Simultaneous Measurement of Two Magnetic Field Components Using a Single U-Shaped MEM Cantilever Device

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A miniaturized sensor capable of measuring simultaneously two orthogonal components of the magnetic flux density is presented. These magnetic field components excite two different resonant modes of a single micromachined U-shaped cantilever. The cantilever vibrations are accomplished by the Lorentz force acting on an alternating electrical current, which flows through a thin film lead attached to the top surface of the silicon cantilever. This lead operates also as a deflecting mirror in an optical readout system which is used to detect the oscillations of the cantilever. By means of two lock-in amplifiers, the output of the readout is converted into two signals related to orthogonal components of the magnetic flux density. The feasibility of the system is proved by measuring contour plots of the magnetic flux distribution of a sample magnet.

Introduction

Micromachined cantilevers enable measurement of a variety of physical parameters such as magnetization or viscosity. These devices offer a high quality factor and achieve a high sensitivity when they are excited at or near a resonant frequency. To measure magnetic fields with cantilever structures, the Lorentz force is utilized on a current carrying lead. Cantilevers vibrating in the fundamental mode are typically used to measure the magnetic flux density in the direction parallel to the arms of the cantilever. The presented approach uses high order oscillation modes to measure the flux density components parallel to the base of the cantilever.

Sensor Principle and Theory

The Lorentz force is used to bend a micromachined cantilever (Fig. 1). Small deflections compared to the length of the cantilever are directly proportional to the applied force. To reach a high sensitivity, the cantilever is excited by a sinusoidal alternating current at the resonant frequency.

The investigated U-shaped cantilever can oscillate in various flexural vibration modes (Fig. 2), whereas the first four modes are of most practical importance. With respect to our design, these modes can be divided into two symmetrical (S1 and S2, where the cantilever arms are moving in parallel) and two antisymmetrical ones (A1 and A2, where the arms move in opposite directions).

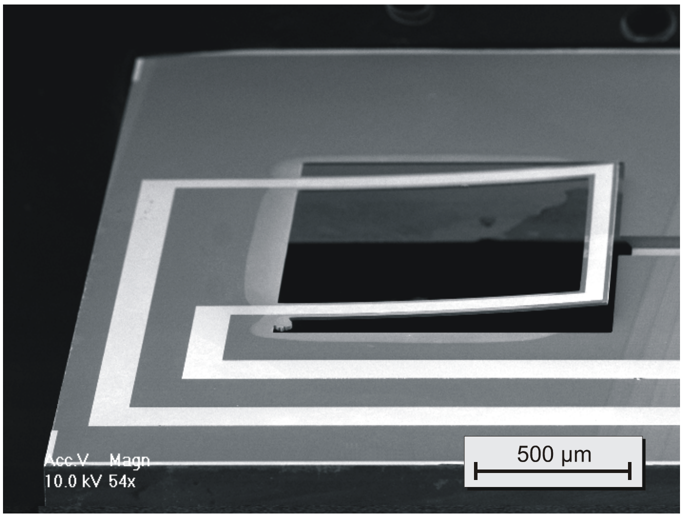

Fig. 1: Micromachined silicon cantilever with a thickness of 12 µm. The bright area represents the gold surface of the lead.

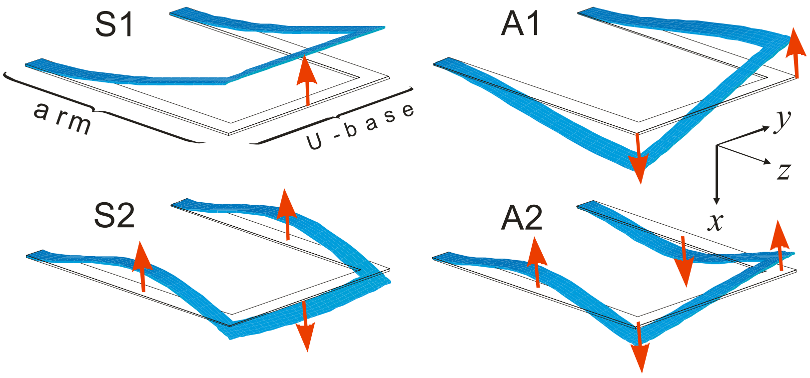

Fig. 2: Visualization of the first two symmetric (S1 and S2) and the first two anti-symmetric (A1 and A2) flexural vibration modes obtained by a finite element analysis.

The oscillating cantilever structure can be described by the classical Euler-Bernoulli beam dynamics theory leading to a set of three (one for each cantilever arm and one for the cantilever base) coupled linear 4th-order partial differential equations which read as

$$\frac{\partial}{\partial\zeta_i^2}\left(EI_i(z)\frac{\partial^2\psi_i}{\partial\zeta_i^2}\right)-\left(f_i-\overline{m}_i(z)\frac{\partial^2\psi_i}{\partial t^2}\right)=0$$

where $i=1,2$ indicates the arms and $i=3$ the base. Regarding this, EI_i denotes the stiffness, ζ_i the coordinate along the cantilever ($\zeta_{1,2}=z$ and $\zeta_3=y$), f_i the external forces, $\overline{m}_i$ the mass per unit length, t the time, and $\psi_i(\zeta_i,t)$ the deflection along the cantilever.

Experimental

Cantilever Excitation

Each mode can be excited by suitable Lorentz force distributions on different parts of the lead. The fundamental mode S1 is excited by a homogeneous magnetic field in z-direction. The field is parallel to the arms of the cantilever and therefore the forces are generated only at the base of the “U”. The first antisymmetric mode A1 is excited by a homogeneous magnetic field in y-direction, where the Lorentz forces develop only along the arms of the cantilever. Due to the different orientation of the electrical current, the arms are bent in opposite directions.

Optical Readout

The vibrations of the cantilever are contact-free sensed using an optical readout. The IR-beam of a commercial available reflective sensor is returned partially by the surface of the gold lead on top of the cantilever and received by the photo transistor of the reflective sensor as shown in the experimental setup of Fig. 3.

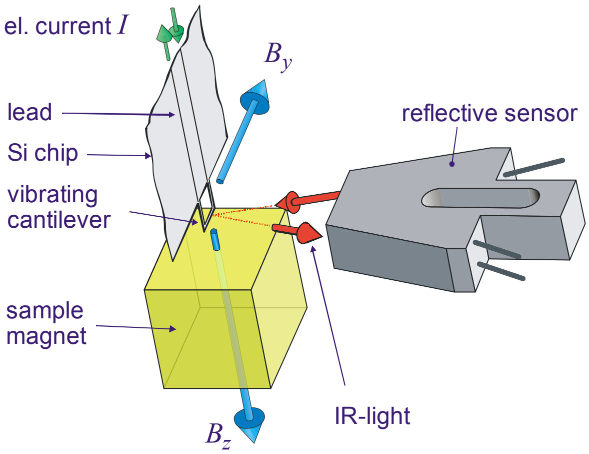

Fig. 3: Experimental setup: The oscillations of the cantilever caused by the Lorentz force modulate the intensity of an infrared beam emitted and detected by a reflective sensor.

Signal Generation for Dual Field Component Measurement

To excite the first symmetric (S1) and the first antisymmetrical mode (A1) simultaneously, the appropriate flux densities have to be present and the composite AC current should match to the resonant frequencies of the flexural vibration modes (Fig. 4). The amplified output signal of the reflective sensor is analyzed by two lock-in amplifiers. Their output signals are proportional to the magnetic flux densities to be measured. The phase information is used to determine the direction of the magnetic field.

Results

A typical measurement example is depicted in Fig. 5, where a permanent magnet of a voice coil actuator which moves the multiple read/write heads of a hard disk is scanned to create a contour plot of the magnetic flux distribution. The distance between magnet surface and cantilever tip is 2 mm.

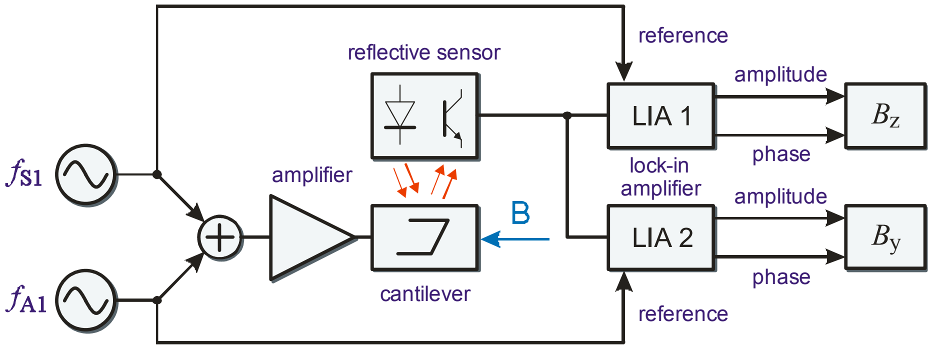

Fig. 4: To excite the symmetric (S1) and the antisymmetric (A1) oscillation modes of the cantilever simultaneously, two AC currents with frequencies according to the resonant frequencies (f_{S1} and f_{A1}) of these modes are added up and amplified. The magnetic flux densities (B_z and B_y) determine the amplitude of the cantilever oscillations and modulate the light reflected by the cantilever surface. The amplified output of the reflective sensor is analyzed by two lock-in amplifiers synchronized to the excitation frequencies. With amplitude and phase information, strength and direction of the magnetic flux density in z- and y-direction can be calculated.

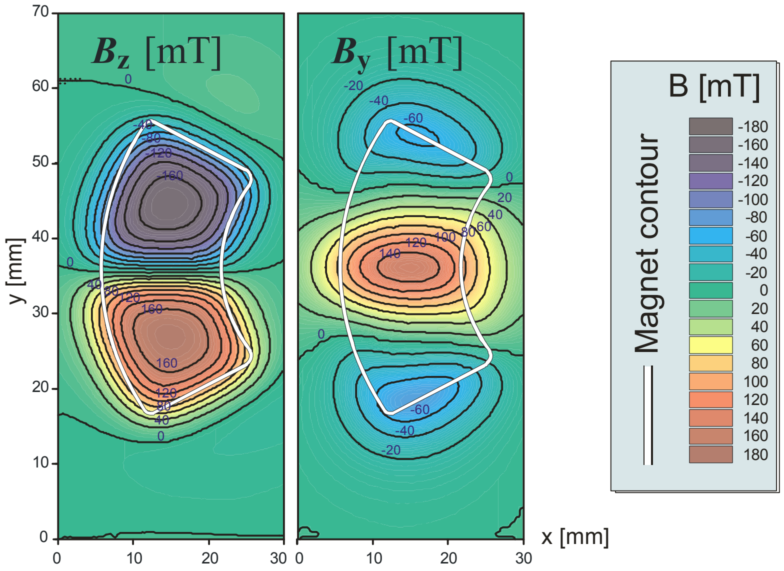

Fig. 5: Contour plots of the magnetic flux density in z- and y-direction of a kidney shaped permanent magnet of a voice coil actuator of a hard disk drive.

Conclusion

Utilization of two vibration modes of a U-shaped cantilever allows simultaneous measurement of two orthogonal flux density components with a single optical read out. The presented design is not feasible for measuring magnetic flux components in x-direction because modes sensitive to this direction have resonant frequencies far beyond 100 kHz and too low amplitudes. To measure all three components, a redesign of the vibrating structure has to be performed.