

# SURFACE MICROMACHINED MICROENGINE AS THE DRIVER FOR MICROMECHANICAL GEARS

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## SUMMARY

The transmission of mechanical power is often accomplished through the use of gearing. The recently developed surface micromachined microengine [1] provides us with an actuator which is suitable for driving surface micromachined geared systems. In this paper we will present aspects of the microengine as they relate to the driving of geared mechanisms, issues relating to the design of micro gear mechanisms, and details of a design of a microengine-driven geared shutter mechanism.

## INTRODUCTION

Geared mechanisms appear in almost every type of machinery used in industry today. In the macro world, geared devices are used to transmit rotary or linear motion (e.g. rack and pinion) to other machine elements. In fact, gears have been in continuous use for over 5000 years [2, 3].

About 2600 B.C., the Chinese used gearing in a direction-indicating mechanism mounted in a chariot. Around 1000 B.C., the Egyptians and Babylonians were using gearing in clocks and water-raising equipment. In the fourth century B.C., Aristotle wrote about gearing and the Chinese were using gearing for power transmission. In the third century B.C., Ctesbius used wooden-toothed gear wheels in a water clock. By 100 B.C., gears were made from both wood and metal! During the Roman Empire, wooden and metal gears were used extensively for water raising equipment, flour milling, and marble sawing.

In the fifteenth century A.D., da Vinci designed devices which incorporated gears and Nicholas of Cusa studied the cycloidal curve. In the sixteenth century, Cardano worked on the mathematics of gearing. Later, in the seventeenth century, Galileo and Huygens began experimenting with cycloidal and involute curves. In the mid-eighteenth century, Euler worked out detailed rules for conjugate action. In the latter part of the eighteenth century, gears began to be made of cast iron.

Modern gearing technology has evolved to quite an advanced state with gears fabricated as both two-dimensional and three-dimensional entities from a variety of materials. Another step in this evolution is the development of microscopic geared systems.

Current micromachining techniques provide us with the opportunity to fabricate two-dimensional gears which use appropriate tooth shapes, i.e., shapes that generate constant angular velocity ratios between gears, and utilize theoretically pure rolling as the gear surfaces interact. This particular motion permits the transmission of torque (or force) with minimal frictional losses and reduced inertial loading.

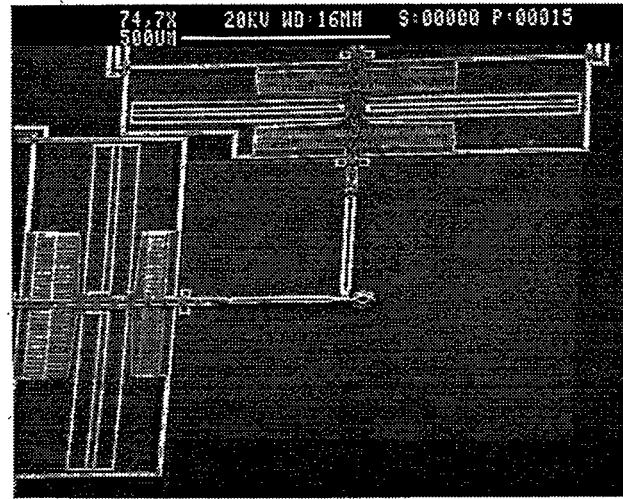


Fig. 1. SEM Overview of the Microengine

Testing of surface micromachined gears has been reported previously for gas-driven devices [4, 5, 6]. LIGA gears have also been fabricated, assembled, and driven by magnetic actuation [7]. The development of an electrostatic microengine [1] (Fig. 1), which is capable of driving a micron-sized pinion gear continuously, leads us to investigate a fundamentally important application: operation of surface micromachined gears.

To use a geared micromechanism successfully, one must address a number of issues. These include gear aspect ratio (i.e., thickness to diameter), tooth geometry and tolerances, gear meshing, friction, lubrication, wear, backlash, bearing issues, loading, material strength, thermal limits, surface condition, and micro fabrication challenges.

## MICROENGINE AS DRIVER

The surface micromachined microengine is capable of delivering power through a continuously rotating output gear. Details of the design, analysis, and performance of the microengine are given in [1]. This device is operated by an arrangement which converts linear motion from electrostatic comb drive actuators into rotary motion of an output gear. The conversion is accomplished by the construction of drive linkages which serve as connecting rods between linear comb drive actuators and the rotating output gear (Fig. 2). This is the analogous case to that of an internal combustion engine, which converts linear motion of the pistons (comb drive actuators in our case) to rotary motion of a crankshaft (microengine output gear). Fig. 3 is a close-up of the output gear which shows a drive linkage passing over the gear and connecting to

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the gear at a radius of 17  $\mu\text{m}$  (referenced to gear center). This connection is made through fabrication of a pin joint between the link and output gear. The output gear is anchored to the substrate through another joint between the substrate and gear which permits the gear to rotate freely. Upon application of appropriately timed forces by the linear actuators, a net torque is applied to the output gear and rotation is achieved. Excess torque is then available at the output gear to drive a mechanical load. Of course, the addition of a mechanical load to the microengine will alter the behavior of the system due to additional inertia, friction, and the mechanical load.

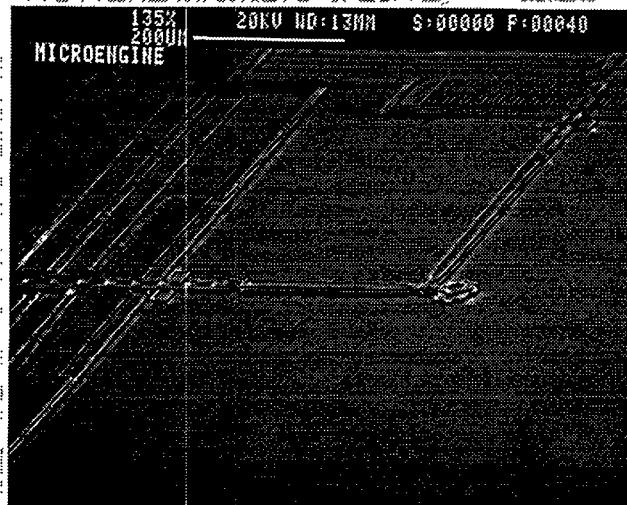


Fig. 2. SEM Image Illustrating Layout of Linkage Connections

The entire microengine is fabricated of polysilicon on one wafer using surface micromachining batch fabrication techniques. Fabrication of the device is accomplished without the need for assembly of multiple wafers requiring alignments, bonding, etc., or the addition of other separately fabricated piece parts. In this design the output gear is readily accessible for connection to a driven gear.

The microengine has been tested to speeds of several hundred thousand revolutions/minute of the output gear. The device can be operated in clockwise and counterclockwise directions and because of the low inertia of the microengine, speeds can be reversed in fractions of milliseconds. Ongoing life cycle testing has shown that at between 10 and 20 million revolutions of the microengine, we begin to notice increased frictional loading to the system, which we define as the onset of failure. Typically the microengine does not fail by complete, immediate seizure, but rather by small perturbations in the rotational speed. The full experimental matrix which explores input waveform, speed, surface preparations, and operating ambient has not been completed.

#### GEARING DESIGN ISSUES

The subject of gearing is covered extensively in the literature and many references [3, 8, 9] can be consulted

for gear design details. We will summarize those details most pertinent to our discussion of micro geared systems.

As previously mentioned, the following items must be considered and understood to successfully design a micro geared system:

1. Fundamental law of gearing and tooth geometry
2. Aspect ratio and gear meshing
3. Gear backlash
4. Bearing configuration and loading
5. Material strength and loading
6. Friction, wear, and lubrication
7. Surface conditions
8. Tooth face uniformity
9. Thermal limits
10. Mechanical system dynamics
11. Fabrication processes required

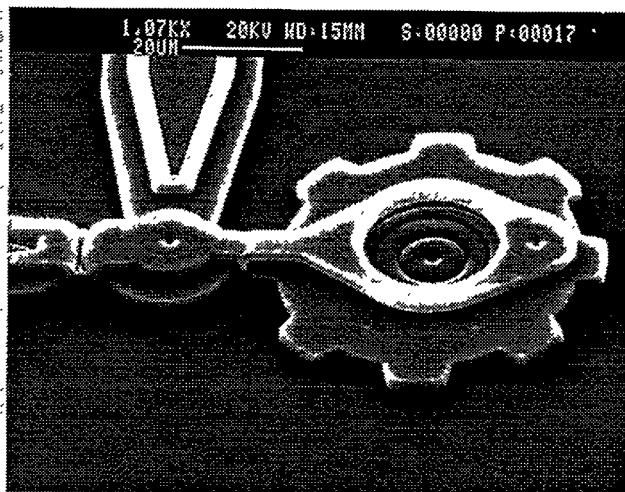


Fig. 3. Close-up SEM View of the Microengine Output Gear

#### Fundamental Law

The fundamental law of gearing refers to tooth profiles required to obtain a constant angular velocity ratio between gears, i.e.,

$$\omega_2 = (r_1/r_2) \omega_1 \quad (1)$$

where  $\omega_1$  and  $\omega_2$  are angular velocities of the meshing gears and  $r_1$  and  $r_2$  are pitch circle radii of the gears. This condition is only satisfied for specific tooth profiles, however, theoretically there are an infinite number of tooth shapes that can be used to generate constant angular velocity ratios. Any pair of tooth profiles satisfying this condition are said to be conjugate. The cycloid profile was used first, but has been replaced by the involute for most applications, one reason being that conjugate action is maintained for involutes even with variations in gear center distances. Cycloid gearing requires center distances to be maintained to obtain conjugate action.

#### Aspect Ratio and Gear Meshing

Surface micromachined elements at present have thicknesses of the order of two microns. Many devices of interest have planar dimensions of hundreds of microns.

For example, a two-micron-thick, 1000-micron-diameter gear can have problems with proper meshing due to out-of-plane flexing of the large gear and rigid-body movements of the large gear due to clearances in the bearing surfaces. One method for insuring proper meshing is to incorporate retaining features which keep the meshing teeth in position such as the retainer shown in Fig. 4. Here the gear cannot displace to a position that disengages from meshing with the adjacent gear. The difficulty with such a configuration is that the retainer can introduce additional frictional loading to the system and reduce performance and efficiency. The use of silicon nitride or other friction reducing material is almost certainly required on the retainer bearing surface.

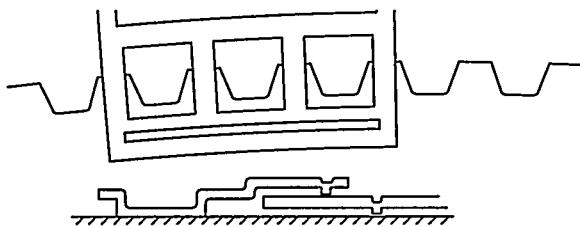


Fig. 4. Example of Gear Retainer Structure

#### Gear Backlash

Backlash in micromachined gears can be more troublesome than with conventionally fabricated gears. This is due to the *in situ* batch fabrication of this system. As part of the process, certain minimal clearances between gears are required to make the polysilicon cuts that separate the individual gears from each other. Depending on the tooth size employed, the backlash can be a considerable percentage of the circular pitch. Typical backlash in a macroscopic geared system might be 3%. To insure proper clearances, we were forced to design one of our micro geared systems to have a backlash of almost 20%. Depending on the application, such a large backlash might be unsuitable. Dynamic simulations of a system with large backlash show instances where impact causes motions of the driven gear to occur opposite to the intended direction due to the bounce of the driven gear. The analysis used values reported by Lee [10] for the coefficient of restitution for polysilicon. A method to virtually eliminate this problem is to allow the required processing spacing only between teeth that are adjacent, i.e., where they mesh in the as-fabricated position, while increasing the tooth dimensions where the teeth are unmeshed. This results in a geared system with reasonable backlash on nearly every tooth except where the original teeth meshed during fabrication processing. It must be noted that clearances in the bearings of both gears contributes to the backlash in the system and must also be monitored.

#### Friction, Wear, and Lubrication

The frictional characteristics of a micro geared system tend to be of primary importance in terms of effects on performance and efficiency. An advantage of a properly selected gear tooth profile set is that we minimize frictional effects to the maximum extent possible by

utilizing "pure rolling" as the teeth interact to transmit forces. Involute tooth profiles provide this characteristic. However, some amount of sliding between tooth faces will still occur and the frictional contribution from the gear bearing itself remains.

The efficiency of a geared system can be estimated from gear parameters, including gear ratio, angle of approach and recess, friction coefficient, gear bearing friction and viscous damping. Not surprisingly, the energy dissipation of a geared system is directly proportional to the friction coefficient [11]. Therefore, the selection of suitable friction and wear reducing material for tooth faces is important. The use of silicon nitride or other suitable material compatible with polycrystalline silicon surface micromachining processing would be required in the absence of a lubricant. Investigations into the frictional behavior of meshing surface micromachined gear systems is, as yet, unexplored.

#### Other Issues

To design a micro geared system, a reasonable model of the entire mechanical system is first required to determine element loads and system response. Obviously tooth loading and material strength must be compatible, and gear bearing design must consider backlash, loading, frictional effects, wear, and clearances. Vertical runout of the teeth (through the thickness) should be small enough to allow the teeth to contact reasonably well through the entire thickness of the teeth. Whether or not the tooth surfaces should be "smooth" is not certain from a tribological standpoint. However, it is clear that the tooth profile must be preserved to reasonable accuracy. In the macro world, thermal difficulties with heavily loaded gear systems are handled by using appropriate lubricants to transfer heat. The critical-temperature hypothesis [11] says that the onset of scuffing occurs when a critical temperature is reached for a specific combination of lubricant and tooth materials. It would appear that a similar situation would exist for micro geared systems, however those effects remain to be investigated.

The processing needed to fabricate surface micromachined gears needs to be further improved, since it plays the pivotal role in what types of general machinery can be realized. We have previously pointed out that, in general, surface micromachined actuators have lagged in development compared to sensors due to processing limitations [12]. Further improvements in processing capability will greatly extend the range of applications for surface micromachined geared systems.

#### APPLICATION TO OPTICAL SWITCHING

The use of a geared system to drive an optical shutter system or optical scanner is illustrated in Fig. 5. This is one example of a design being considered for driving a 1600  $\mu\text{m}$  diameter shutter gear with the 50  $\mu\text{m}$  diameter microengine output gear. The square section in Fig. 5 is the shutter element. The thickness of both gears is 2.5  $\mu\text{m}$ . Hence the aspect ratio (thickness/diameter) for the large gear is 1/640. Several other designs for driving

gears of sizes comparable to the drive gear are also being fabricated.

The tooth profiles used in these designs are involutes. Since the diameter of the shutter gear is very large compared to the tooth size, the tooth profile is almost straight compared to the tooth profile for the microengine gear which is easily seen to be curved. In ordinary gear practice, more teeth would be used for the microengine gear than shown. The reason for the small number of teeth being used on the microengine gear is related to the size requirement of the connecting link which attaches to the output gear.

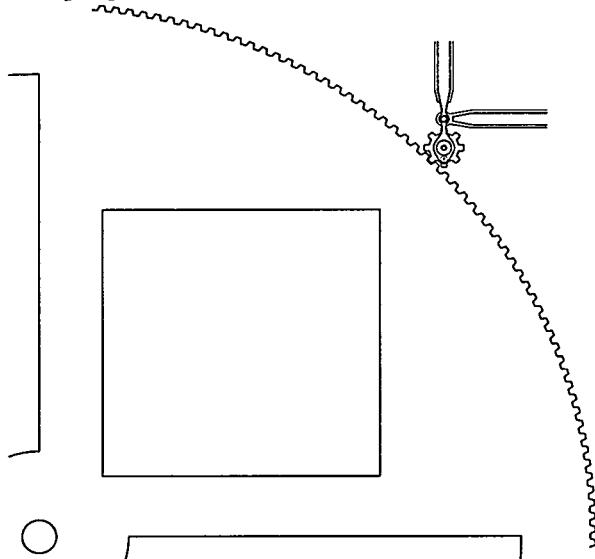


Fig. 5. Optical Shutter System

Due to the conformal nature of the polysilicon depositions, and the various topologies introduced by the photolithography/etch process, it is desirable to have the link pass over the outermost edge of the tooth. This can be understood by referring to Fig. 3. Here it can be seen that if the link does not pass over the outermost edge of the gear tooth, the link will cause interference with gear rotation. The tooth width must be wider than the width required for the link to handle the loading transferred by the link to the output gear. Hence, the tooth width requirement limits the number of teeth that can be used. In addition, the clearances in both gear bearings require

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that the teeth have sufficient depth to accommodate the clearances and still maintain gear engagement. Fig. 6 illustrates details of the link and gear meshing configuration. Details of the testing and evaluation of these systems will be reported later.

## CONCLUSION

The development of a surface micromachined actuator that conveniently permits power take-off to drive mechanical loads has been described. Issues relating to the design and operation of micro geared systems were summarized. Many issues related to the mechanics of micro geared systems are as yet unexplored. Fluid-driven micro geared systems have been demonstrated previously, however, electrically-driven micro geared systems have not been investigated to date. The microengine-driven optical switching or scanning system, and a series of multiple-gear-train devices, will serve as a test bed for our investigations into the mechanics of micro gearing.

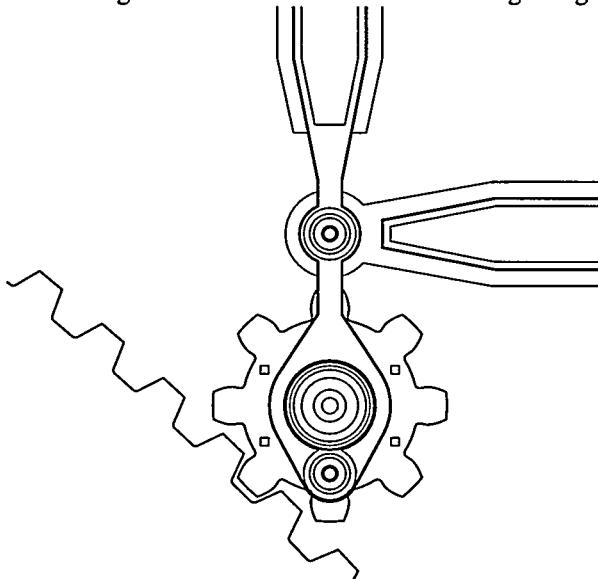


Fig. 6. Link/Gearing Detail

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