Ultra-sensitive micron-cantilever detection for MRI

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Introduction: Resonant LC surface coil technology is the predominant technology for MR detection. However, the performance of these coils is limited by the quality factor *Q*. Here we propose and evaluate the performance of an alternative to inductive detection for measurement of harmonic signals using mechanical mixing and filtering based on AC magnetic force microscopy (AC-MFM). AC-MFM uses micron-scale cantilevers, which can have an extremely low damping ratio and can be high $Q_{\text{mechanical}}$ detectors.

Materials and Methods: We used a custom-made receiver coil with primary and secondary loop radii 2 mm and 60 micron respectively, oriented orthogonal to the primary one. This orientation gives negligible mutual coupling between the two coils, hence undistorted fields. Working like a transformer, the same current flows through both coils, the larger primary coil enabling *in-vivo* detection. The absence of capacitor in our inductive loop makes it untuned and hence wideband. The $Q_{electrical}$ of our coil is thus predicated on the $Q_{mechanical}$ of an ultra sensitive cantilever mounted above a tiny secondary loop. The transmitter coil was attached to a signal generator (HP 83650L, 10 MHz-50 GHz).Current in the loop on cantilever was sent through another signal generator (HP 83620A, 10 MHz-20 GHz).We measured time-harmonic magnetic fields by measuring the amplitude change of the photodiode current as we changed the current and frequency of the sinusoidal signal applied to the coil-cantilever system. The photodiode signal was measured from the MFM scope (Topometrix 0696-017).

Results: We know that the signal-to-noise ratio (SNR) of any resonant transducer (whether such transducer be electrical or mechanical) is proportional to the square root of the product of the resonant frequency and the quality factor (Q), and inversely proportional to the product of the effective spring constant and the absolute (thermodynamic) temperature of the transducer. The inductive coil detection approach used as present art achieves a modestly high SNR by operating at a very high resonant frequency. The approach used with the cantilever detection system achieves a high SNR by using a transducer with a very low mechanical stiffness, relative to the resonant frequency. Resonant LC coil detection systems used as present art operate with a SNR very close to the theoretical limit, and thus there is very little that can be done to improve the SNR of such systems. In contrast to SNR-limited resonant coils, our cantilever-coil system has vastly more room for SNR improvement via the use of small, high aspect ratio (length/transverse cross sectional area) cantilevers. Size reduction of cantilevers will increase resonant frequency and the use of a high aspect ratio will yield cantilevers with high resonant frequency to stiffness ratios.

We have performed a battery of simulations to determine the stiffness of the commercially produced, solid trigonal planar cantilevers used in previous cantilever heterodyne detection experiments. The loads chosen for these simulations consisted of a force applied to the tip of the cantilever, and the load cases chosen were those of 0.1, 0.2 and 0.3 micronewtons magnitude. The result of a typical simulation is illustrated graphically in Fig 1. We found that the deformation/stress is linear through this range of loads, with the spring constant remaining immutable at 12.54 N/m. What is interesting about this result is that this stiffness value is much higher than the value given or assumed in the majority of the literature, where it is often quoted as being approximately 0.05 N/m. It was also found that the maximum flexural stress under the design load of 0.3 micronewtons was on the order of 780 kPa; the flexural yield strength of Si_3N_4 is 750 MPa, thus affording a nearly 1000 fold design safety factor. It is thus apparent that such trigonal planar cantilevers are tremendously overdesigned, and a less stiff, higher aspect ratio cantilever is needed. Thus we intend to buy commercially available, high aspect ratio modified trigonal planar or rectangular cantilevers to suit our needs.

Conclusion: In this study we have demonstrated that a non-resonant (capacitor free) coil, in combination with an AC MFM, can be used as a frequency agile magnetic signal detector. The use of a micro-mechanical cantilever-filter rather than as LC tuned filter substantially enhances the quality factor of signal detection. Unlike conventional surface coil, the center frequency of the filter circuit of our coil is tuned actively. This enables detection of different frequency signals by a single coil. Though the system is thermal noise limited, signal improvement can be achieved through efficient geometrical optimization and cryogenic cooling.

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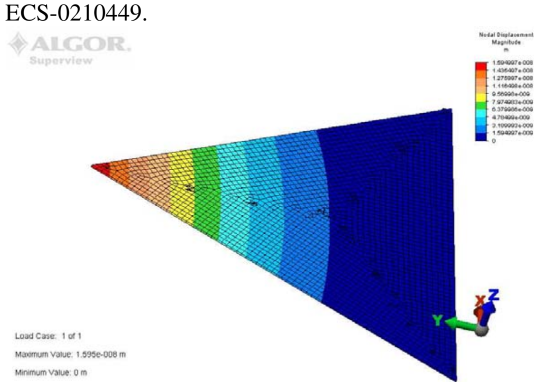

Fig.1. Displacement profile for 200 micron-cantilever with 0.1 micronewton load applied at tip.