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DEVELOPMENT OF A NON-MAGNETIC INERTIAL SENSOR FOR VIBRATION STABILIZATION IN A LINEAR COLLIDER*

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Abstract

One of the options for controlling vibration of the final focus magnets in a linear collider is to use active feedback based on accelerometers. While commercial geophysics sensors have noise performance that substantially exceeds the requirements for a linear collider, they are physically large, and cannot operate in the strong magnetic field of the detector. Conventional nonmagnetic sensors have excessive noise for this application. We report on the development of a non-magnetic inertial sensor, and on a novel commercial sensor both of which have demonstrated the required noise levels for this application.

SENSOR REQUIREMENTS

Room temperature linear colliders require relative position stability of the electron and positron beams at the Interaction point at the nanometer lever. The most sensitive beam line elements for vibration effects on the beam are the final focus doublets, which produce approximately one-to-one motion of the beam spots at the IP. With a beam rate of 120Hz, a feedback based on the beam interaction typically has unity gain around 10Hz. Gain at 1Hz is 10-1000 [1].

An accelerometer-based feedback system to mechanically stabilize the final doublets, with gain at frequencies above ~1 Hz can reduce the beam / beam motion at the IP [2]. While there is not a simple relationship between the accelerometer noise and ultimate feedback performance, it is clear that an integrated sensor noise of < 1nm for frequencies above ~1Hz is desirable, corresponding to a sensor acceleration noise of $<3\text{x}10^{-8}\text{M/s}^2/\text{Hz}^{1/2}$ at frequencies above 1Hz.

The acceleration sensors are attached to the final doublet magnets, and must operate in a detector magnetic field of the order of one Tesla. They must also be physically compact (approximately 20x20x10cm) due to volume constraints in the final focus design.

COMMERCIAL SENSORS

Good commercial piezoelectric seismometers have specified noise of $\sim6\text{x}10^{-7}\text{M/s}^2/\text{Hz}^{1/2}$ at 1Hz [3]. Tests at SLAC measured a noise level of these sensors of $2\text{x}10^{-6}\text{M/s}^2/\text{Hz}^{1/2}$ at 1Hz with an integrated noise of 50nm above 1Hz. [4], too large for this application.

A commercial magnetic geophone of the type used in vibration stabilization experiments at SLAC [5], the GS-1 from Geospace [6] has a moving mass of 700 grams and a mechanical Q of ~0.5. The theoretical thermal noise of the sensor is $5\text{x}10^{-10}\text{M/s}^2/\text{Hz}^{1/2}$ (see below), however the actual sensor noise is not specified and may be higher.

Previous measurements of a similar sensor, a Mark Products L-4C at SLAC gave a noise of $<4\text{x}10^{-8}\text{M/s}^2/\text{Hz}^{1/2}$ (measurement limit), with an integrated noise of 0.3nm above 1Hz. This meets the noise requirements for final focus stabilization, but this type of sensor can not be used in the strong magnetic field of the detector.

Geophysics feedback seismometers such as the Streckeisen STS-2 have noise levels of $\sim10^{-9}\text{M/s}^2/\text{Hz}^{1/2}$ with a corresponding integrated noise above 1Hz of ~.07nm [7], much better than our requirements. All commercial sensors of this type use magnetic internal components for temperature compensation and for force feedback, and cannot be used for our application. The prototype NLC vibration uses the same basic design concept, adapted for non-magnetic operation.

Micromachined accelerometers such as the “Si-flex” [8] accelerometer from Applied Mems have a specified noise of at $3\text{x}10^{-7}\text{M/s}^2/\text{Hz}^{1/2}$ at 1Hz. This does not meet our requirements, but future devices may improve on this performance.

Electrochemical Sensor

A novel commercial sensor SP-400 based on electrochemical detection of motion has recently been developed by PMD/Eentec [9]. This sensor is specified at $10^{-8}\text{M/s}^2/\text{Hz}^{1/2}$ at 1Hz, sufficient for our application. However this sensor uses magnetic coils for force feedback and cannot be used in this application without modification. The company estimates that replacing the magnetic components (which would remove the force feedback) would increase the noise by a factor of ~3, still within our requirements.

NLC SENSOR DESIGN

The lack of suitable sensors for NLC final focus stabilization led to the design of a low noise, nonmagnetic sensor. The sensor operates on the same principal as geophysics feedback seismometers, however the non-magnetic and compact size requirements lead to some design changes. The prototype sensor was designed for vertical sensing as this was considered to be the more technically challenging problem.

Sensor Noise Sources

All acceleration sensors can be modeled as a suspended mass, with a position measurement between the mass and the body of the sensor. The ultimate thermal noise of the

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sensor is given by $A=(4K_bTw_0/mQ)^{1/2}$ [10] , with K_b Boltzman’s constant, m the moving mass, Q the sensor Q, and w_0 the resonance frequency. The mass position readout can contribute to the noise of the sensor, but for most designs this noise can be made small.

At low frequencies temperature variations of the sensor typically provide the major noise source. For a vertical sensor, the suspension is acting against the $9.8M/s^2$ acceleration of gravity. Typical engineering materials will exhibit changes in length and stiffness on the order of 10^{-5}/ºC. For our requirements this corresponds to a temperature stability of 10^{-9} ºC for the suspension during a measurement time (~1 second).

Geophysics seismometers like the STS-2 use temperature compensated spring materials (eg. Nispan [11]), however these materials are magnetic and cannot be used in our application. Fortunately our requirements do not extend significantly below 1Hz, allowing thermal time constants to reduce temperature variations.

Convection currents can disturb the test mass, so most low noise sensors, including the NLC sensor are operated in vacuum. External varying magnetic fields can also produce noise in the sensor. In addition to using non-magnetic materials, with the exception of the suspension spring, the NLC sensor also uses non-conducting materials in the suspended mass in order to avoid forces from eddy currents.

Suspension Design

An ideal suspension provides a low primary resonant frequency, high Q, and low thermal sensitivity. Other modes of the suspension system should have resonant frequencies above the frequency band of interest. Since it is desirable to have a suspension frequency of ~1Hz, and higher (transverse) frequencies >~100Hz, the suspension must be very soft in one direction, stiff in the others.

The design chosen is to use a “pre-bent” leaf spring which has a 90 degree bend with no load, and is flat under gravity load. For the NLC sensor, Beryllium Copper was used as the spring material. For the first prototype sensor, an Aluminum “Y” frame was used for the cantilever, and tungsten for the mass. For the next prototype, the cantilever will be Aluminum Oxide, and for ‘the mass a heavy insulator, either Hafnium Oxide, or tungsten powder loaded epoxy.

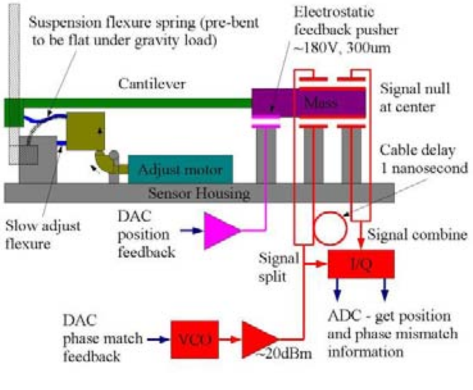

Figure 1. Sensor block diagram

The Suspension spring creeps with time and changes with temperature. A piezoelectric motor (Picomotor [12]) is used to adjust the position of the spring support to compensate. Long term studies were conducted of the behavior of the BeCu spring under design load, and the creep was found to be acceptable for a lifetime of >10 years.

Electronics

The position of the mass relative to the sensor frame is measured using a differential RF capacitor system. RF at ~400MHz, 100mW is applied out of phase to two electrodes capacitively coupled to the mass. The summed signal on the mass is capacitively coupled to synchronous detection electronics to read the in-phase, and quadrature components. The capacitive gaps are approximately 300 microns, giving a full range of motion of 600 microns.

In-phase errors are proportional to the position error of the mass. These are corrected by moving the mass position actuator. Control is through an electrostatic pusher which applies 0-180 Volts to an electrode on the frame next to a grounded part of the test mass

Quadrature errors are proportional to errors in the 180-degree phase difference between the drive electrodes. These are corrected by changing the RF drive frequency, which in conjunction with the 180 degree RF delay results in a phase shift.

The combination of in-phase and out-of-phase loops allows nulling of the RF signal from the detector, and the use of high gain, low noise RF amplifiers.

Feedback

The in-phase and out-of-phase signals are amplified and digitized at 16 bits, 2 kHz. Feedback is performed using a TMS320C40 DSP. Presently, a PID algorithm is used for control; “optimal” control may be implemented in the future.

The force required to hold the mass position fixed (square of the applied voltage), is a measure of the acceleration of the sensor. This signal is then corrected with the residual mass position to measure motion above the feedback bandwidth.

Sensor Parameters

The sensor is enclosed in a vacuum box, 20cm long, connected to an ion pump to maintain $<10^{-4}$ Torr. The box is gold plated to reduce thermal radiation

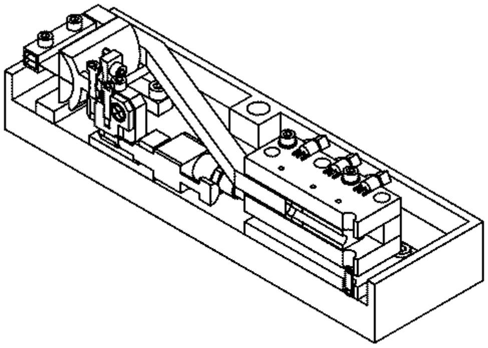

Figure 2. Sensor cut-away, leaf spring to left.

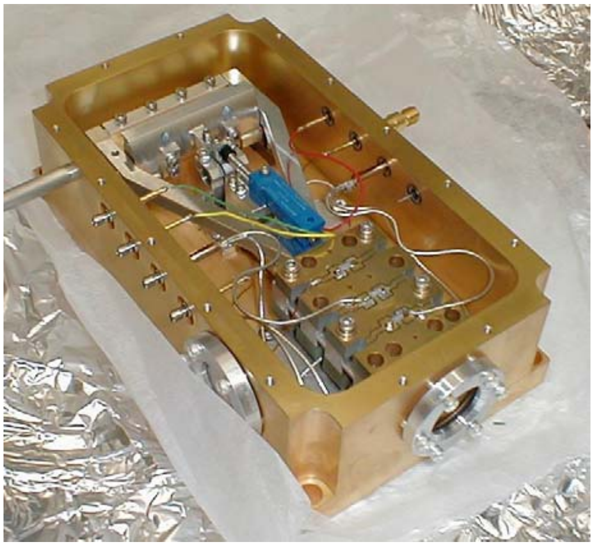

Figure 3: Photo of prototype sensor

Table 1: Sensor Parameters

Test Mass	40 grams
Suspension Frequency	1.4Hz
Mechanical Q	>100 (but see below)
Theoretical thermal noise	1.5×10^{-10}M/s^2/Hz$^{1/2}$
Capacitive sensor gap	300 microns
RF drive power	100 mW
Theoretical electrical noise	< thermal mechanical noise

SENSOR PERFORMANCE

The noise of the sensor was measured by correlating with a STS-2. Measurements were performed in a noisy environment (integrated noise ~50nm above 1Hz), and may not represent the sensor limit.

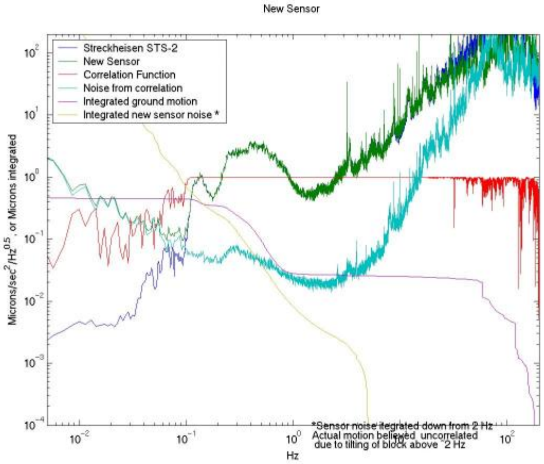

Figure 4: Sensor noise from correlation with STS-2

The measured noise is ~2×10^{-8}M/s^2/Hz$^{1/2}$ which meets the NLC requirement, but is substantially worse than the expected sensor noise.

A possible cause of the higher than expected noise was recently uncovered: While the mechanical Q of the sensor is >100 for large amplitude (>50 micron) motions, it is quite small for low amplitude motions see figure 5. The decay for small amplitude motion suggests hysteretic damping – possibly due to a poor connection between the leaf spring and its supports.

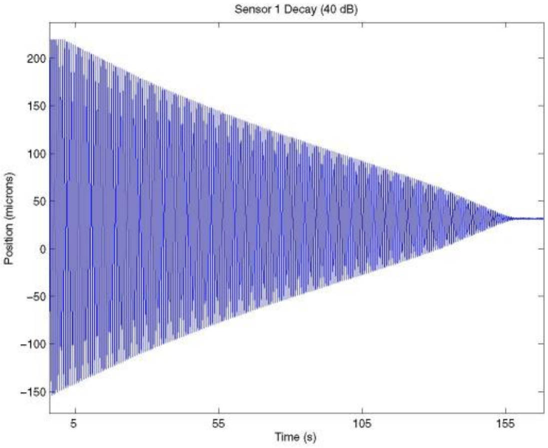

Figure 5. Evidenced of hysteretic damping in sensor. Note that apparent "beating" is an artifact of the image reproduction. Vertical scale approximate.

Work is under way to improve the spring to mount connection by either brazing, or diffusion bonding the connection .

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