# Design of a Micromachined Geneva Wheel as a mechanism to obtain intermittent motion from a constantly rotating source

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## ABSTRACT

Converting constant rotary motion into intermittent rotary motion gives rise to a range of useful applications in silicon micromachining. This paper discusses the design and fabrication of one such mechanism called the Geneva Wheel mechanism. The standard SUMMiT process has been made use of in developing this. All the related mathematics of the Geneva wheel was developed and the system was analysed.

*Keywords:* Geneva Mechanism, Microengines, Sandia SUMMiT Process

# **1. INTRODUCTION**

With the introduction of 4 and 5 level polysilicon surface micromachining technology by the Sandia National Laboratories, a whole new range of mechanisms have been made possible at the micro level. Primary amongst these are the microengines that have, in turn, been used in a variety of applications. Since the output of a microengine is some sort of a continuous motion, most of the applications so far using microengines have been restricted to similar kinds of motion. In this paper, we discuss the details of design and fabrication of a mechanism called the Geneva Wheel mechanism, using which, continuous motion can be converted into intermittent motion. A conversion technique like this can be made use of in a variety of applications such as discretized positioning of micromirrors in optical switching applications.

## 2. GENEVA WHEEL MECHANISM

The basic structure of a four slot Geneva wheel is shown in Fig.1. The system consists of a constantly rotating disk coupled with a slotted disk, which gives rise to the desired discrete motion. A rotation of  $2\pi$  radians of the former causes  $2\pi/N$  radians of rotation of the latter, where N is the number of slots available on the slotted disk. Thus, one complete rotation of the slotted wheel requires N complete rotations of the other disk, thereby also increasing the total time period. The conversion mechanism of this disk system is as follows.

Referring to Fig.1, pinwheel W rotates constantly about axis A and as shown below, has a pin 'a' attached to it. This pin 'a' engages into the slots 's' of the Geneva Wheel G (a basic 4-slot Geneva mechanism is shown here) and rotates it as long as it is engaged with the slot. While the wheel W rotates continuously, the Geneva wheel G has a discrete rotation about axis 'b'. Wheel G has a rotation time Palani Kumaresan Department of Mechanical Engineering University of California, Berkeley

period of  $t_r$  when it is moving along with disk W and an idling time period  $t_i$ , when the pin 'a' is not inside one of the slots 's' and is moving freely. The three quarter wheel 'L' is placed in order to prevent any unintentional rotation of wheel G while it is idling. For a four slot Geneva mechanism, the rotation time period  $t_r$  is one third the idling time period  $t_i$  [1].

By varying the number of slots on G, one can vary the time period and the angular displacement of the same. If this system is now coupled with some optical system like a micromirror (through a rack and pinion kind of arrangement), then it can be used to deflect light rays in different directions (by discretely positioning the moving mirror by using the discrete angular positions of the Geneva wheel) thereby giving rise to an optical switching technique.



Fig.1. Mechanism of Geneva Wheel

In the following sections, four slot and six slot Geneva wheels have been analysed and a design layout has been provided. Along the same lines, multiple slot wheels can be designed. The basic criterion that has to be maintained in designing any number of slotted Geneva wheel is that, the pin has to enter and leave the slots radially. This will again be discussed in detail in the following sections.

# **3. DESIGN**

Design of the Geneva wheel has been done using the 4-level polysilicon surface micromachining technology by Sandia National Laboratories. All the four levels of polysilicon are required for designing this mechanism. The SUMMiT process [2,3] and the layout design have been discussed in detail in this section.

# **3.1 The SUMMiT Process**

The Sandia Ultra-planar, Multi-level MEMS Technology (SUMMiT) process[2,3,4] is a standard process developed by the Sandia National Laboratories. A cross-section of the main layers in the process is shown in Fig.2. In this process four layers of polysilicon alternated by sacrificial silicon dioxide layers are laid down. The first level is a silicon dioxide and nitride stack layer. The oxide layer in this level is used as an insulating layer. The nitride layer acts as an etch stop and protects this oxide layer when the sacrificial oxide etch is carried out. The four polysilicon layers function as the structural layers used for developing various micromachined structures. The oxide layers alternating between the polysilicon layers are used to physically isolate the polysilicon layers. Once the whole structure has been developed, these oxide layers are etched away and polysilicon structures are released. The thickness of the various layers is given in Fig.2.



Fig.2. Layers of the SUMMiT process *Courtesy: Sandia National Laboratories* 

The two things that are unique to this process and which make a variety of designs possible at the micro level are the conformal SACOX2 layer and planarized SACOX3 layers.

#### 3.2 Wheel design

Two types of slot designs for the Geneva wheel were considered. The designs were laid out using the *Cadence* software for MEMS layouts. Since the technology file available with the software allowed for only three levels of polysilicon, the structural poly0 level was not laid down.

For any N slotted wheel, the angle by which the slotted wheel rotates for a given rotation of the constantly rotating wheel is  $2\pi/N$ . The slots are thus placed at  $2\pi/N$  radians intervals. An important requirement is that during every rotation, the pin should enter and leave the slots in such a way that the tangent to the constantly rotating wheel at the pin passes through the center of the slotted wheel. This means that if 'r' is the radius of the constantly moving disk, then the distance 'D' between the centers of the two disks has to be:

$$\mathsf{D} = \mathsf{r}/\mathsf{sin} \ (\pi/\mathsf{N})$$

and the radius of rotation 'R' of the Geneva wheel is given by:  $R = r/tan(\pi/N)$  The minimum length of the slot through which the pin on disk W moves should be:

$$S = D-[(D-R)+(D-r)]$$
$$= R+r-D$$

Applying these relations to the wheel shown in Fig.1 we get:

$$Aa = ab = Ab/\sqrt{2}$$



Fig.3. Layout of a four slot Geneva wheel using Cadence

The layout of a four slotted wheel in Cadence is shown in Fig. 3 with projections on the constantly rotating wheel to so that it can be moved with a probe. The constantly rotating disk can be rotated using а Sandia microengine [5,6,7,8] driven by comb-drives. The gears of the microengine can be made to mesh with the gears of the constantly rotating wheel that can be provided on it. To avoid unintentional rotation of the Geneva wheel, a truncated wheel (with a chopped arc angle of  $4\pi/N$  radians) is placed on the constantly moving disk, which stops any rotation of the Geneva wheel when the pin is moving freely and is not engaged with any of the slots.

The design should therefore, have the truncated disk and the Geneva wheel on the same polysilicon layer and the constantly moving disk in another layer, which would mesh with the microengine. The Geneva wheel and the chopped disk are made on the Poly2 layer and the constantly moving disk lies below in the Poly1 layer. The engaging pin on this disk is placed on Poly2 layer. The pins holding the Geneva wheel and the other disks are then placed on Poly3 layer, which gets contacted to the Poly0 layer and allows rotation of the disks after release.

A gear can be fabricated on polyl layer concentric with the Geneva wheel, which can then be meshed with a rack to convert the intermittent rotation of the disk into discrete linear motion. This can then be applied to micromirrors and other systems requiring such motions.

# 4. TEST STRUCTURES

Keeping in mind the working of a Geneva wheel, a few test structures were designed to analyze the working of this system. The typical torque values obtained from a microengine fabricated at the Sandia National Laboratories are in the range of  $6.0*10^{-11}$ Nm to  $1.2*10^{-10}$ Nm[5]. We plan to

use one of these microengines at a later stage to move our constantly rotating disk. The micromirror systems currently being used for optical switching purposes need around  $10\mu N$  of force for actuation. We can also have some other systems that require similar forces and motion for actuation.

With these in mind and also that friction between the engaging pin and the slots is going to play a very important role in determining the performance of our system, we decided to have four basic types of arrangements for a chosen radius of the constantly rotating wheel. The first arrangement checks for the basic engagement without any type of load applied. For this, a pin is simply moved through a slot in the Geneva wheel configuration and the motion is carried out externally through probes. Any other micromachined system is avoided to ensure that the system's working is not effected by any other parameter. This structure would ensure that the dimensions chosen for the structure are correct and the expected motion can be obtained if all other parameters work out well. The other structures involve simulation of 10µN force in configurations that either are opposing or assisting the Geneva wheel rotation. This simulation of the force is done using micromachined springs (serpentine beams), which are either in tension, compression or unstretched position when the motion of the Geneva wheel begins. This is achieved by anchoring the springs at different points relative to the Geneva wheel. The spring initially in tension simulates a situation where a system exerts an opposing force, which increases as the pin moves towards the line joining the wheel centers. An example of this case is shown in Fig.4. The compressed spring system simulates an assisting force and the neutral spring simulates a situation where the motion of the wheel is not hindered initially, but once the system starts moving, the opposing force increases. If the system works for all these cases, the wheel mechanism is most likely to work in a more complex system like the one coupled with the microengine and the micromirrors, to obtain intermittent lifting of the micromirrors. These basic layouts have been laid out for four different radii of the pin-wheel. Also the engaging pin size has been varied and similar structures have been laid down for the six slot Geneva wheel.



Fig.4. A test structure where the spring is initially in tension and opposes rotation of the slot

# 5. EXPECTED RESULTS

Some simple calculations have been performed to evaluate the performance of the Geneva wheel. These include evaluation of the torque transmitted by the Geneva wheel, the sliding friction between the pin and the slot while it is sliding through the slots and the angular velocity of the slotted wheel while it is rotating. All the quantities have been evaluated as a function of the angular rotation of the constantly rotating disk and for both the four slot and six slot structures.

Eq.(1a) and (1b) give the basic relation between the fractional torque output and the angular rotation of the pin when it is engaged with the slot. The output torque is a fraction of the microengine torque applied to the pin wheel. For a four-slotted wheel the fractional torque goes as:

$$\tau_4 = \tau_{in} \left( \sqrt{2} \cos \theta - 1 \right), \quad -\pi/4 < \theta < \pi/4 \tag{1a}$$

For a six-slotted wheel with the same radius of the pin wheel as that of the pin wheel in a four-slotted mechanism, the fractional transmitted torque goes as:

$$\tau_6 = \tau_{in} (2\cos\theta - 1), \quad -\pi/3 < \theta < \pi/3 \tag{1b}$$

where,  $\tau_{in}$  is the input torque and  $\theta$  is the angle of rotation of the pin with respect to its axis of rotation. The plot is shown in Fig.5.



Fig.5. Fractional torque transmitted as a function of angle of rotation.

The variation in velocity of the slotted wheel with respect to  $\theta$  is given in Fig.6. The velocity has a multiplying factor coming from the angular velocity of the constantly rotating wheel. For a four-slotted Geneva wheel,

$$\omega_{Gen,4} = \omega(\frac{\sqrt{2\cos\theta} - 1}{3 - 2\sqrt{2}\cos\theta})$$
(2a)

For a six-slotted Geneva wheel,

$$\omega_{Gen,6} = \omega(\frac{2\cos\theta - 1}{5 - 4\cos\theta}) \tag{2b}$$

where,  $\omega$  is the angular velocity of the constantly rotating disk.  $\theta$  variations are same as in Eq. (1a) and (1b).



Fig.6.Velocity variation as a function of angle of rotation.

Eqs. (3a) and (3b) give the nature of the frictional force experienced by the pin as it slides through each slot. For a four-slotted wheel,

$$F_4 = \mu F(\frac{\sqrt{2}\sin\theta}{\sqrt{3 - 2\sqrt{2}\cos\theta}}) \tag{3a}$$

For a six-slotted wheel,

$$F_6 = \mu F(\frac{2\sin\theta}{\sqrt{5 - 4\cos\theta}}) \tag{3b}$$

where,  $\mu$  is the coefficient of kinetic friction of polysilicon sliding on polysilicon. Even though  $\mu$  is not exactly constant over the stated range of operation and depends on a number of factors, for our study it is assumed to be constant at 0.42. A lot of research is going on in this area and it forms a topic for separate analysis[9]. F is a constant force applied by the pin on the slotted wheel which is a result of the torque being applied to this wheel by the microengine.



Fig. 7. Nature of frictional force as a function of angle of rotation.

# 6. DISCUSSION

Summarizing, Geneva wheel mechanism can be an excellent mechanism for obtaining intermittent motion from a continuously moving source. The system is simple to lay out and can be fabricated using the standard SUMMiT process. Also depending on the application, the time period and the discrete motion can be varied by varying the number of slots in the Geneva wheel. It can be seen from the graphs that even though the fractional transmitted torque increases as the number of slots increase, the velocity curve drops down. This is because even though the transmitted torque has increased, it acts over a much shorter period of time. The frictional force seems to remain fairly constant as the number of slots is increased.

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