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Design of a Variable Reluctance Asymmetric Stepping Millimotor

Ernest J. Garcia, William H. Greenwood and Andrew D. Oliver
Electromechanical Engineering Department
Sandia National Laboratories, Albuquerque, New Mexico, 87185-0329 USA

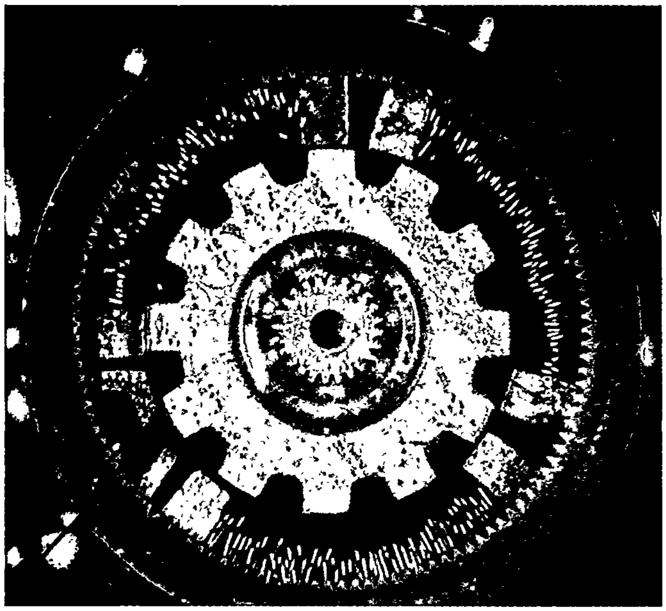

Figure 1 Millimotor Prototype

Abstract

This paper reports on the design, simulation, and preliminary testing of a three phase variable reluctance stepping motor. This motor is pancake-shaped with an overall outside diameter of 8 mm and a height of 3 mm. The outside diameter of the rotor is 4.7 mm. The rotor and stators occupy 2 mm of the height with the remaining 1 mm reserved for a 6:1 planetary gear reductor. The rotor and stators were constructed of Hyperco 50 using conventional miniature machining. The reductor was assembled using copper and PMMA (polymethylmethacrylate) components that were constructed using the LIGA (Lithographie Galvanoformung Abformung) microfabrication process. The maximum measured stall torque of the motor without the reductor is 0.47mNm at 4W and the maximum speed is 2400 rpm.

Introduction

The development of fundamental actuators of varying sizes has been driven in many cases by specific applications. The advent of fabrication techniques such as silicon surface micromachining and LIGA has enabled the development of fundamental actuators in both the micro and mesoscopic domains [1, 2]. Silicon surface micromachining [3] permits the fabrication of multi-layered structures with micron-sized features that can be configured as fundamental drivers. Such devices have been utilized to perform positioning or switching functions such as the realignment of a mirror.

There are a number of applications where the volume available for the operating mechanism and actuator is severely constrained in one dimension. In that situation, given x, y, and z dimensions, the z dimension is much smaller than the other two. A specific positioning application, with such a constraint on the volume available for the actuator, lead us to develop the stepper motor described in this paper. For this application we take advantage of the LIGA microfabrication process [4, 5] to construct a mesoscopic-sized actuator with a planetary gear reductor that could not be fabricated otherwise. The actual motor designed (Figure 1) is constructed using a combination of conventional miniature machining and LIGA. This paper will discuss the design, modeling, and initial testing of a new asymmetric-configured stepper motor that, with its pancake-shaped aspect ratio, is ideally suited for applications where the available volume is very constrained in one dimension.

Design

The small size of the motor led us to consider variable reluctance stepper designs rather than permanent magnet stepper motors due to the difficulty of fabricating and installing small magnets. The small volume available makes coil winding on the stators quite difficult. A partial arc or segmented stator design allows the coils to be wound directly onto the stator pieces. The ends of the segmented stators would be the salient poles. A three phase 15° stepper with symmetric spacing is shown in Figure 2. This is a straightforward adaptation of slotted motor stators to a pancake configuration with stator segments.

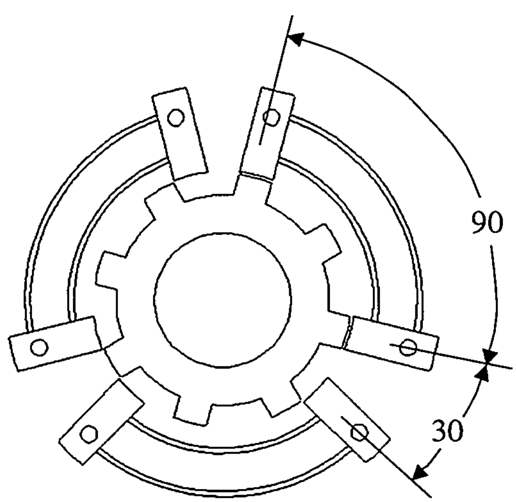

Figure 2 Symmetric Stepper

DISCLAIMER

As shown, the rotor has eight salient poles with a width of 15° and a pitch of 45°. The salient poles on the stator also have a width of 15° between the stator segments.

A disadvantage of the three-phase design is low initial torque due to no overlap of the poles at the start of the stroke. This causes substantial torque ripple [6]. If the torque ripple is objectionable, the common solution is to go to four or five phases. A novel possibility with a segmented stator is a configuration that allows pole overlap with only three phases.

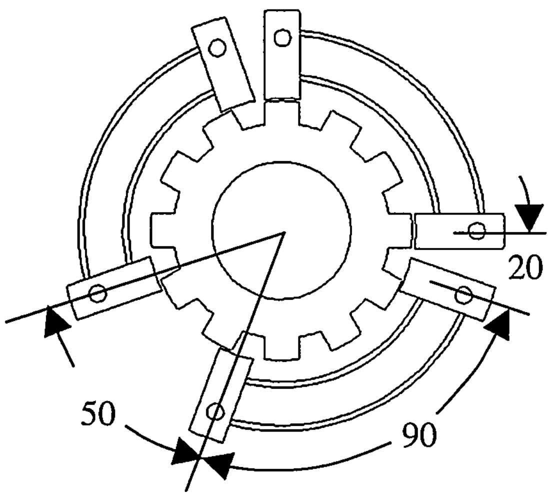

Figure 3 Asymmetric Stator Configuration

This is shown in Figure 3 where the segmented stator is identical to that of Figure 2. The rotor still has 15° pole widths but now has 12 teeth. Hence, with one phase fully aligned and no net torque output, the other phases have 5° overlap at the poles for full torque output when that phase is energized. The result is a 10° stepper of three phases with little torque ripple between phases.

Another advantage of the non-symmetric stator spacing is that it allows room to incorporate an independent inductive pick-up that can be used for closed-loop control. Such a device can be seen in Figure 1.

The non-symmetric spacing of the stator segments in Figure 3 can be made symmetric by using an odd number of teeth on the rotor. Such a case is shown in Figure 4 where the rotor has eleven teeth. That configuration allows more spacing for the coils and gives a step size of 10.9°. Where the large gap between two of the stator segments of Figure 3 is not useful then the symmetric stator gaps of Figure 4 is recommended.

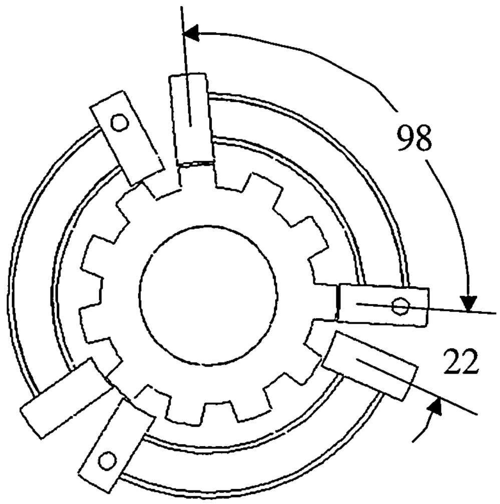

Figure 4 Asymmetric Rotor Configuration

One overall warning with the three-stator segments is unbalanced magnetic forces on the rotor and the resultant large lateral force on the bearings. Since this design uses ball bearings, the low friction results in low torque loss but this would not be the case if a journal bearing were used.

The torque requirement for the application was such that a gear reductor was needed to multiply the output torque of the motor. A planetary gear system was used with a 6:1 torque increase. The small size precluded conventional fabrication so LIGA formed gears were made of copper. Nickel is also a common LIGA formed material and would probably be preferred for better wear than copper but was not possible since a non-magnetic material is needed. Figure 5 shows the gear set with the planets assembled.

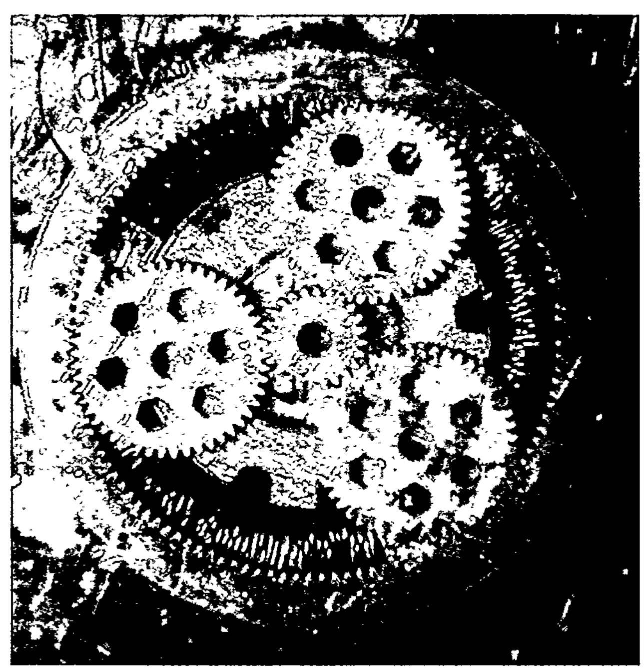

Figure 5 Millimotor with Planetary Gear Reductor

The rotor and stator were made of Hyperco 50 due to the very high saturation flux density (B=2.3 Tesla) of the material. The stall torque was modeled by the electromagnetic circuit model of Roters [7] and Hanselman [8]. The simple circuit model for a stator and rotor is shown in Figure 6 where MMF is the magnetomotive force in Amp-turns and R is the reluctance of the stator and rotor sections based on cross-sectional areas, element lengths, and the B-H curve of the material. The air gap permeance P is calculated by Roter's closed form solutions to approximate the geometry of the gap, which includes the main effect of the gap annulus as well as fringing. The stall torque is then proportional to the rate of change of the air gap permeance with respect to the change of rotor angle.

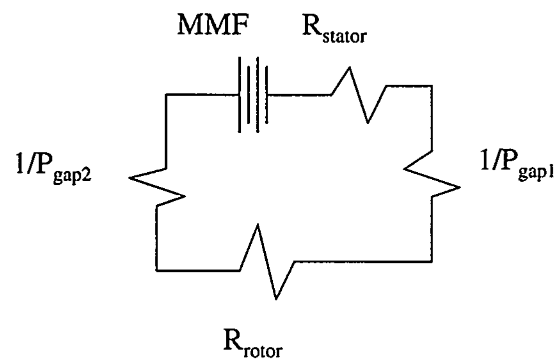

Figure 6 Magnetic Circuit Model

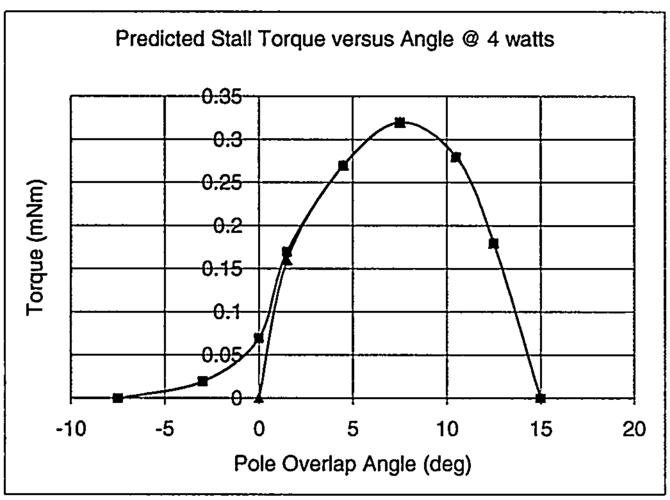

Figure 7 Predicted Stall Torque. The squares are for the 8 pole rotor and the triangles are for the 12 pole rotor

A comparison of predicted stall torque versus angle of pole overlap is shown in Figure 7 for the 8-pole rotor of Figure 2 and the 12-pole rotor of Figure 3. The air gaps are 50 microns and the coil power is 4.0 watts. The plot with the left-hand tail is the 8-pole rotor configuration, and the torque in the zone before pole alignment is low since magnetic flux paths are by fringing and not across the 50 micron air gap. The 8-pole rotor configuration has a 15° step so the phases are switched at -1° and 14° alignment where the torque is low, and much torque ripple results.

In contrast, the 12-pole rotor configuration has sharp torque crossovers at 0° and 15° but the step size is 10°. Hence, the phases can be switched at 2.5° and 12.5° where the torque is 50% of the peak torque, and little torque ripple results.

Fabrication

The motor was built using a combination of conventional and LIGA-based fabrication methods. In the LIGA process, a highly collimated synchrotron x-ray source is used to expose a thick layer of photosensitive material (PMMA), which functions as a photoresist, which is then developed and used either as mechanical parts, or as a mold for subsequent electroplating of metal parts.

LIGA has several advantages in fabricating miniature parts. The major advantage is that metal and plastic parts can be fabricated in sizes that cannot be accomplished by miniature machining techniques. The planetary gear reductor shown in Figure 5 was fabricated from copper (sun, planets, and ring) and PMMA (output gear). These materials were chosen to minimizing magnetic flux leakage.

The rotor and stators were fabricated using standard miniature machining processes. Hyperco 50 (Co-Fe) was chosen due to the very high saturation flux density (B=2.3 Tesla) of the material. At present this material is not one that can be electroplated in the LIGA process. Work is progressing to add this material to the suite of materials available in the LIGA process. Such parts when produced by the LIGA process should be less expensive compared to fabrication by conventional machining. The stators were subsequently wound with 44-gauge wire. Ball bearings were lightly press fit into the 2.5 mm through hole in the rotor at the top and bottom. Conventionally fabricated pins were used to hold the rotating portions (rotor and output gear/planet gear connection) of the motor in place. The pins used are commercially available gauge pins, which were cut to length and deburred.

One disadvantage of both conventional miniature machining and LIGA is that the endpoints for these processes are piece parts, which must be manually assembled. Because automated methods of assembly are both impractical and unavailable for the construction of a small number of motors, hand assembly was required. The motor was assembled under a microscope using epoxy to mount the stators around a conventionally machined fixture onto a brass plate. Because the motor torque is inversely proportional to the length of the air gap between the rotors and the stators, the placement of the stators was critical. With our current fabrication setup, it was difficult to place the stators in the proper position relative to the rotor to less than 25 microns of the desired location. The dimensions of the airgaps between the rotor and the three stators on the test motor were as follows: stator 1, 71μm and 23μmm; stator 2, 30μm and 149μm; stator 3, 141μm and 113μm. Once the stators were in place, the rotor fixture was removed and the rotor was press fit with it's two ball bearings onto the previously installed center shaft. The next iteration of the motor will have LIGA produced fixtures that will more accurately guide the motor elements into place.

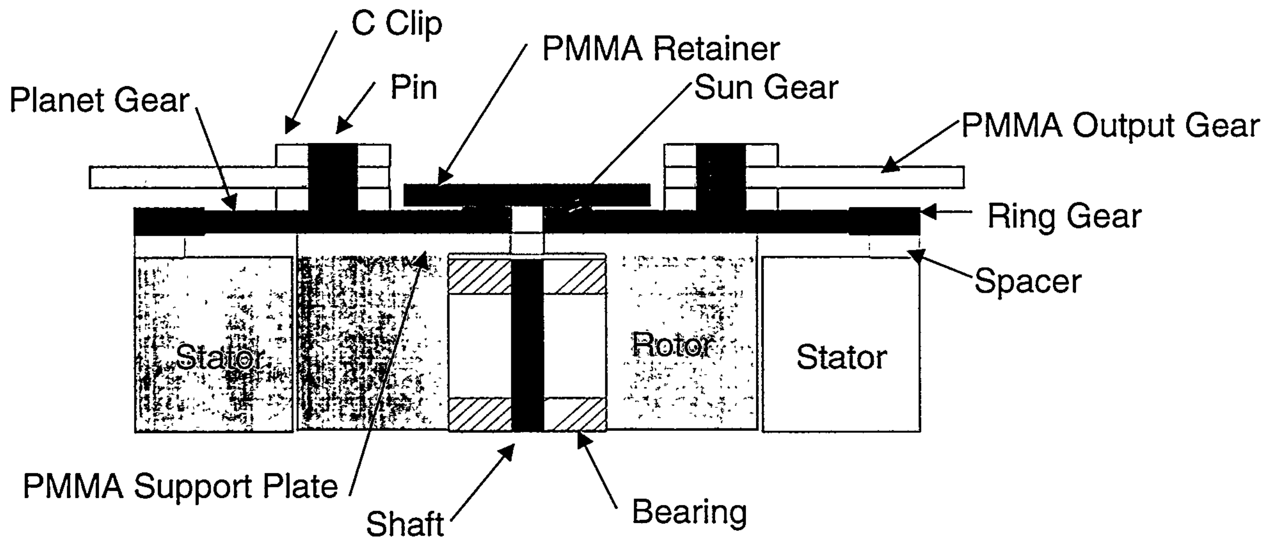

Figure 8 Millimotor Cross-Section

The planetary gear reductor was assembled using LIGA produced retaining clips, gears, and ~0.5-mm conventionally machined pins. The parts were assembled by hand under a microscope. A PMMA support plate was attached to the rotor with epoxy. The sun gear was then attached to the support plate. The ring gear was attached to the three stators using epoxy. Again these parts required careful alignment to achieve concentricity. Each of the various elements is identified in Figure 8.

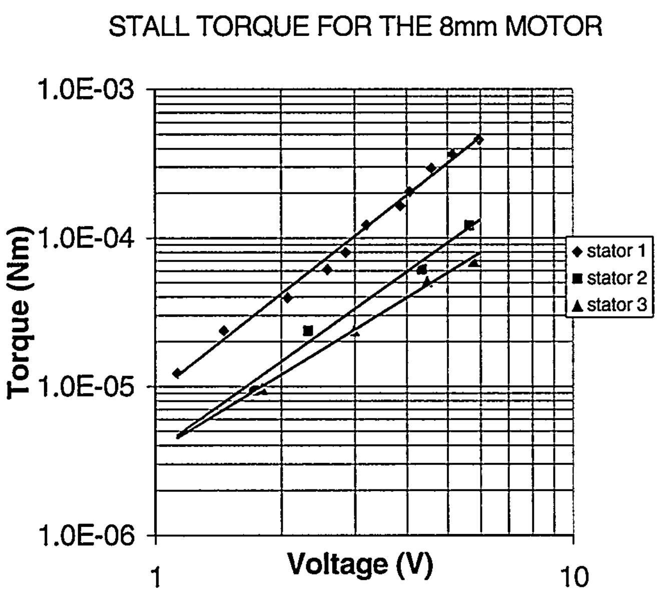

Figure 9 Experimental Torque-Voltage Relationship

Testing

The motor was tested in both static and dynamic test modes. Open loop dynamic testing indicated that, due to non-linear effects, there were points along the torque speed curve where the motor torque dropped precipitously. At slow speeds the rotor commonly overshot the stator and would oscillate into position. At certain input excitation frequencies, the motor would vibrate instead of rotate. Again, this is due to non-linear effects, which is a topic for future investigations. Overlapping the input excitations to each stator can circumvent such effects. A larger inertial load applied to the motor also reduced these effects. These effects will be addressed in a future study that will examine the coupled non-linear mechanical-electromagnetic system.

Static torque measurements as a function of applied voltage to the coils were made for the case where each stator was energized one at a time. These results are shown in Figure 9 where the resistance of the stators are about 10 Ohms . Torque measurements were inferred by determining the maximum weight that the motor could maintain in static equilibrium. Figure 10 illustrates the test setup. In this arrangement a machined spool was placed over the output gear pins shown in Figure 11 and a small thread was attached to the spool. In other tests the thread was attached to one of the nine pins shown in Figure 11.

For the higher voltage levels, the resistance of the wire started to increase because of Joule heating and decreased the amount of current flowing through the coil. However, if the measurements were made quickly, this was not a large experimental problem. In addition, measurements made using a constant current supply instead of a constant voltage supply gave similar results. The torque amounts vary considerably and are mainly caused by the differences in the length of the air gap between the rotor and the stator. The torque values as expected are essentially proportional to the square of the voltage. Rotary torque measurements were made using an Instron load cell. Rotary measurements were also made on the motor with the gear reductor.

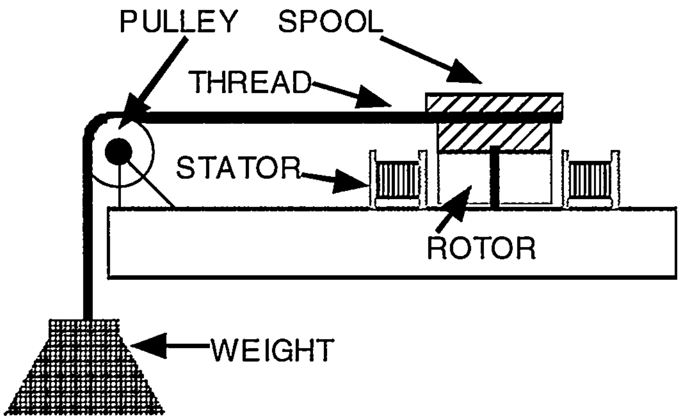

Figure 10 Torque Test Configuration without Reductor

Figure 11 shows the test configuration with pins inserted into the nine holes. The thread shown in Figure 10 is connected to these pins and enables the connection with the test weight.

Figure 11 Test Configuration with Output Gear

Conclusions

A pancake-shaped stepper motor was designed, fabricated and tested for an application with a severe constraint in the motor axial direction. The combination of conventional and MEMS-based fabrication techniques made feasible the fabrication of such a motor. The incorporation of LIGA fabrication to even more of the motor sub-elements will further reduce the motor cost. The use of LIGA gages and fixtures further facilitates the assembly of the millimotor and will be a central element to mass producing such a motor. We would like to acknowledge the fabrication, testing, and other assistance of A. A. Jojola, V. E. Lucero, B. G. Carlen, T. R. Christenson, W. D. Bonivert, M. A. Bankert, J. T. Hachman, D. R. Boehme, A. M. Morales and J. M. Hruby.

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