an advantage of high reduction ratio per unit volume [1]. However its mechanism is so complicated that relatively few attempts have been made to miniaturize the gear systems [2-3]. Suzumori et al. [2] used the mechanical paradox planetary gear mechanism to drive a robot for 1-in pipes forward or backward. They employed a single motor to drive the gear mechanisms with high reduction ratio. Precise gear fabrication was enabled by micro wire electrical discharge machining (micro-EDM). These parts, however, should be assembled before the drive motor is attached to the gearbox. Takeuchi et. al. [3] also used micro-EDM to fabricate the micro planetary gears. They suggested special cermets or High Carbon Steel for possible materials. While the design can achieve a reduction ratio of 200, the gears should also be assembled and motor driven.

To enable the driving of the planetary gear by onchip means, Sandia Ultra-planar Multi-level MEMS Technology (SUMMiT-V) process [4] for planetary gear fabrication is adopted in this study. The SUMMiT-V process is the only foundry process available which utilizes four layers of releasable polysilicon, for a total of five layers (including a ground plane) [5]. Due to this fact, it is frequently used in complicated gear mechanisms being driven by on-chip electrostatic actuators [5]. However, in many cases, the microengines may not produce enough torque to drive the desired mechanical load, since their electrostatic comb drives typically only generate a few tens of micronewtons of force. Fortunately, these engines can easily be driven at tens of thousands of revolutions per minutes. This makes it very feasible to trade speed for torque [7]. Rodgers et al. [7] proposed two dual level gears with an overall gear reduction ratio of 12:1. Thus six of these modular transmission assemblies can have a 2,985,984:1 reduction ratio at the cost of the huge space.

With the desire for size compactness and at the same time, high reduction ratios, the planetary gear system is presented in this paper. It will be the first mechanism using planetary gear surfacemicromachining, to the authors knowledge. The principles of operations of the planetary gear mechanism. fabrication. and the expected performance of the planetary gear systems are described in this paper.

Principles of operation

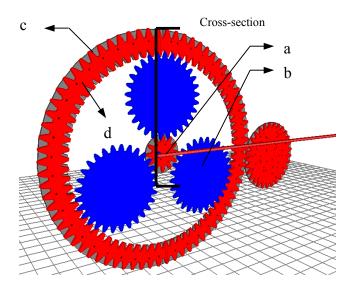


Figure 1. The schematic of the planetary gear mechanism generated from SUMMiT V design layout software

An alternative way of using gears to transmit torque is to make one or more gears, i.e., planetary gears, rotate outside of one gear, i.e. sun gear. Most planetary reduction gears, at conventional size, are used as well-known compact mechanical power transmission systems [1]. The schematic of the planetary gear system employed is shown in Figure 1. Since SUMMiT V designs are laid out using AutoCAD 2000, the Figure 1 is generated automatically from the lay out masks (Appendix [1]). One unit of the planetary gear system is composed of six gears: one sun gear, a, three planetary gears, b, one fixed ring gear, c, one rotating ring gear, d, and one output gear. The number of teeth for each gear is different from one another except among the planetary gears. An input gear is the sun gear, a, driven by the arm connected to the micro-engine. The rotating ring gear, d, is served as an output gear. For example, if the arm drives the sun gear in the clockwise direction, the planetary gears, b, will rotate counter-clockwise at their own axis and at the same time, those will rotate about the sun gear in clockwise direction resulting in planetary motion. Due to the relative motion between the planetary gears, b, and the fixed ring gear, c, the rotating ring gear, d, will rotate counterclockwise direction. This is so called a 3K mechanical paradox planetary gear [1].

Fabrication procedure and test structures

The features of the SUMMiT V process offer four levels of structural polysilicon layers and an electrical poly level, and also employ traditional integrated circuit processing techniques [4]. The SUMMiT V technology is especially suitable for the gear mechanism. The planetary gear mechanism can be driven by the on-chip engine and thus is another reason of using the SUMMiT V process.

Since the Sandia process is such a well-known procedure [5-7], only brief explanation is presented. Figure 2 represents the cross-sectional view of Figure 1, and also was generated from the AutoCAD layout masks (Appendix [1]). The discontinuity in the cross-section is for the etch holes. The poly1 (gray) is used for the hubs and also patterned to make the fixed ring gear, i.e., c, the sun gear, i.e., a, the rotating ring gear, i.e., c, and the output gear is patterned in the poly2. Since the



Figure 2. A schematic cross-section of the planetary gear system generated by SUMMiT-V technology

planetary gear needs to contact both the fixed ring and rotating ring gear, poly2 is added to poly3, where the gear teeth are actually formed. The poly4 layer is used for the arm that drives the sun gear. After the release etch, the planetary gears will fall down so that those will engage both the ring gears.

The figures for the test structures are presented in Appendix [2]. Since the aim of this paper is to suggest a gear reduction mechanism, the planetary gear system is decomposed to several gear units to verify its performance. The first test structure is about the arm, which rotates the sun gear, connected to the on-chip engine. The angular velocity of the arm depends on the engine output speed. The second test structure describes the point at which the sun gear and planetary gears are engaged to the fixed ring gear. Because of the fact that the ring gear is fixed, the planetary gear is just transmitting the torque from the sun gear to the fixed ring gear without planet motion, e.g., rotating its own axis not around the sun gear. When the rotating ring gear is mounted on top of the fixed ring gear, i.e., the third test structure, the planetary gears begin to rotate around the sun gear so that the planet motion are enabled. Therefore, once one output gear is attached to the rotating ring gear, i.e., the final test structure, the whole reduction unit is completed. Dismantling the planetary gear into three test structures allows the pinpointing of possible errors in the gear system.

Solutions procedure and expected performance

The reduction ratio is defined as the ratio between the angular velocity of the driver gear and that of the driven gear. High reduction ratios indicate trading speed for torque. For example, a 10:1 gear reduction unit could increase torque an order of magnitude. Since the gears in the planetary system should be meshed to one another the design of gear module should follow a restriction. For example, the number of teeth for the sun gear plus either that of the fixed ring gear or that of the rotating ring gear should be the multiple of the number of planets, P (equation 1). Equation 2, which represent the reduction ratio, should observe the equation 1 first. The N is the number of the teeth for corresponding gear.

$$N_s + N_c (or N_d) = Multiple of P$$
 (1)

$$\frac{\omega_{a}}{\omega_{d}} = \frac{1 + \frac{N_{c}}{N_{a}}}{1 - \frac{N_{c}}{N_{d}}}$$
(2)

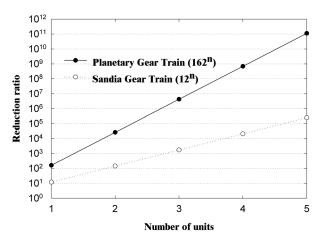


Figure 3. The comparison of reduction ratios as a function of the number of units

Gears, a, b, c, d in the planetary gear system have a tooth module of 4 μ m, which is a comparable size of the current gear reduction units [5], and the tooth numbers are 12, 29, 69, and 72 respectively. Therefore the overall reduction ratio is 162:1 from equation (2). Rodgers et al. [7] reported a 12:1 reduction unit using surface micromachining, which is less than order of magnitude for the gear reduction ratio of the planetary gear system. Although the reduction from Rodgers et al. [7] needs to be occupied in approximately 0.093 mm², the planetary gear system only utilizes an area of approximately 0.076 mm². Thus, this planetary reduction design can achieve an order of magnitude higher reduction ratio with less space. Since the reduction module is composed of several reduction units, the advantage of using a planetary gear system is self evident in Figure 3.

Figure 3 shows the comparison of reduction ratios between the proposed planetary gear mechanism i.e. 162^n , and the Sandia gear system [7], i.e. 12^n , as a function of the number of units, i.e., n. The ordinate is drawn in log scale so that the orders of magnitude differences between two modules are evident. For example, in a module with five numbers of units, the reduction ratio difference between two is approximately six orders of magnitudes. Furthermore, the planetary gear system can save $8500 \ \mu\text{m}^2$ in such a five-unit reduction system.

Conclusion and discussions

The planetary gear reduction system using surface-micromachining, driven by an on-chip engine, first appears in this paper within the authors' knowledge. The single reduction unit can achieve an order of magnitude higher reduction ratio than that of the previous design. However, due to the surface friction, and the backlash, which is inevitable for the gear manufacturing process, the overall reduction ratio may be less than 162:1 in the real situation. Even though some loss might be expected in the real application, the overall reduction ratio should be order of magnitude higher and the space consumption is less than the previous design [7].

The authors learned a lot about the surfacemicromachining process during the project grant, and realized that a lot of the design needed to be revisited and corrected. This became prevalent when drawing the cross-sectional views of the design. Since the authors utilized the SUMMit V Advanced design Tools Software package and verified the design rules, the planetary gear layout is ready for fabrication. The authors hope that this planetary reduction unit will continue to be updated by successive researchers.

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