

DESIGN AND FABRICATION OF A LIGA MILLIENGINE

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SUMMARY

This paper reports on the design and fabrication of a new milliscale magnetic actuator that is ideally suited for LIGA processing [1]. LIGA processing permits the fabrication of millisized machine elements that cannot be fabricated by conventional miniature machining techniques because of their small feature sizes. The Milliengine is a magnetically driven device that utilizes a unique design to extend the 2-dimensional fabrication capability of LIGA to create 3-dimensional machinery [2].

Keywords: Actuator, LIGA, Magnetic Actuator

INTRODUCTION

Millimachinery, also referred to as mesoscopic machinery, fits within a size spectrum bridging MEMS devices at the small end, to the smallest size limits of conventionally fabricated machines and structures at the large end. Millimachinery can provide us with a vehicle for interfacing MEMS devices with the macroscopic world and fabrication of suitable millistructures may also assist in solving packaging difficulties encountered with MEMS devices. In addition, there are instances where millimeter sized devices scale more favorably than microscopic devices. The development of the LIGA

Milliengine has been targeted to milliscale applications where microscopic motors cannot provide sufficient torque and conventionally fabricated motors are not available in the desired sizes.

DESIGN

The Milliengine consists of several elements: magnetic circuits to convert magnetic energy to mechanical energy, structural elements such as movable actuators, bearings, linkages, and drive pinions, and output gearing for connection to an external mechanical load. This work is an extension of previous magnetic and electric microactuator designs [3, 4].

Figure 1 is a schematic of the Milliengine design. Two magnetic linear actuators are used to drive two pinion gears which in turn drive a single output gear. This arrangement permits the conversion of linear motion to rotary motion. The two actuators operate 90° out of phase with respect to each other and are connected to the pinion gears by linkages. By operating the actuators 90° apart, we insure that torque delivered to the output gear is positive for all gear positions. The linear actuators used in the Milliengine are direct gap, i.e., the force across the gap is directly used. For this case the force varies as approximately $1/(\text{gap})^2$.

MASTER

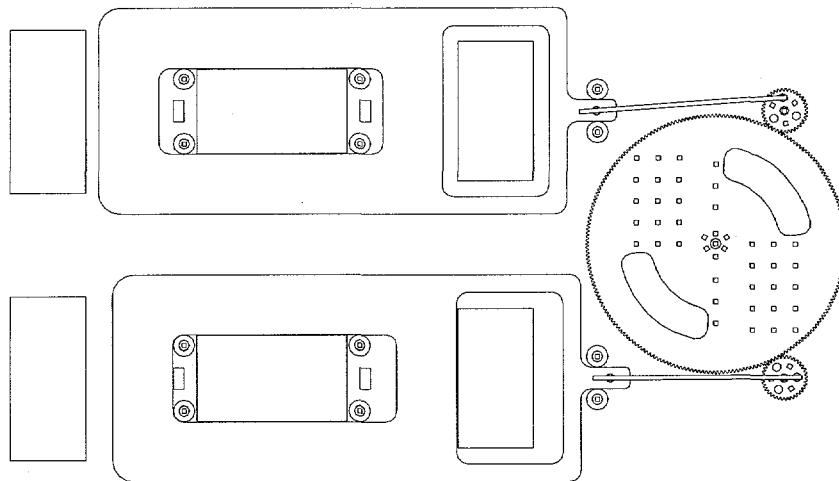


Figure 1 Milliengine Schematic

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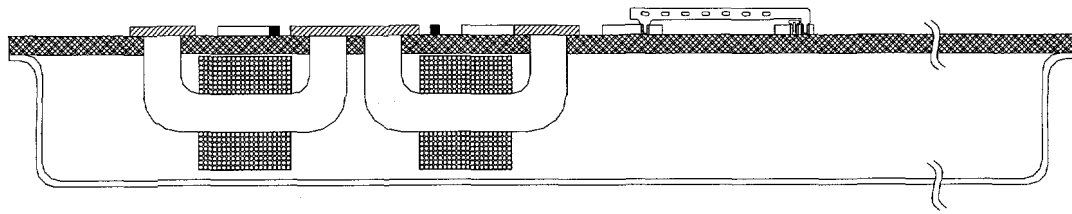


Figure 2 Milliengine Cross-Section

Figure 2 shows a cross-section of one version of the design in which the electromagnetic coils used to drive the Milliengine are located on the back side of the substrate. Openings through the substrate allow for connection of the coil cores to the remainder of the magnetic circuit located on the top side of the substrate. The magnetic circuit used in this actuator uses a unique design to transfer magnetic flux from fixed stators to the moving actuator. Undesired lateral motion of the actuator is controlled by the use of roller bearings. All movable mechanical elements are located on the top side of the substrate.

the right. Here the linkage has been rotated 90° from its' original plane of fabrication to form a 3-dimensional mechanism. The rectangular ends of the linkage are inserted into bearing elements which were previously inserted into the actuator end and pinion gear. The bearing elements permit the linkage to rotate relative to the actuator and pinion. The pinion gears and output gear are positioned over shafts that have been fabricated as fixed members of the substrate. The pinion shaft shown in Figure 5 has a rectangular opening in the center which is designed to accept a retaining clip that is used to secure the gear to the substrate while permitting rotary motion of the gear. The retainer clip is another example of the use of an element that is rotated 90° to its' original plane of fabrication.



Figure 3 Link Connection to Pinion and Actuator

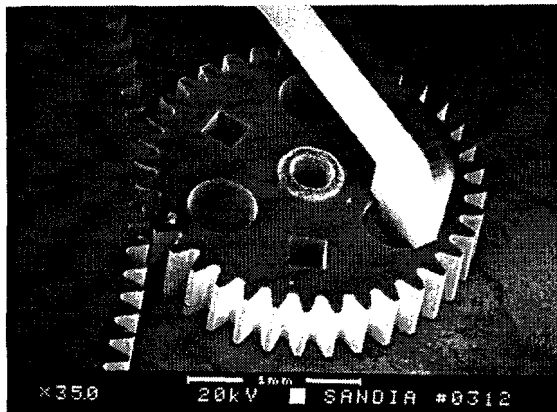


Figure 4 Output Gear/Pinion/Link Connection

The use of LIGA elements fabricated as 2-dimensional structures and rotated 90° out of the plane of fabrication is illustrated in Figures 3, 4 and 5. Figure 3 illustrates a drive linkage connection to the actuator element on the left and a pinion gear on

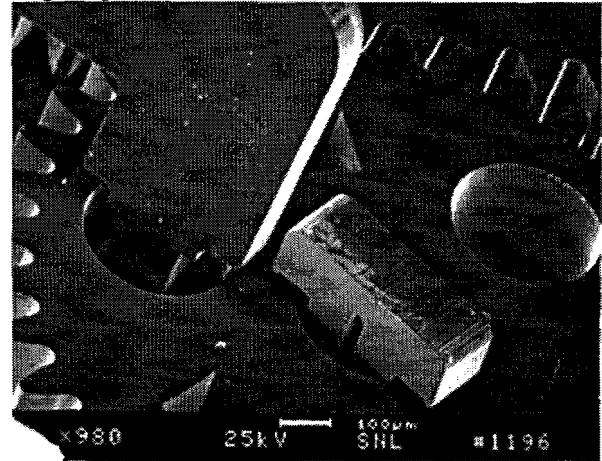


Figure 5 Link/Pinion Connection

MAGNETIC CIRCUIT

The circuit used to convert magnetic energy to mechanical energy is shown in Figure 6. Four such circuits are used to drive the Milliengine as explained above. A coil wound around a solid circular core produces magnetomotive force in the circuit. This coil is positioned under the substrate of the device as shown in Figure 2. The coil core is connected with the remainder of the magnetic circuit through openings in the substrate that permit the core to be positioned so that the core ends are in direct contact with the Milliengine stators.

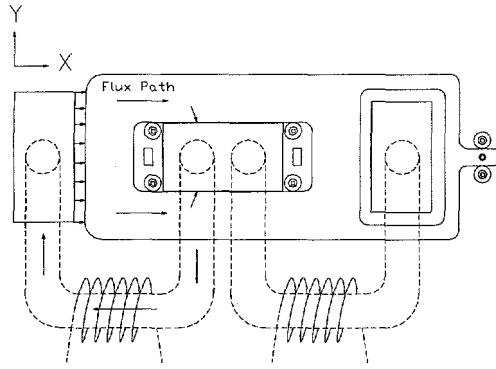


Figure 6 Milliengine Circuit

In Figure 6, the magnetic flux path is shown. The magnetic flux path passes through the coil core into the stator. The flux path then passes across the air gap and into the actuator. Because the actuator moves to the left and to the right, the air gap dimension between the fixed stator on the left, and the movable actuator on the right varies. The flux path then divides into 2 parallel paths through the actuator to the regions where there are fixed gaps. The gaps are fixed since the roller bearings (shown in Figure 1) only permit motion of the actuator along the x-axis. The flux path passes across the fixed air gaps to the central stator. From the central stator the flux path then passes back into the coil core to complete the circuit. The circuit described is used to pull the actuator element to the left. The other circuit shown on the right side of Figure 6 is used to drive the actuator to the right. By alternating the excitation of the drive coils, the actuator can be made to move both to the left and to the right. It is this motion that is harnessed via a drive linkage to produce motion of the drive pinion and output gear.

Force and Torque

A one dimensional magnetic circuit model of the flux path illustrated in Figure 6 was formulated to estimate drive forces generated by the actuator. Reluctances over regions of the flux path were estimated and combined into a series-parallel circuit to yield an overall reluctance for the circuit. This reluctance varies with the stroke of the actuator and is used to compute a system energy. The variation of the energy with actuator stroke was then used to estimate a drive force due to an applied magnetomotive force (MMF in amp-turns). The force expression derived turned out to be proportional to the inverse of a second degree polynomial in the gap.

For a given MMF, a magnetic flux will be established in the circuit ($\text{Flux} = \text{MMF} / \text{Reluctance}$) until the material used in the actuator reaches a state

of magnetic saturation. The maximum magnetic saturation flux density for the material used in the circuit establishes an upper bound on the force that can be generated within the actuator and must be accounted for when estimating force outputs. For the actuator and stators, the material used is electroplated permalloy consisting of 78% Ni and 22% Fe. Previous investigations [5] indicate B_{sat} for permalloy in the as-plated condition equal to approximately 1.0 Tesla. B_{sat} for the soft Fe used in the coil cores is also estimated to be 2.2 T. The calculated force curve at a given MMF is shown in Figure 7. Here the maximum force generated is limited by saturation in the circuit. It should be noted that the one-dimensional circuit model of this system is only an approximation to a three-dimensional problem. The effects of magnetic fringe fields are not taken into account and it turns out that ignoring fringe fields in this case does not give a conservative answer for force generated. A preliminary look at fringe fields indicates that for large gaps the force is somewhat higher and for small gaps the force is less than that predicted by the simple one-dimensional circuit model.

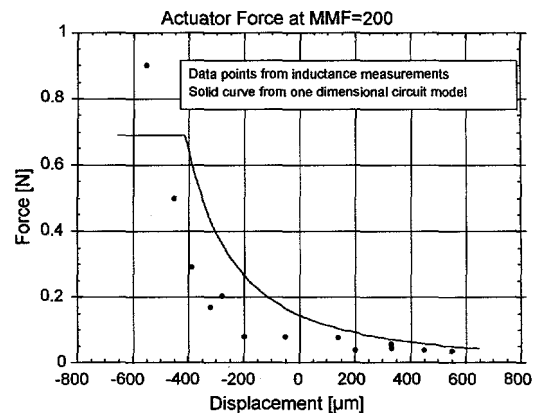


Figure 7 Force vs. Displacement

With an estimate of force versus stroke available, the output torque can then be determined. It can be seen from Figure 1 that at certain positions of the pinion gears torque cannot be generated by one of the actuators. However, by phasing the actuators 90° apart the opposing actuator is able to produce torque about the output gear. To calculate torque about the output gear we use a vector equation $\underline{\text{Torque}} = (\underline{r}_1 \times \underline{E}_1 + \underline{r}_2 \times \underline{E}_2)(r_{\text{gear}}/r_{\text{pinion}})$ where \underline{E}_1 and \underline{E}_2 are the actuator force vectors and \underline{r}_1 and \underline{r}_2 are the pinion moment arm vectors about their respective pivots. The ratio of the output gear radius r_{gear} to the pinion gear radius r_{pinion} gives the torque amplification at the output gear

pivot. Output gear torque as a function of pinion gear angle is shown in Figure 8.

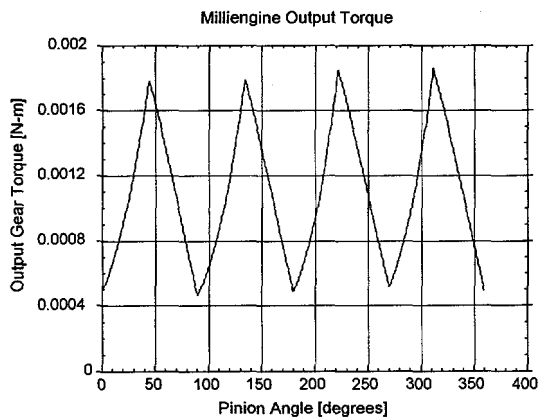


Figure 8 Output Torque vs. Pinion Angle
Inductance Measurements

Inductance measurements as a function of actuator stroke x were performed on the first prototype unit fabricated. The force generated at various actuator positions can be determined by evaluating the coenergy U^* as a function of inductance where $U^* = (1/2) L(x) i^2$ and determining the change of coenergy with respect to stroke x . The force generated is then equal to $(1/2) i^2 d(L)/dx$. Figure 7 gives a comparison of the force versus stroke estimate obtained by differentiating the inductance data with the results from the one dimensional circuit model.

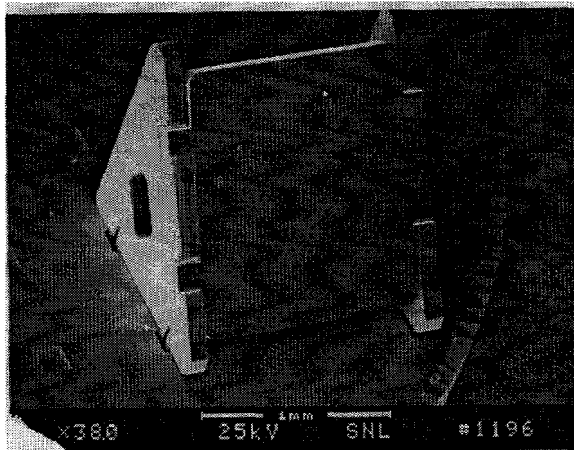


Figure 9 Millimirror Structure on Output Gear
APPLICATIONS

Figure 9 illustrates an application of the Milliengine for mirror positioning. Here two LIGA fabricated elements (millimirror support structures) are rotated 90° from their original plane of fabrication and inserted into receptacles in the output gear. Protruding spring elements built into the support structures' base secure them in place. A LIGA fabricated millimirror with 4 tabs is then positioned

on the support structure (as shown) to form another 3-dimensional structure. Rotating the output gear then enables positioning of the millimirror to desired orientations.

CONCLUSIONS

A milliscale LIGA actuator has been designed, fabricated, and operated in a stepping mode. This device appears to have great potential as a high torque driver in the milliscale domain. This device is the first of its kind demonstrated in LIGA technology with several new innovations including three dimensional structures such as the link/bearing arrangement used to connect and drive linear actuators and pinions, and the use of retainers inserted into pre-fabricated openings in shafts to retain pinions, actuators and roller bearings. In anticipation of packaging, the drive coils have been placed on the backside of the substrate where, along with any additional required electronics, the entire backside can be sealed from the environment.

Preliminary inductance measurements have been made and compared to pre-design force calculations. Issues related to wear of bearings and other contacting surfaces remain to be evaluated. Measurements to determine mechanical and magnetic material properties such as friction, magnetic flux density B versus magnetic field intensity H , and stress-strain properties remain to be completed. Direct measurement of force and torque output has not been completed and is planned for the near future as well as speed versus torque loading.

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