Progress toward a thousandfold reduction in 1/*f* noise in magnetic sensors using an ac microelectromechanical system flux concentrator (invited)

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The potential advantage of some magnetic sensors having a large response is greatly decreased because of the $1/f$ noise. We are developing a device, the microelectromechanical system (MEMS) flux concentrator, that will mitigate the effect of this $1/f$ noise. It does this by placing flux concentrators on MEMS structures that oscillate at kilohertz frequencies. By shifting the operating frequency, the $1/f$ noise will be reduced by one to three orders of magnitude depending upon the sensor and the desired operating frequency. We have succeeded in fabricating the necessary MEMS structures and observing the desired kilohertz normal-mode resonant frequencies. Only microwatts are required to drive the motion. We have used spin valves for our magnetic sensors. The measured field enhancement provided by the flux concentrators agrees to within 4% with the value estimated from finite element calculations. No difference was detected in noise measurements on spin valves with and without the flux concentrators. This result provides strong evidence for the validity of our device concept. Solutions to the sole remaining fabrication problem will be discussed. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2170067]

I. INTRODUCTION

Low-frequency or $1/f$ noise is found in such diverse places[1] as electronic devices, the stock market, emissions of quasars, highway traffic, the global temperature, and the flow of the river Nile. Thus, it is not surprising that $1/f$ noise is also found in magnetic materials[2,3] and that it is a serious problem in magnetic sensors. The $1/f$ noise in magnetic sensors can be either electronic or magnetic.[4] In addition, magnetic sensors also have Johnson, shot, and magnetic white noise.[4] White-noise magnetization fluctuations in magnetoresistive heads are a fundamental limit on their signal-to-noise ratio.[5] Table I lists the type of noise sources that are found in some types of magnetoresistive sensors.

There has been a focus on magnetoresistive sensor technology because it shows the most promise for producing low-cost magnetic sensors. The reasons for this is that magnetoresistive sensors can be fabricated by batch processing and the drive and read out electronics are relatively simple. The earliest type of magnetoresistance sensor was the anisotropic magnetoresistance sensor (AMR),[6] but other types of magnetoresistance sensors have been invented that have larger changes in resistance in response to an applied field. These other types of magnetoresistance sensors include giant magnetoresistance (GMR),[7] extraordinary magnetoresistance[8] (EMR) sensors, and magnetic tunneling junction[9] (MTJ) sensors. Magnetoresistance values as large as 220% have been observed in CoFe(100)/MgO(100)/CoFe(100) MTJ sensors[10,11] at room temperature. These large values are the result of the properties[12] of the wave function in both electrodes and in the MgO barrier. The majority state with Δ_1 symmetry couples from the Fe into the MgO. However, the $1/f$ noise of these other types of sensors is a major obstacle in these sensors reaching their full potential. Figure 1 illustrates how serious this problem is in the case of a MTJ sensor. Unfortunately, the magnetoresistive sensors that have the largest magnetoresistance also tend to have considerable $1/f$ noise.[13] Anisotropic magneoresistance sensors are probably the most sensitive, commercial, magnetoresistance sensors to use at frequencies of 1 Hz or less. This is true despite the fact that their magnetoresistance, about 5%, is small. The reason for this is that AMR sensors have less $1/f$ noise. There has been an attempt[14] using electronic switching to remove $1/f$ noise. Jander *et al.*[15] investigated using three chopping techniques to address the problem of $1/f$ noise. These attempts have been largely unsuccessful.

II. CONCEPT OF THE MEMS FLUX CONCENTRATOR

This paper describes the concept and development of a device, the microelectromechanical system (MEMS) flux concentrator,[16,17] that has the potential to solve the problem

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TABLE I. Selected magnetoresistive materials and their corresponding low-frequency noise sources delineated by their spectral dependence.

	white			$1/f$ noise	
	Johnson[a]	Shot[b]	Magnetic[c]	Electronic[d]	Magnetic
Anisotropic magnetoresistance	√		√	√	√
Giant magnetoresistance	√	√	√	√	√
Tunneling magnetoresistance	√	√	√	√	√

[a]Sets ultimate noise floor.
[b]May set ultimate noise floor, depending on current bias.
[c]May set ultimate noise floor, depending on sample volume and magnetic properties.
[d]Charge trapping or defect motion, depending on materials system.

of $1/f$ noise in many low-cost magnetic sensors. The concept of the device is illustrated in Fig. 2. Shown is a magnetic sensor between two flux concentrators. Flux concentrators are frequently used to enhance the field at the position of the magnetic sensor by a factor ranging from 1.5 to as much as a 100 in favorable geometries. Flux concentrators are composed of soft magnetic materials such as permalloy. What is unusual in our approach is that the flux concentrators are deposited on MEMS flaps. The MEMS flaps are driven to oscillate at frequencies of the order of 10 kHz by electrostatic comb drives. Electrostatic comb drives have the advantages that they provide sufficient force to drive MEMS structures and that, unless the amplitude of the motion is too large, the force is independent of the displacement. The flaps on each side of the sensor are connected by a spring so that they have a common normal-mode frequency. This is an important design feature because, if the motion of the two flaps were not coupled, the relative phase between the motion of the flaps would tend to drift. When the flux concentrators oscillate, they modulate the field at the position of the sensor. This shifts the operating frequency of the device from the high $1/f$ noise region at low frequencies to higher frequencies where the sensor noise is orders of magnitude lower.

There are at least two major matters that have to be addressed before the potential advantages of this device can be realized. First, it is necessary that the sensor element is responsible for most of the $1/f$ noise and not some other part of the sensor system. The second issue, the design and fabrication of the device, will be discussed in the next section. Consider the first concern. The MEMS flux concentration described above will greatly reduce the $1/f$ noise of the magnetic sensors. It does nothing to reduce the $1/f$ noise of the flux concentrators. Thus, if the concept is going to be useful, it is necessary that the $1/f$ noise of the flux concentrators must be much less than the $1/f$ noise of the magnetic sensors. This requirement motivated a series of experiments to see if this requirement was fulfilled. The noise power spectrum was measured on spin valves, a kind of GMR sensor, both with and without flux concentrators. The measurements were repeated with different currents passing through the spin valves. The results of these measurements are shown in Fig. 3. The curves are labeled by the value of the resistor in series with the spin valve that limited the current I through the spin valve. The resistance of the spin valve was about 400 Ω. The noise is much higher for lower values of the series resistance because the $1/f$ noise is expected[18] to increase as I^2. Of more importance, the noise power spectra are indistinguishable for different currents passing through the spin valves with and without the flux concentrators. This result implies that the $1/f$ noise of the flux concentrator is much less than the $1/f$ noise of the spin valve. The likely explanation for the result that the $1/f$ noise of the flux concentrator is much less than the $1/f$ noise of the spin valve is that the flux concentrator is much larger than the spin valve. It is expected[18] that the $1/f$ noise power is proportional to

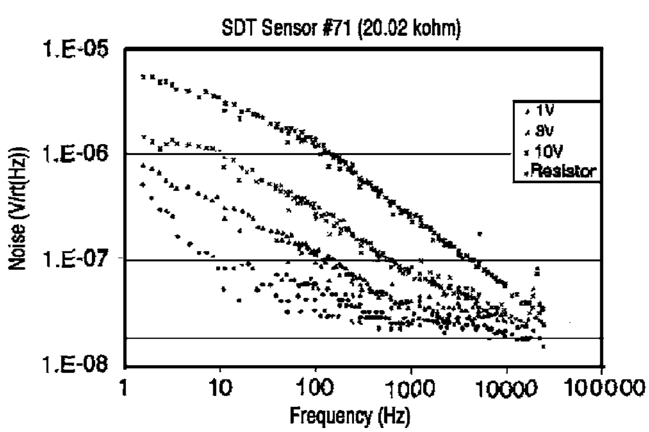


FIG. 1. Example of $1/f$ noise in a magnetic tunneling junction sensor. The curves with higher noise were taken using higher measuring currents. Data were provided by NVE.

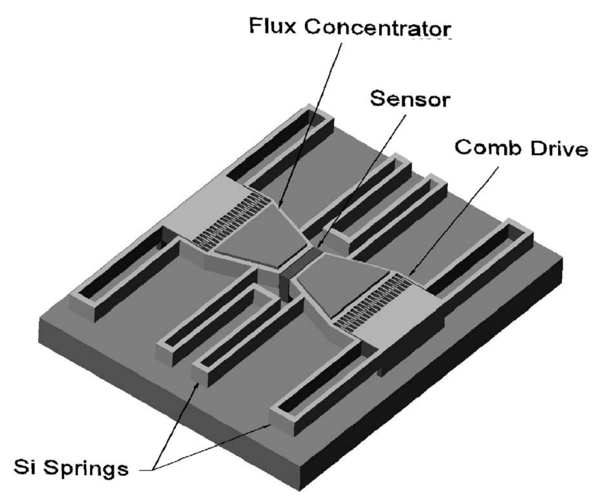


FIG. 2. Illustration of the concept of the MEMS flux concentrator.

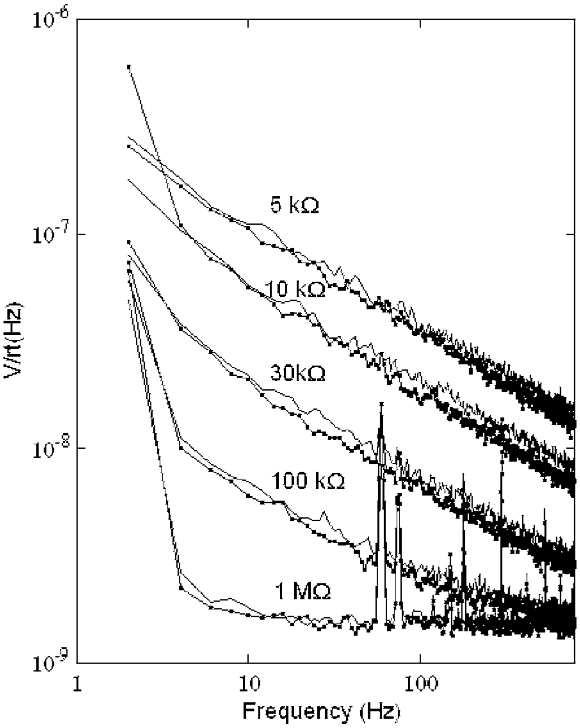


FIG. 3. The noise voltage of spin valves with (line with symbols) and without (solid line) flux concentrators. The curves are labeled by the value of the resistor in series with the spin valve.

$1/N$ where N is the number of atoms in the system. The flux concentrator is about 1500 times larger than the spin valve. It is not possible to put a useful experimental bound on the noise from the flux concentrator using this set of data. It will be much easier to estimate the noise in flux concentrators once the noise in the sensor is minimized through the operation of the MEMS flux concentrators. Nevertheless, this experiment provides strong support of the concept of the MEMS flux concentrator.

III. DESIGN AND FABRICATION

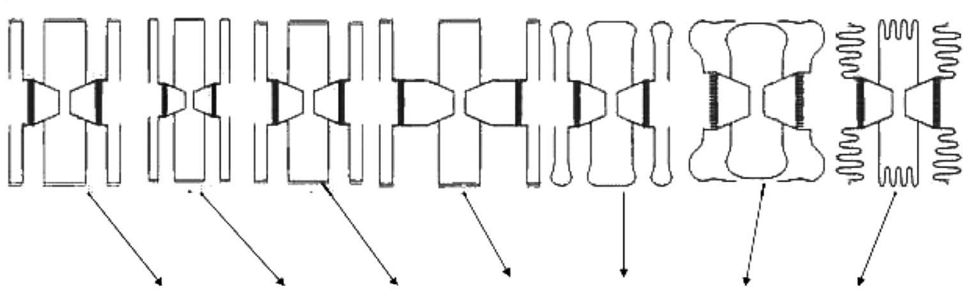
In this section the design and fabrication of the device are discussed. Designing a successful fabrication route that combines MEMS technology and magnetic sensor technology is nontrivial. We have had to modify our design to solve the problems we have encountered.

Though we started out using plain silicon wafers, we soon switched to using silicon-on-insulator (SOI) wafers because fewer processing steps are required and they provide a flat surface for fabricating the magnetic sensor. SOI wafers consist of a thin device layer of Si separated from a thick layer of Si, called the handle wafer, by a 1–5 μm layer of SiO_2. We found that the bonding in most SOI wafers between the device layer and handle wafer is so poor that the HF etch rate is not isotropic and it is difficult to maintain the structural integrity between the MEMS structure and the handle wafer. Special SOI wafers were ordered that did not have this defect.

Spin valves were chosen as the magnetic sensor because they represent a mature technology with a significant amount of $1/f$ noise. Spin valves are four-layer structures consisting of an antiferromagnetic layer and two thin ferromagnetic layers separated by a thin conducting layer. The rotation of the magnetization of one of the ferromagnetic layers, the pinned layer, is hindered by exchange interactions at the interface with the antiferromagnet. The magnetization of the other ferromagnet layer rotates in response to an applied field. The resistance of the four-layer structure has its minimum value when the magnetizations of the two ferromagnetic layers are parallel. The first step in the fabrication process was the deposition of the spin valves.

The spin valves we employed were fabricated by NVE Corp. and had a magnetoresistance of about 5%. The magnetic films were deposited on Si_3N_4-covered silicon substrates by rf diode sputtering in a Perkin-Elmer system. A

TABLE II. Designs of the MEMS flux concentrator and their normal modes.



Freq. mode (Hz) ↑↑	21 278	4623	8 570	6123	7 885	5727	8560
Freq. mode (Hz) ↑↓	38 647	8198	14 871	10 292	12 011	7886	9371
Force to 10 μm disp. (μN)	135.8	6.0	19.3	19.3	12.5	5.14	7.73

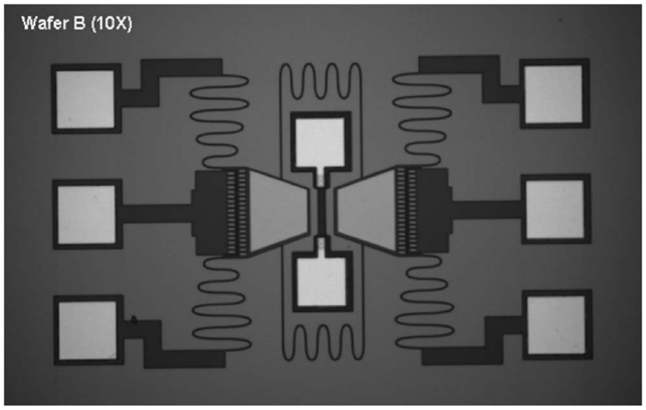


FIG. 4. SEM picture of a MEMS flux concentrator.

magnetic field of 20 Oe was applied during the deposition to induce the magnetic easy axes and pinning direction. The spin valve stack consists of (from the substrate, up) NiFeCo/Ta/NiFeCo/CoFe/Cu/CoFe/CrPtMn. The antiferromagnetic CrPtMn is used to pin the top CoFe layer in the stack, and the NiFeCo/Ta/NiFeCo serves as a double free layer.[19] After the thin-film deposition, the unpatterned wafers were annealed in forming gas at approximately 200 °C for 2 h. Following the patterning of the device stripes, the wafers underwent a final sequence of annealing steps (temperature up to 265 °C) to establish the magnetization of the pinned layer across the stripe and the magnetization of the free layer down the stripe. The devices patterned are 3 μm wide and 88 μm long.

The flux concentrators were trapezoidal in shape and made by dc magnetron sputtering of two repeats of 40 Å Cr/1500 Å permalloy (Py) films deposited on photoresist-covered SOI wafers. The base pressure was about 2×10^{-7} Torr. No bias voltage or substrate heating was applied during the deposition. Cr was deposited at 1.5 mTorr with 60 W of dc power. Py was deposited at 1.25 mTorr at 300 W. The deposition conditions were chosen to maximize domain size and to minimize film stress. The intervening Cr film served to break up the magnetic and structural continuity of the Py film and thus suppress the formation of a stripe-like magnetic domain configuration and to achieve high permeability.[20] The gap size at rest between the inside edges of the flux concentrators is 52 μm. The height of the trapezoid is 104 μm. The short side of the trapezoid is 80 μm long and the longer, back side is 150 μm long. The larger flux concentrators that will not be used in the complete device were 80 μm long at the short side and 300 μm long at the long side and 315 μm high. The size of the flux concentrators is limited by the need to keep the resonant frequency of the MEMS structure in the range of several kilohertz or higher. The values for the enhancement provided by the flux concentrators were calculated when the separation between the MEMS flaps was at their planned maximum and minimum displacements using a finite element code Maxwell from Ansoft Corp. These values were 1.5 and 3.5, respectively.

The mechanical resonant frequencies of seven different MEMS structures were calculated using ANSYS, a software package for making mechanical finite element calculations. Table II shows the result of these calculations. The two low-frequency normal modes for in-plane motion are for the two MEMS flaps to move in phase with one another or 180° out of phase. The later mode is the desired mode. It is higher in frequency because the spring connecting the two flaps must be compressed.

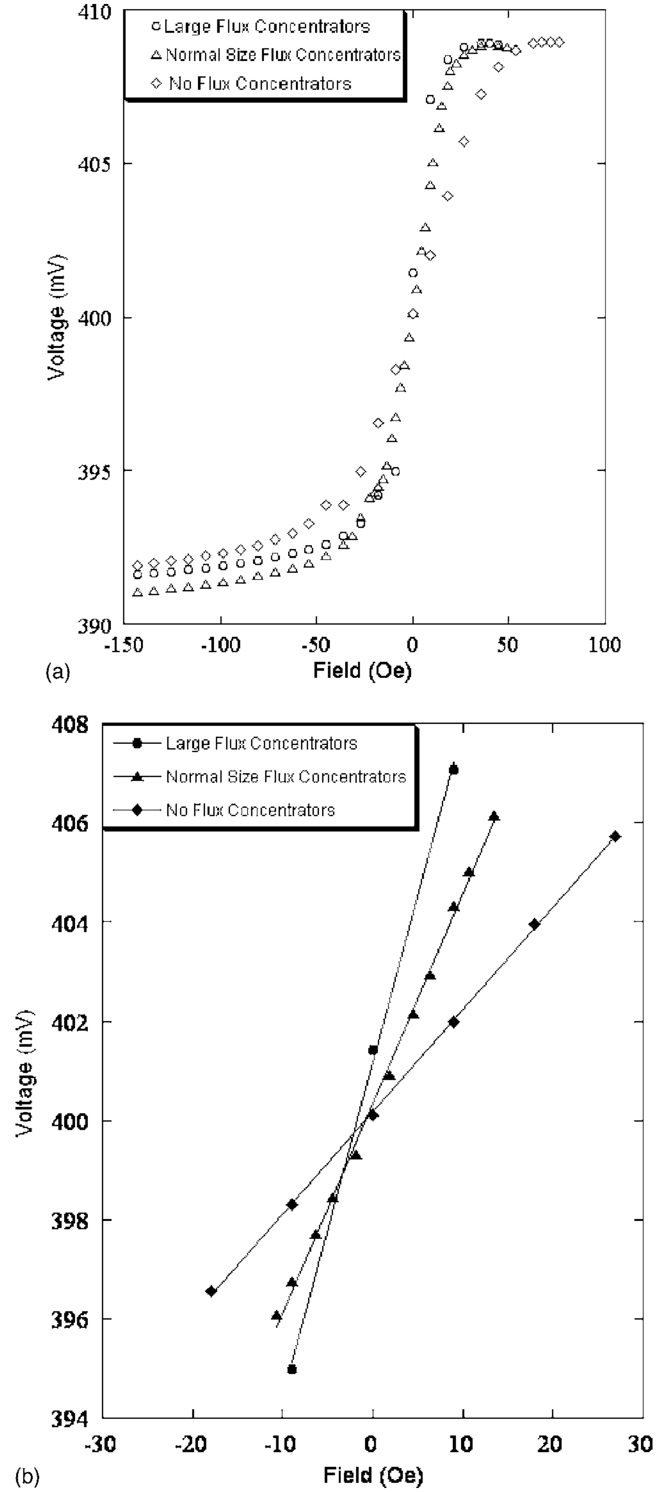


FIG. 5. (a) Magnetoresistance of a spin valve with small and larger flux concentrators. (b) Enlarged view of the data near zero applied field.

The MEMS structure is formed by removing silicon from the device layer using deep reactive ion etching

TABLE III. Properties of the spin valves and the enhancements provided by the flux concentrators.

	Ave. linear region slope (mV/Oe)[a]	Measured enhancement	Calculated enhancement
No flux concentrator	0.211 33	[b]	[b]
Small flux concentrator	0.418 26	1.98	1.93
Large flux concentrator[b]	0.695 86	3.29	3.36

[a]Voltage across spin valve set to ~400 mV in all cases.
[b]These flux concentrators are too large to be used in the device.

(DRIE). The structure is released by dipping in HF acid to remove the underlying SiO_2. Figure 4 shows an scanning electron microscopy (SEM) picture of the device. The thickness of the springs and separation of the teeth in the comb drive are only 2 μm. Laser dicing was used to separate different devices. It took 50 V to attain the 12 μm motion described in the next section. Vacuum packaging will greatly increase the Q to values of about 300 or more and thus reduce the voltage required to drive the motion. Only one fabrication problem remains. The HF used in the release step damages the spin valves. Three very different routes are currently being investigated for solving this problem. The potential solutions are using (1) protective silicon nitride/gold bilayers, (2) Si/epoxy/Si wafers (in this case, the release is done in a plasma that will not affect the spin valves), and (3) flip-chip bonding (the MEMS structure and the spin valve are fabricated on separate wafers and the spin valves will not be exposed to HF).

Solutions (2) and (3) eliminate the problem, because HF is not used on the wafer containing the spin valves. We are confident that one of these routes will be successful and we will be able to fabricate complete, functioning MEMS flux concentrators.

IV. TESTING

We have been successful in separately fabricating the MEMS structure, the spin valve, and flux concentrator. Figure 5 shows the resistance of spin valves with and without flux concentrators. The amount that the flux concentrators enhance the field is compared with the calculated values in Table III. One sees that the agreement is good. Figure 6 shows a MEMS structure driven at its normal mode resonant frequency of 15 kHz. The part of the MEMS structure that appears out of focus is oscillating at 15 kHz. The amplitude of the motion of each MEMS flap is 12 μm. Figure 7 shows the amplitude of the motion of a typical MEMS structure versus frequency. One sees the two normal modes discussed earlier. The Q of the out-of-phase mode that will be used to modulate the field is about 30. Based on this value for Q we estimate that it will only require microwatts of energy to drive the motion

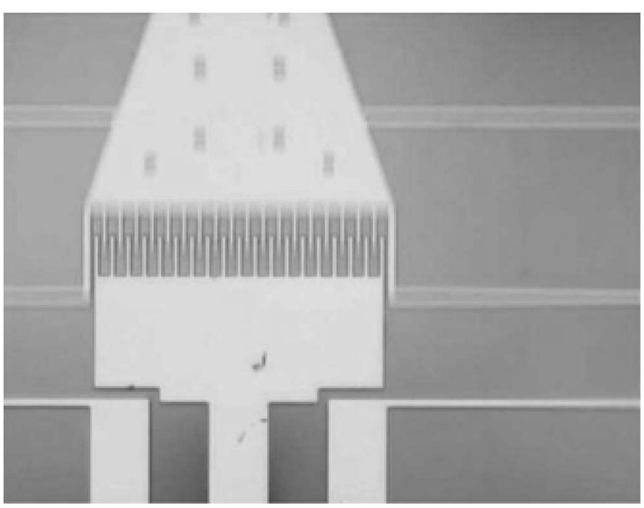


FIG. 6. MEMS structure driven at its normal-mode resonant frequency of 15 kHz. The portion of the picture that appears out of focus shows the portion of the structure that is oscillating with an amplitude of 12 μm.

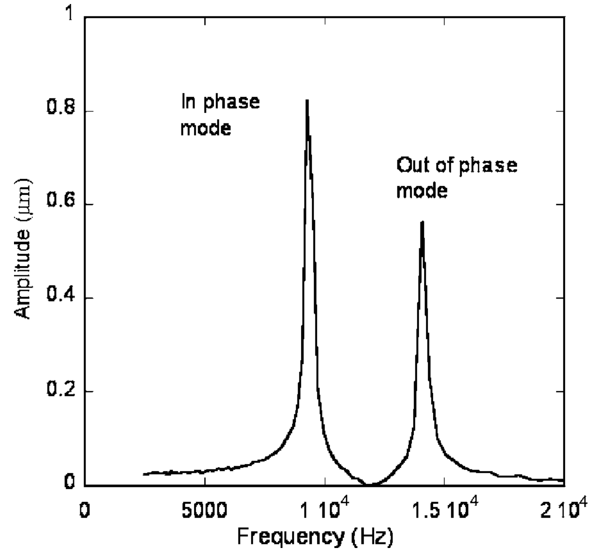


FIG. 7. Amplitude of the motion of a MEMS structure showing the two low-frequency normal modes.

V. CONCLUSION

The problem of $1/f$ noise in magnetic sensors and the development of a device, the MEMS flux concentrator, for minimizing the effect of the $1/f$ noise in magnetic sensors have been discussed. The major problem in fabricating the device is combining two very different technologies, MEMS fabrication technology and magnetic sensor technology. This device has the potential to increase the sensitivity of small, low-cost, magnetic sensors by one to three orders of magnitude. The general fabrication process was presented. The device can be fabricated on wafers by low-cost, mass production techniques. Powering the motion of the MEMS flaps only requires microwatts of energy. Noise spectrum data have been presented that provide strong evidence that the device concept is valid. Progress is being made on several fabrication methods for solving the problem of the release step without damaging the magnetic sensor. It is likely that the complete device will be successfully tested in the near future.

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