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Optical measurement of LIGA milliengine performance

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ABSTRACT

Understanding the parameters that affect the performance of milliscale and microscale actuators is essential to the development of optimized designs and fabrication processes, as well as the qualification of devices for commercial applications. This paper discusses the development of optical techniques for motion measurements of LIGA fabricated milliengines. LIGA processing permits the fabrication of precision millimeter-sized machine elements that cannot be fabricated by conventional miniature machining techniques because of their small feature sizes. In addition, tolerances of 1 part in 10^3 to 10^4 may be maintained in millimeter sized components with this processing technique. Optical techniques offer a convenient means for measuring long term statistical performance data and transient responses needed to optimize designs and manufacturing techniques. Optical techniques can also be used to provide feedback signals needed for control and sensing of the state of the machine. Optical probe concepts and experimental data obtained using a milliengine developed at Sandia National Laboratories are presented.

Keywords: Micromachines, actuators, optical probe/feedback.

1. INTRODUCTION

Millimachinery, also referred to as mesoscopic machinery, fits within a size spectrum bridging Microelectromechanical Systems (MEMS) devices at the small end to the smallest size limits of conventionally fabricated machines and structures at the large end. Millimachinery can provide 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.

Integration of LIGA^{1,2} micro-fabricated actuators into a complete microelectromechanical system requires an understanding of their dynamic behavior and may entail position feedback control. A device which is being pursued as a generic actuator for LIGA based microsystems is the LIGA "milliengine."³ The milliengine is an extension of a planar processed polysilicon device, the microengine,⁴ which has proven to be a fundamental actuator in many surface micromachined devices.⁵ The structure of the LIGA milliengine is shown in Fig. 1 which reveals a linear to rotary motion conversion mechanism achieved via two complementary phased magnetic linear actuators coupled with linkages to corresponding pinions and an output gear. Fabrication is carried out on a non-magnetic substrate material such as silicon or alumina. Each linear actuator magnetic circuit consists of a coil residing beneath the substrate which couples to a magnetic path feeding through the substrate whereupon it couples to the stator of the actuator. The linear actuator slider and magnetic counterpart material is electroplated 78 Permalloy and the adjoining mechanical parts are electroformed from nickel. The three dimensional construction of the mechanical linkage is achieved by assembly of LIGA fabricated components including spring clamps.

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Two possible means to monitor motion of the milliengine mechanism include inductive and optical sensing. Optical interrogation has proven to be particularly straightforward to instrument in the initial testing phase. Two optical sensing schemes have been previously reported for monitoring LIGA component motion. One method uses photodiodes fabricated into the underlying substrate to detect motion of a LIGA fabricated rotary motor positioned above the photodiodes.⁶ The motion of the rotor thus acts as a shutter over the photodiodes. Another scheme uses an inserted optical fiber within a LIGA fabricated structure to monitor reflected light signals.⁷ The method reported here makes use of a remotely located optical probe in a similar manner to that used previously for surface micromachined devices.^{8,9,10} Optical probe techniques are particularly suitable for characterization and testing of milliengines. In general, optical measurements can be made using existing milliengine structures such as gear teeth eliminating the need for additional optical patterns. In addition, the techniques can be used to remotely sense motion at any unobstructed point in the mechanism.

Fig. 1 Milliengine schematic.

This paper discusses the design concept and implementation of the optical probe measurement system. Resulting measurements from a LIGA milliengine are presented. Data obtained using optical techniques can be used to support model verification, tribological performance analysis, and provide feedback require for system applications.

2. OPTICAL SYSTEM CONCEPTS

An important part of the development process for a device such as the LIGA milliengine is the experimental determination of the motion of the system for various drive inputs and loads. This information is used to design or modify milliengine components, design appropriate input drive signals, and characterize failure modes. Parameters such as system damping and inertia can be estimated from appropriate motion measurements. Frictional effects can also be estimated from motion measurements. In addition, a closed-loop feedback control system could be incorporated into the milliengine if a suitable means for position, speed, and acceleration detection was available.

2.1. Measurement requirements

A large class of LIGA fabricated systems are milliengines containing gears and gear driven structures. For this case, the measurement and characterization of gear angular motion should provide the information needed to provide feedback signals and perform failure analysis. As a minimum, one would like to measure the following quantities associated with the gear rotation:

1. Rotation rate or angular rate (speed).
2. Fluctuations in angular rate within a cycle and over a number of cycles.
3. Phase of the gear motion relative to a reference signal as a function of frequency or other parameter.

The absolute position of a gear or the structure being driven could be computed from rotation rate and direction information if the starting position is known. The scale of LIGA milliengines also allows for absolute position encoding marks to be added to the component parts such as the gear surface. It is quite possible to develop optical encoders at the LIGA milliengine scale.

An illustration of the output gear, pinion and link connection for the milliengine shown schematically in Fig. 1 is shown in Fig. 2. The pinion (small gear) has 36 teeth, a diameter of approximately 2 mm, and a thickness of 0.5 mm.

Fig. 2 Output gear/pinion/link connection.

2.2. Optical probe geometries

There are a large number of optical configurations that can be used to detect the motion of milliengine components. As a minimum, the configurations can be divided into the following classes:

1. Reflection based systems:

An optical beam is generated and detected on the same side of the engine. The modulation of the optical beam is induced by reflection from moving engine components such as a tooth or special patterns on various structures. The modulated beam is then detected to assess motion.

2. Transmission based systems:

An optical beam is transmitted from one side of the engine to the other. The modulation of the optical beam is induced by the motion of an engine component and then detected to assess motion. Transmissive features such as holes may be added to facilitate measurement.

3. Integrated optical fiber or waveguide systems:

In this approach, optical probe beams would be directed on moving milliengine surfaces by optical waveguides that are coplanar with the engine substrate or base.

Generally, the determination of the direction of rotation requires two probe signals or an asymmetry in the detected signal. The two probe signals can frequently be obtained with one optical source and two sets of properly arranged collection optics.

Classes 1 and 3 are illustrated generically in Figures 3 and 4, respectively. In Fig. 4 a beam is reflected off the tooth part of the gear. The gear teeth modulate the beam as the gear rotates. Detecting this modulation gives a

measure of angular motion. Since the pinion has 36 teeth, this approach readily gives an angular resolution of 10 deg and the resolution for the output gear would be 1.67 deg (29 mrad) corresponding to a gear ratio of 6. The rotation direction can be sensed by two probe beams that are properly phased or by detecting the backscattered light off the tooth as well as the forward reflection.^{8,9} In this approach, it is possible to improve the resolution by adding more probe beams around the periphery of the gear in a vernier arrangement. The resolution could also be increased by impressing a small feature on the gear structure and focusing the input beam to a correspondingly small spot. Beam spot and feature sizes on the order of a micron could be obtained. This would give a basic resolution on the order of 1 mrad.

Fig. 3 Focused beam reflection based probe.

Fig. 4 Integrated waveguide probe.

The integrated approach shown in Fig. 4 has the advantage of simplicity. In the figure, the center waveguide is the source waveguide and the two outer waveguides collect the optical radiation scattered (reflected) off the milliengine component (gear teeth). The orientation of the waveguides can be adjusted to maximize signal strength and direction information. There are many possible arrangements for the waveguides in addition to that shown in the figure, for example, a vernier arrangement discussed above. For a single mode waveguide or fiber the beam size would be on the order of a few micrometers, and for multimode waveguides or fibers, the beam size would typically be in the range of 50 to 100 μm . This gives a basic angular resolution for single mode waveguides of the order of a few milliradians and a basic resolution in the range of 50 to 100 milliradians for multimode waveguides. The resolution can be enhanced by signal processing or a vernier technique. It should be noted that the ability to do signal processing is strongly dependent on signal-to-noise ratio.

3. EXPERIMENTAL DATA

A probe was developed using a reflection-based approach as discussed in Section 2.2 and illustrated in Fig. 3. A visible laser was focused by an achromatic lens one of the two pinion gears. A 1 mm core fiber was used to collect the forward scatter light and bring it to a detector and amplifier. For the initial studies, the incoming beam was directed tangentially to the gear at roughly 45° from normal incidence. For one complete rotation of the pinion gear, four stationary signal levels are typically seen, with signal excursions occurring during transitions. This situation is illustrated in Fig. 5. The four optical signal levels occur because the gear stops at four distinct positions determined by the four milliengine square wave drive signals, which are 90° out of phase. At each stopping point, a gear tooth may be completely or partially scattering the beam in the forward direction. The signal excursions should represent the gear teeth passing quickly through the beam during a drive signal shift. Unfortunately, oscilloscope memory limitations make it difficult to collect the signal for a complete rotation and sample sufficiently often to collect the finer structure. Windows of the main signal were expanded in time to resolve this structure.

For the trace of Fig. 5, the pinion gear was rotated at 1/9 Hz. As seen at about the 1 s point, there is a further feature occurring between one of the transitions. At slow rotation rates such as this, this feature was audible as a slight double stepping sound. The gear was stopping at an intermediate point between stationary positions. Most likely, some foreign material was interfering with smooth engine operation. The engine was then disassembled and cleaned, and this behavior no longer occurred.

Fig. 5 Forward scatter trace for pinion gear rotating at 1/9 Hz. The gear moves quickly between the four stationary positions determined by the square wave drive signals.

Fig. 6 shows signals collected from the forward scatter beam incident on the large gear. In this figure, windows were used to collect the fine structure occurring during transitions. The beam was moved to the large gear for this measurement, but the time of the complete trace still corresponds to two rotations of the pinion gear, which was rotating at 1 Hz. Since the pinion gear contains 36 teeth, 36 total peaks were expected among the 4 windowed traces. Roughly 9 peaks were expected per transition. Windows 1 and 2 conform to these expectations. Windows 3 and 4, however, contain significantly more peaks. Most likely, the gear is overshooting the rest position and returning, generating additional peaks. In fact, the driver mechanisms generate more force in one direction than the other, which should generate artifacts in two of the four pinion transitions. Also notice the varying time between peaks, which reveals accelerations in the mechanism. Peak detection methods can be used to extract the velocity and acceleration data.¹⁰

Issues such as gear overshoot make it desirable to determine gear direction as well as position. By using the phase difference between forward and back scatter signals, directional information can be obtained.⁸ Back scatter signals were collected from the gear with a 1 mm core fiber, which carried the signals to a detector. The results are illustrated in Fig. 7, where the incoming probe beam was incident on the pinion gear at 45° to the tangent. For this case, the pinion gear was driven back and forth between two stopping positions 180° apart. It thus traveled in opposite directions for each half of a drive period. The two window periods shown in Fig. 7(a) occur where the gear was traveling in opposite directions. The first window is expanded as signal 1 in Fig. 7(b). Except around the first peak, the back scatter signal follows the forward scatter signal by a phase of roughly 90° . The behavior at the first

peak is probably due to backlash during drive startup. The second window, where the pinion gear is traveling in the opposite direction, is expanded as signal 2 in Fig. 7(b). In this case, the back scatter signal leads the forward scatter signal by a phase of roughly 90° . In other words, the relative phase between the forward and back scatter signals has reversed for the two windows. Through this method of recording the phase relationship between the two signals, the system reveals the direction of gear travel.

Fig. 6 (a) Signals from large gear for two rotations of the pinion gear. (b) Expanded windows from the trace. The numbered signals correspond to the numbered windows in (a). These show the four transitions occurring during one complete rotation of the pinion gear.

When using forward and back scatter phase relationships, it is necessary to induce a phase difference other than 180° , so that one direction can be differentiated from another. A 90° phase difference between signals is ideal. This phase difference can be changed by varying the position and orientation of the incoming beam on the gear surface, as well as the position and orientation of the back scatter collection fiber. As the tooth side wall sweeps under the incoming beam, the back scattered radiation sweeps also. This sweeping provides opportunities to change the relative phase of the signal by moving the position of the collection fiber. We found good results with the incoming beam oriented at 45° to the gear tangent. The backscatter signal was collected in a nearly tangential direction. The signal reflected from both the tooth side wall and the substrate before entering the collection fiber.

With the ability to collect directional information, gear overshoot can be identified. Fig. 8 illustrates a directional change for the pinion gear driven at 1 Hz in a single direction. In the expanded window shown in Fig. 8(b), a gear direction change is seen at 15 ms. The forward and back scattered signals have reversed relative phase. There are additional peaks outside of the window in Fig. 8(b).

4. INTEGRATED OPTICAL FEEDBACK SYSTEMS

Perhaps the most important application of optical probe technology is in an integrated feedback system. Feedback would be important in applications where the state of a mechanical system must be known. It would also be important in commercial uses of LIGA millieengine technology to insure that the gear was running correctly, as a self testing process. The probe in Fig. 4 illustrates a typical feedback system. A source fiber or waveguide is positioned close to the gear, with two flanking receiver fibers. An LED or diode laser would provide the source signal. The phase difference from the two receiver fibers would provide direction, and the signal count would record gear motion. Ultimately, the waveguides would be fabricated within the LIGA process. Several technologies may offer a deposition process compatible with these devices. It is also possible to bond standard optical fibers to the engine substrate or base.

The symmetry of the probe in Fig. 4 would have the advantage of enabling a precise determination of the gear rotation direction. However, there are many possible configurations that might be useful for an integrated probe system. For example, waveguides could be located below the substrate surface and the beam coupled to the gear or other physical structure by various waveguide coupling techniques. Another approach is to use waveguides that are

Fig. 7. Forward and back scatter traces where the pinion gear is oscillating between two positions. (a) Two drive periods. (b) Expanded time scales of the signals. The upper traces are for the window at 580 ms in (a). The lower traces are for the window at 1080 ms in (a).

Fig. 8. Forward and back scatter traces showing overshoot and return in the pinion gear. The gear is rotating CCW. (a) Two drive periods. (b) Expanded time scales of the signals for the window at 580 ms in (a). Notice that the forward and back scatter signals change relative phase at 15 ms.

raised above the surface or optical fibers positioned on the surface of the substrate to probe the edge of the gear or other machine structures. There is also the possibility of some of the optical probe components being integrated on or in the substrate and other components mounted above the engine.

5. SUMMARY

In this paper we have presented an optical probe technology for assessing the performance of LIGA fabricated milliengines for research, development, and applications. A particular configuration of the probe that measures both forward and back scatter was described. Experimental data generated with a prototype optical probe illustrated the robustness of the technique. The data demonstrate that the probe generates signals that are adequate for measuring rotation rate, intra-period fluctuations in rotation rate, phase of the rotation relative to the drive signals, and rotation direction of micromachine gears. The quality of the data also suggests that the technique is quite capable of being automated. This technique can also be applied to the detection of motion of other millimachine physical structures. This technology can provide the basis for integrated feedback control signals and sensing signals needed for LIGA systems applications.

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