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An optical probe for micromachine performance analysis

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ABSTRACT

Understanding the mechanisms that impact the performance of Microelectromechanical Systems (MEMS) is essential to the development of optimized designs and fabrication processes, as well as the qualification of devices for commercial applications. Silicon micromachines include engines that consist of orthogonally oriented linear comb drive actuators mechanically connected to a rotating gear. These gears are as small as 50 μm in diameter and can be driven at rotation rates exceeding 300,000 rpm. Optical techniques offer the potential for measuring long term statistical performance data and transient responses needed to optimize designs and manufacturing techniques. We describe the development of Micromachine Optical Probe (MOP) technology for the evaluation of micromachine performance. The MOP approach is based on the detection of optical signals scattered by the gear teeth or other physical structures. We present experimental results obtained with a prototype optical probe and micromachines developed at Sandia National Laboratories.

Key words: Micromachines, optical probe, performance analysis

1. INTRODUCTION

Microelectromechanical Systems (MEMS), an emerging technology with the potential for revolutionary impact in a wide array of commercial and defense applications, present a unique characterization challenge. The challenge is how to measure the time-dependent spatial position of moving MEMS components, which are on the order of tens of microns in dimension. Such measurements are essential not only to characterize the performance of MEMS actuators, but also to identify and characterize fundamental degradation and failure mechanisms associated with these new types of devices. An infrastructure does not currently exist for easily and fully characterizing micron-sized devices that can move at speeds in excess of 300,000 revolutions per minute.

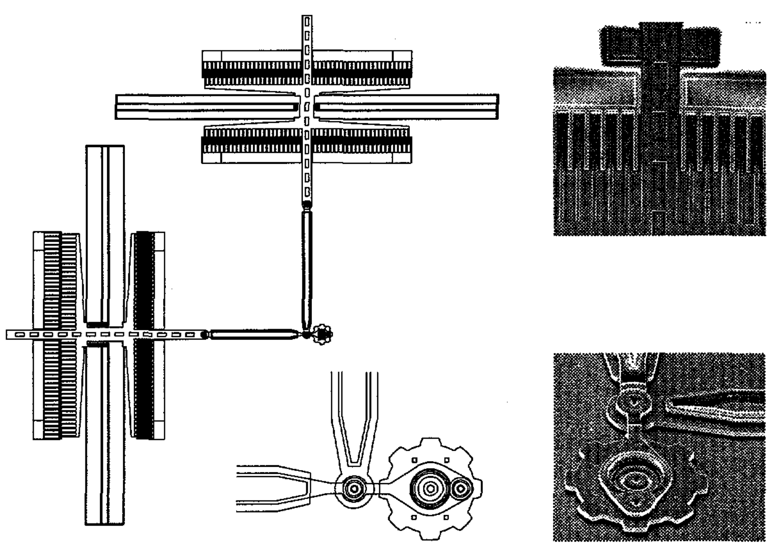


Fig. 1 Microengine diagram.

DISCLAIMER

Consider, for example, the microengine shown in Fig. 1.[1,2,3,4] This devices consists of linear electrostatic actuators that are mechanically coupled to an output gear. Electrostatically applied forces are transmitted to the gear through mechanical linkages in a way that results in continuous rotation of the output gear. The output gear can be used to apply torque to a load device. A complete description of the technology used to fabricate the microengine is given elsewhere,[3] as is additional design information.[4] In order to infer fundamental microengine device properties, such as spring constants, electrostatic force constants, and damping coefficients, measurements of the engine response to various applied drive voltages must be made. Time-dependent position measurements of the output gear are also required to measure frictional forces between the gear and hub, and to make performance tradeoffs of the engine in different applications.[5,6] Finally, real-time position measurements are anticipated to be instrumental in identifying fundamental degradation and failure mechanisms associated with the microengine.

In the past, position measurements of moving MEMS devices have been made using a strobe light when the engine is driven with periodic signals.[5,6] The strobe technique typically provides images that are the superposition of multiple strobe flashes, resulting in an averaging effect. While this is not a problem when the motion of the device being measured is strictly periodic, non-periodic fluctuations are not able to resolved with the strobe technique. Such fluctuations may be important to understand underlying failure mechanisms of MEMS devices. In addition, automation of the data collection and analysis using the stroboscopic technique requires extensive two-dimensional data processing.

In this paper, we present a new method of measuring MEMS device motion that permits the recording of real-time non-periodic position fluctuations. The application of the method consists of measuring light scattered from the gear teeth or other physical structures. In the next section we discuss optical probe concepts and requirements. In Section 3 we describe the design of our developmental probe. In Section 5 we discuss the potential integration of an optical probe onto the MEMS chip to provide important feedback needed for system applications. Experimental data obtained using the probe is presented in Section 4 and the work is summarized in Section 6.

2. OPTICAL PROBE SYSTEM CONCEPTS

Microelectromechanical systems development requires the measurement of the motion of MEMS components. This information provides important feedback for the design of actuator drive signals and to characterize degradation and failure modes. The information required can be divided into two classes. One class is the information needed to determine basic parameters of the system such as damping coefficients and spring constants. The other class is the information needed to describe system performance such as gear rotation rate and direction. Currently, the major approach to the measurement of MEMS component motion is the use of high resolution video microscopy combined with the stroboscopic effect. However, motion measurements based on the stroboscopic effect are limited by video camera rates. In other words, the use of the strobe assumes periodic motion. Since gear rotation and the motion of other components can be reduced to a one dimensional problem, a direct optical measurement could virtually operate in real time. That is, since optical detectors can provide bandwidth in the GHz range, the probe can track the mechanical motion with effectively unlimited temporal resolution.

2.1. Measurement requirements

Microengines containing gears and gear driven structures make up a large class of MEMS devices. For this case, the measurement and characterization of gear angular motion should provide the information needed to perform MEMS performance 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.

This information could also provide important feedback needed for the application of MEMS systems. For example, the position of a gear or the structure being driven could be computed from rotation rate and direction information if the starting position is known.

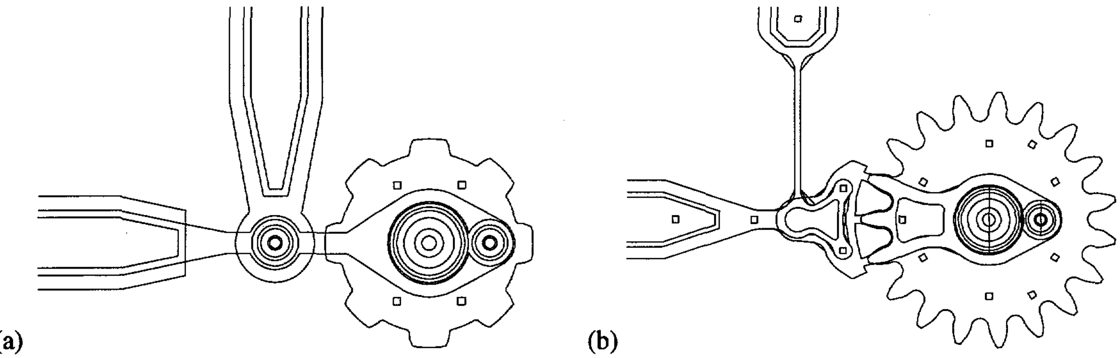


Fig. 2 (a) Gear structure used for MOP experimental work. (b) Next generation gear structure.

Two gear structures developed at Sandia National Laboratories are shown in Fig. 2. The gear shown in Fig. 2(a) is has a diameter of 50 μm and eight teeth. The gear is driven by the two drive arms shown on the left which are coupled to the gear at the pin joint on the right. The experimental work described in this paper was done using gears of this type. A next generation structure, the gear in Fig. 2(b) has nineteen teeth with a more optimal shape. The measurements listed above can be accomplished by delivering an optical probe beam to the gear teeth and measuring the scattered light. The measurement of rotation rate and the deviation in rotation rate can thus be made by counting pulses generated by the gear teeth passing through the beam. The number of teeth provide a sampling of the gear rotation and aliasing limits the resolution of rotation rate.

2.2. In-situ measurement of spring and damping parameters

The sampling limit mentioned above might not provide adequate resolution needed to determine spring constants and damping coefficients using current techniques. The current technique[5,6] is to pull the gear through 90 degrees, release the holding force and measure the transient response. The transient response is then fitted to the step function of the homogeneous differential equation describing a damped oscillator. In contrast, a swept frequency response to the inhomogeneous oscillator equation is more suitable to the techniques described in this paper. Also, the swept frequency response allows for smaller signal excitations and correspondingly a more linear approximation.

The swept frequency approach assumes that the driven oscillator can be approximated by the second order differential equation

$$m\frac{d^2x}{dt^2}+c\frac{dx}{dt}+kx=aV_0^{\,2}e^{i\omega t}, \tag{1}$$

where k is the spring constant, c is the damping coefficient and a is a proportionality constant relating force and voltage. Since Eq. (1) describes a linear system, we can work with the complex excitation and take the real part when appropriate. Dividing by m, Eq. (1) can be put in the standard form

$$\frac{d^2x}{dt^2}+2\zeta\omega_0\frac{dx}{dt}+\omega_0^2x=\alpha V_0^{\,2}e^{i\omega t}, \tag{2}$$

where the coefficients are defined by their position in the equation and $\zeta = c/c_c$ with c_c being the damping coefficient corresponding critical damping. A drive voltage given by $V = V_0\sqrt{\sin\omega t}$ is used to obtain a sinusoidal driving force.

The steady state (particular) solution of Eq. (2) is given by

$$x(t) = \frac{\gamma V_0^{\,2}}{-\omega^2 + i\omega 2\zeta\omega_0 + \omega_0^2} e^{i\omega t} = A(\omega) e^{i\{\omega t + \phi(\omega)\}}. \tag{3}$$

The phase ϕ in Eq. (3) is given by

$$\phi(\omega) = \arctan\left(-\omega 2\zeta\omega_0 / -\omega^2 + \omega_0^2\right). \tag{4}$$

The following relations are satisfied by the solution: $\phi = 0$, $\omega \to 0$; $\phi = -\pi/2$, $\omega = \omega_0$; and $\phi = \pi$, $\omega \to \infty$. These three phase relations are adequate to determine c and k, given m. However, a two parameter fit of experimental data to the phase function would give a better estimation of the parameters. Since the phase is a continuous function of frequency, it can be measured by observing the delay between the drive signal and one of the pulses scattered from a gear tooth. The measurement would consist of tracking the position in time of one of the pulse like responses of the probe within a period of the drive signal at each drive frequency used to estimate the phase function. Since the amplitude of gear oscillation also changes with drive frequency, one must be careful to maintain tracking of a given pulse. However, this is readily accomplished because the phase is a continuous function of drive frequency. A statistical distribution of the phase is obtained by using phase data from multiple periods of the drive signal. It should be noted that the phase measurement is continuous, not sampled. That is, the phase is determined by tracking the shift in location of the same output pulse in successive cycles and the phase resolution is determined by the ability to do peak or other parameter (leading edge) detection on the pulse. The technique should be suitable for small signal (displacement) excitation of the micromachine. This method compares favorably with the current transient measurement technique. It offers much quicker data collection since the data stream is one dimensional. In addition, by measuring every rotation, it offers statistical information for the spring parameters, instead of just average information. Finally, it should allow the gear to operate in a more linear region during this measurement.

Although we have not used the amplitude information in Eq. (3), this information could potentially be used to enhance the analysis of machine parameters. For example it could be used to measure the force-voltage constant.

2.3. Probe geometries

There is a large number of optical configurations that can be used to detect the motion of gear teeth. They are based on illuminating the region of the teeth with a spot that is on the order of or smaller than a tooth element and detecting the scattered radiation falling in a given cone. The most general measurement would be a bistatic scatter, that is, measuring the scattered radiation in a direction that different from the incident direction. In fact, the central ray defining the receiving direction need not be in the incident plane. We will refer to radiation scattered back along the incident ray as backscatter and radiation scattered in the specular direction (with respect to the nominal plane) as forward scatter.

Generally, the scattered radiation will depend strongly on the geometry of the scattering object, and a strong signal can be obtained when the reflectances of the various surfaces of the scattering object (gear and substrate) are approximately equal. This is illustrated in Fig. 3. In the figure, an optical beam is incident from the left on a gear tooth above a substrate. The light scattered back toward the source by the two-dimensional corner is indicated by the arrows. The remaining parts of the beam are either trapped between the gear and substrate or scattered (reflected) in the in the forward direction. The motion of gear teeth and or other physical components could also be detected using confocal optical ranging and profiling techniques.[7] A confocal system is a backscatter system with the axis of the illuminating beam normal to the surface being measured and where the collected light is focused on a limiting aperture.

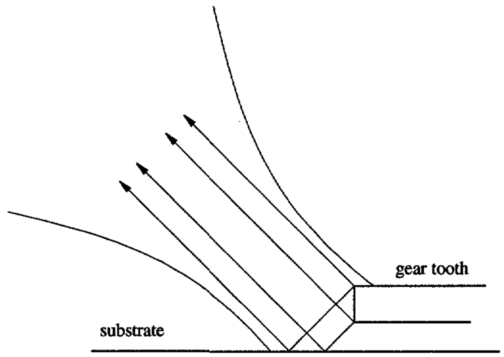
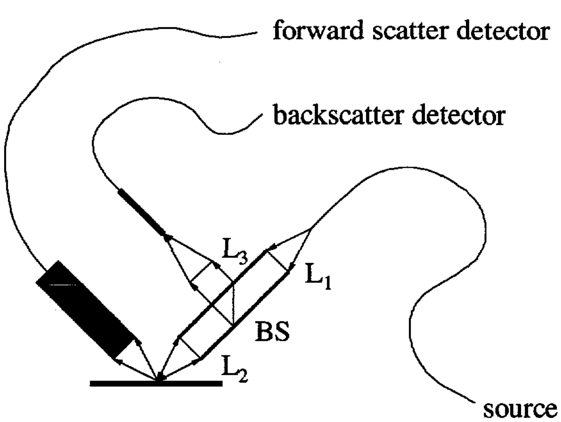


Fig. 3 Scattering of incident beam by a two-dimensional corner.

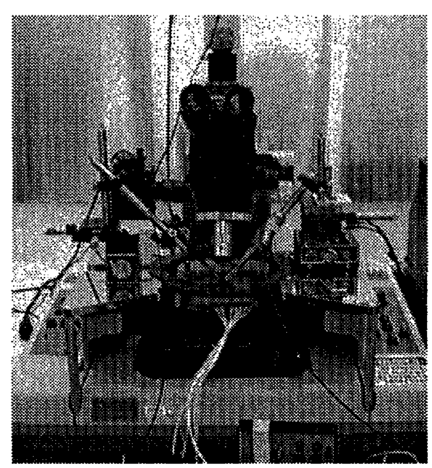
The direction of rotation can generally be determined from the shape of the pulse as the tooth passes through the beam since the scattered signal would not generally be symmetric with respect to a reference point on a tooth. If the signal were symmetric, the needed asymmetry could be introduced by shaping the input beam. Another approach to determining direction of rotation is to use two beams that are strategically positioned and observe the phase between the received signals.

3. MICROMACHINE OPTICAL PROBE DESIGN

Based on the discussion in the last section and some preliminary experimental work, we based the design of our prototype probe on the simultaneous measurement of forward and back scatter. A schematic of the probe is shown in Fig. 4(a). The source is a HeNe laser which is coupled to a 5 mm core single-mode fiber. Lens L_1 collimates the fiber output and lens L_2 is chosen to give a nominal 3 μm focused spot at the working surface. The light collected by L_2 is directed to lens L_3 by the beamsplitter and focused on a 1 mm multimode collecting fiber. The forward scatter light is collected by a 1 mm multimode fiber. The axes of the incident (backscatter) and forward scatter beams are coplanar and directed at an angle of 45 degrees with respect to the surface normal. The forward scatter fiber surface is approximately 5 mm from the working surface, giving a collecting cone half angle of approximately 5.7 degrees. A photograph of the prototype probe installed on a probe station is shown in Fig. 4(b). In the figure, the forward scatter pickup is on the left and the source backscatter part of the probe is on the right.



(a)



(b)

Fig. 4 (a) Schematic diagram of the optical probe for forward and backscatter signal detection.
(b) Photograph of probe setup.

For development purposes, MEMS gears can be driven at rates below 1 Hz to rates approaching 5 KHz. In order to measure fluctuations in the gear motion one would want to have a system bandwidth that is considerably wider than the drive frequency. The forward and backscatter detectors used in the prototype system have 100 KHz bandwidths, which is adequate for the development of the technique. The use of an optical probe beam (speed of light) and combined with the use of optical detectors in an effectively one-dimensional configuration offers the potential of bandwidths in the GHz range.

4. EXPERIMENTAL PROBE DATA

The source probe was mounted to a piezoelectric stage that allowed fine (~ 0.1 μm) translations, although it did not provide any positional information. The data that follows are drawn from results on several different engines, some of which had different surface treatments and therefore different surface finishes. The probe appeared largely immune to these differences, which is consistent with a view that the geometry of the gear determines the signal changes as the probe rotates. Vibration was investigated by applying the probe to a blank section of substrate and recording the signal. No appreciable signal was seen.

Typical forward scatter signals are shown in Fig. 5. Fig 5(a) shows an average of many rotation cycles, and figure 5(b) shows the output for a single rotation. This particular gear was running at 500 Hz. The peaks correspond to points where the gear tooth is passing under the probe beam. The trace shows eight peaks, which agrees with the eight teeth of the gear. The cluster of four peaks indicates that this gear is running through 1/2 of its rotation in less than 1/5 of a drive signal period. This behavior was noticed on many gears in this series. The drive signals were not optimized to achieve constant angular speeds.[5,6] A peak asymmetry, where the left side slopes more gently than the right, appears clearly on all but two of them. These two peaks are not well resolved in time, so it is difficult to define their shape. Also, a small hump follows all of the peaks, regardless of their width. Further investigation will attempt to match this behavior with a model of the scattering process. This asymmetry may allow finer resolution of gear tooth motion than the current method of tracking the tooth peaks allows.

As discussed in the introduction, a primary advantage of the MOP technique is the high data collection rate. This allows continuous data collection for each gear rotation, rather than the average data collected by stroboscopic techniques. This advantage comes into play in the tracking of non-periodic gear rotation. In Fig. 5(a), the forward scatter signal has been averaged for 32 traces. The signal looks periodic, and one might assume that this signal represents the motion of the gear at all times. The final peak contains a flat area, which indicates that the gear tooth is slowing or stopping at this position. Fig. 5(b) shows a single gear rotation that resembles the general pattern. The single gear rotation in Fig. 5(c), however, differs from the general pattern, especially at the last peak. The lack of directional information prevents a firm analysis, but it appears that the gear tooth is ringing at this location. In other words, it is passing through this location, stopping and backing through the location again, and finally passing through a third time as it continues around. The persistence trace in Fig. 5(d) shows that many types of non-periodic behavior are occurring at this location. Only through continuous data collection can non-periodic behavior such as this be studied.

The utilization of both forward and back scatter can allow the direction of gear rotation to be determined. As discussed in section 2.3, this is due to the different geometries of the gear that produce strong forward and back scatter signals. There is thus a phase difference between the two signals that can be exploited to determine gear direction. Fig. 6 shows an average of 32 traces for a gear rotating both CCW and CW at 500 Hz. The phase between forward and back scatter reverses as the gear direction is reversed. The forward scatter peaks have a somewhat different shape in this figure than for Fig. 5. This is because the probe position was adjusted to maximize both the forward and back scatter signals in the traces of Fig. 6. The peak amplitude variations for the back scatter signal are interesting. The sensing circuitry had a bandwidth of 20 kHz, which should not attenuate these peaks. A more likely explanation is tilt in the gear, which has been visually observed at low speed. The forward scatter signal tended to show less amplitude variation, probably because the pickup fiber was smaller than the cone of light coming up from the gear. This would reduce the effects of tilt variations as the gear rotated.

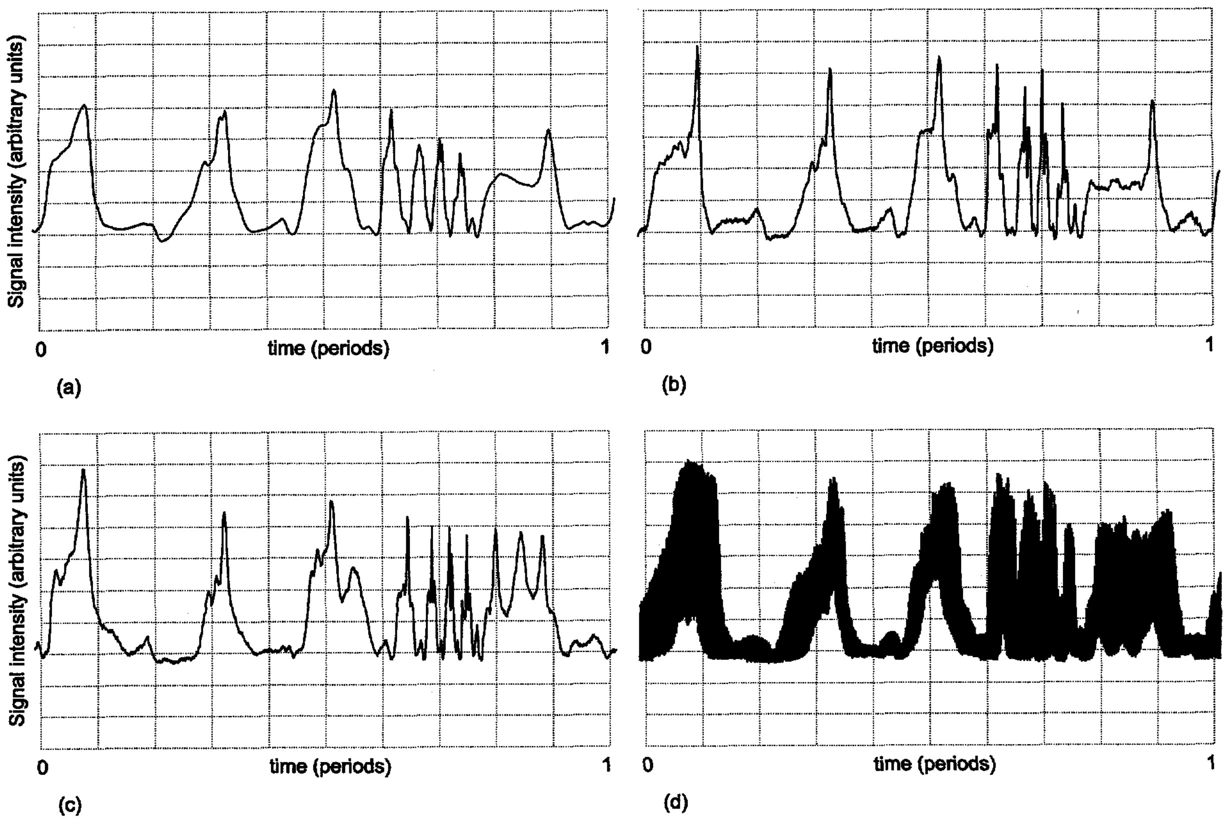


Fig. 5 Forward scatter traces showing non-uniform rotation of the gear. (a) Average of 32 traces showing general rotation pattern. (b) Single trace that conforms to the general rotation pattern. (c) Single trace that differs from the general rotation pattern, especially on the last peak. (d) Persistence trace showing that the final peak exhibits many types of behavior. All traces show one period of the drive signal.

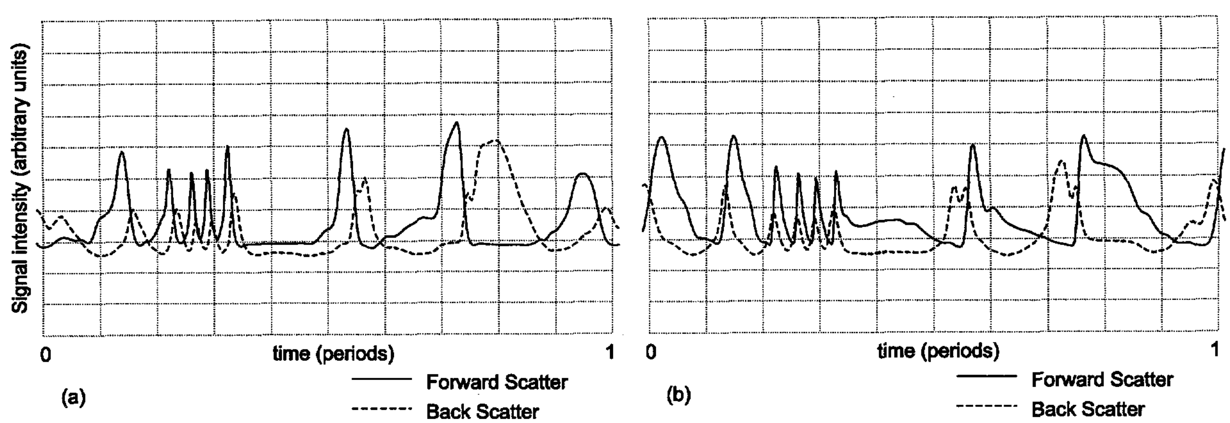


Fig. 6 Traces show one rotation period. (a) Gear rotating CCW. (b) Gear rotating CW.

Besides being used to determine gear direction, the phase between the forward and back scattered signals can also be used to insure that the gear is making a complete revolution, rather than oscillating between two positions. Fig. 7 shows a single trace from a gear that is oscillating between two positions. Notice that the phase between forward and back scatter traces reverses twice during a single period of the drive signal.

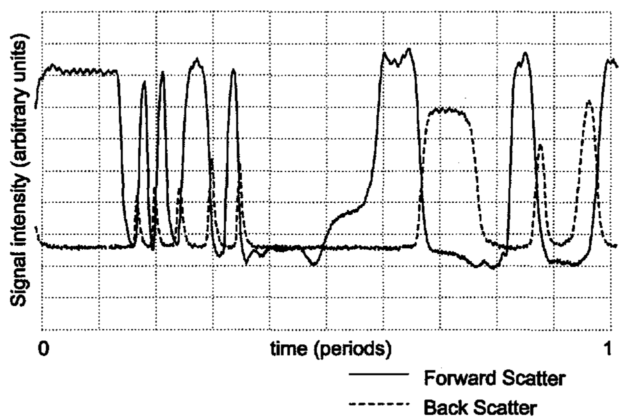


Fig. 7 Gear oscillating rather than rotating. One drive signal period is shown.

Since the forward scatter mode was expected to provide the strongest signals, the early testing focused on the forward mode, using the back scatter mode mainly for directional information. The probe beam arrived at the gear in a tangential direction, shown by position #1 in Fig. 8. As discussed in section 2.3, the forward scatter was maximized when the beam was at the top of a tooth, because the geometry of the spaces between teeth blocked the beam otherwise. A simple model suggests that the back scatter was maximized by the reflections formed from the tooth wall and the substrate at 90° to each other. Later testing began to examine the effects of changing the probe location, and using the back scatter mode as the primary measure of the gear position. Clean back scatter signals were observed when the probe beam was incident on the gear at 45° to the tangent, as shown by position #2 in Fig. 8. It was felt that the probe signal is reflecting a corner cube arrangement formed by the tooth wall, the inner edge of the gear, and the substrate below the gear. Fig. 9(a) shows back scatter signals observed at this position. Fig. 9(b) includes the forward scatter signal. The phase between the signals can again be used to determine rotation direction.

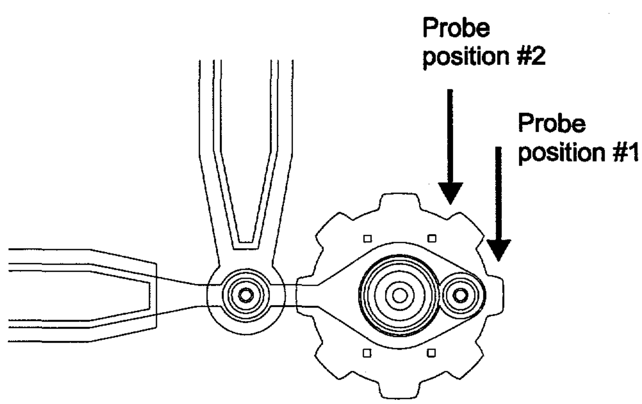


Fig. 8 The second incoming probe target point and direction (#2) produced better signals.

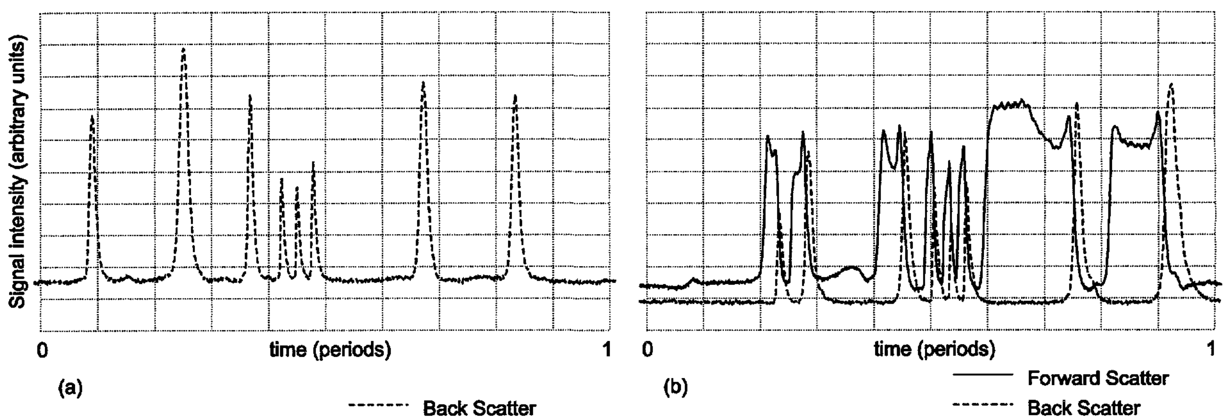


Fig. 9 (a) Back scatter signal with the probe position optimized (position #2 in Fig 8). (b) Another trace including the forward scatter. The probe position differed slightly between these traces. One period of the drive signal is shown.

Finally, the sensitivity of the probe to position variations was qualitatively examined. From visually observing the position of the beam with the microscope, there was roughly ± 10 μm of tolerance for tangential motions and ± 3-4 μm of tolerance for radial motions where the forward and back scatter signals did not appreciably deteriorate. Phase changes with probe motion should occur, but have not yet been quantified.

5. INTEGRATED OPTICAL FEEDBACK SYSTEMS

Perhaps the most important application of the MOP technology is 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 MEMS technology to insure that the gear was running correctly, that is, to perform system tests. Fig. 10 illustrates such a feedback system, with a 19-tooth gear design. 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 deposited during one of the MEMS fabrication steps. Several technologies may offer a deposition process compatible with MEMS devices.

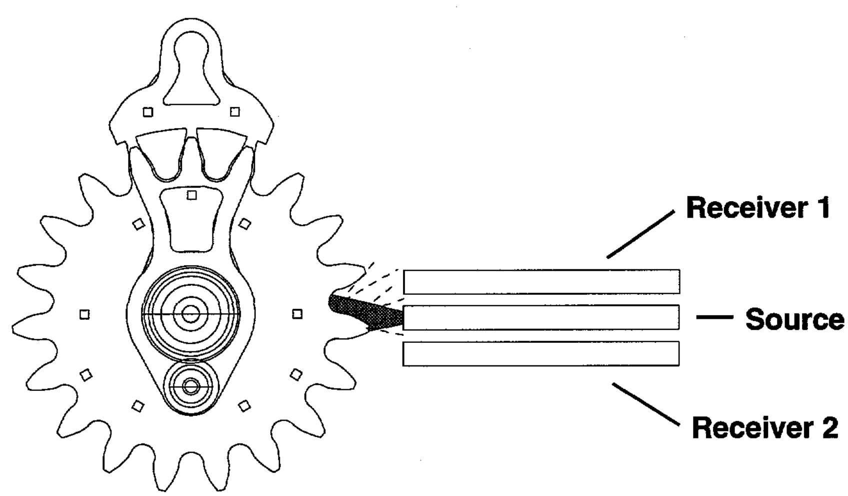


Fig. 10 Integrated feedback system.

The symmetry of the probe in Fig. 10 would have the advantage of enabling a precise determination of the gear without using tightly focused beams. However, there are many possible configurations that might useful for an integrated probe system. For example, waveguides could be diffused 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 raised above the surface or optical fibers on the surface to probe the edge of the gear or other structure. There is also the possibility of some components being integrated in or on the substrate and other components mounted above the substrate.

6. SUMMARY

In this paper we have presented an optical probe for assessing the performance of silicon micromachines or other actuators 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 was presented that showed the robustness of the technique. The data demonstrates 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 micromachine physical structures.

7. ACKNOWLEDGMENTS

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