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Inertial Sensor Development for Active Vibration Stabilization

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Abstract

Future Linear Colliders require nanometer stability of the beams at the interaction point. One approach to stabilising the beams is to use feedback based on inertial sensors (accelerometers / seismometers) to control the positions of the final focus magnets. Commercial seismometers developed for geo-science applications have sufficient noise performance (nanometer noise down to a fraction of a hertz), but due to their large size and magnetic sensitivity are unsuitable for use in a linear collider detector. We report on the development of a high sensitivity, compact, non-magnetic inertial sensor for this application. In addition to its use in linear colliders, the sensor is also expected to have application in vibration measurement and control in synchrotron light sources

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Abstract

Future Linear Colliders require nanometer stability of the beams at the interaction point. One approach to stabilising the beams is to use feedback based on inertial sensors (accelerometers / seismometers) to control the positions of the final focus magnets. Commercial seismometers developed for geo-science applications have sufficient noise performance (nanometer noise down to a fraction of a hertz), but due to their large size and magnetic sensitivity are unsuitable for use in a linear collider detector. We report on the development of a high sensitivity, compact, non-magnetic inertial sensor for this application. In addition to its use in linear colliders, the sensor is also expected to have application in vibration measurement and control in synchrotron light sources

LINEAR COLLIDER STABILIZATION

The vertical beam spot sizes at the IP of linear colliders are on the order of a few nanometers, and in order to maintain luminosity the relative beam positions must be stabilised to a fraction of the beam size. Various technologies have been proposed for beam stabilization [1], [2]. Here we focus on mechanical stabilization based on inertial sensors for the final focus magnets for the NLC.

One of the largest contributions to beam motion is ground motion coupling to the final focus magnets. The differential motion of the ground at the frequencies of interest (0.1-100Hz), and at typical final focus magnet separations varies substantially between sites [3]. At a quiet site no additional mechanical stabilization is required; however technologies are being developed to allow operation at noisy sites.

Stabilization of the beams at low frequencies (typically below a few Hz) is provided by feedback based on the beam / beam deflection at the IP. At higher frequencies mechanical stabilization based on inertial sensors as described here, or on interferometers [4] is used. High frequency beam motion will be corrected with a fast intra-train feedback system [5].

INERTIAL SENSOR REQUIREMENTS

Feedback from inertial sensors has been used at SLAC to stabilise the 6 solid body degrees of freedom of a 40Kg aluminium block [6]. The performance of this system was limited by the noise of the compact geophones used for feedback.

Due to uncertainties in the expected ground motion levels, and in the amount of amplification of high frequency beam noise allowed from the beam-beam feedback, it is not possible to give a specific requirement for the inertial sensor noise For reasonable parameters, however, a noise level of $\sim 3\times10^{-9}M/s^2/Hz^{1/2}$ at frequencies above 0.1 Hz is sufficient.

The NLC final focus magnets are located within the detector solenoid, and must therefore be physically small, and able to operate in a ~ 1 Tesla magnetic field.

Commercial accelerometers designed for machinery vibration are compact, and those based on piezoelectric sensors are not sensitive to magnetic fields, but their noise floors are typically $\sim 10^{-6}M/s^2/Hz^{1/2}$. Commercial geophysics sensors (eg. Streckheisen STS-2) have noise floors $< 10^{-9}M/s^2/Hz^{1/2}$ but are physically large and are sensitive to magnetic fields.

We were unable to find commercial sensors which met our requirements, and began a project to develop a new inertial sensor, referred to here as the "NLC inertial sensor".

INERTIAL SENSOR THEORY

All inertial sensors consist of a mass suspended from a frame, with a measurement of their relative positions. Position sensor technologies can have very low noise, and the theoretical limit on the sensor sensitivity is the thermal noise of the mass and suspension. This thermal noise limit is due to thermal excitation of the fundamental mode of the mass, which due to the finite mechanical Q, has frequency components off of the resonance frequency. The acceleration noise due to thermal noise of the suspension and mass is given by $A=(4K_bTw_0/mQ)^{1/2}$ [7].

For linear collider applications it is the beam - beam separation, not acceleration which is of interest, so the low frequency noise is typically the most critical issue. In addition, various sources of 1/f noise contribute to low frequency noise.

High frequency performance is typically limited by the second mechanical resonance of the suspension system. The suspension is designed to maximise the lowest frequencies of higher order modes.

Sensors for vertical motion have an additional difficulty that they must measure accelerations which are (for our parameters) 10^9 smaller than the background gravitational acceleration. This manifests in the form of spring creep, and in temperature sensitivity due to changes in spring elastic modulus.

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For a simple mass on a spring suspension, the resonant frequency f is related to the change in spring length under gravity $L=g/(2\pi f)^2$. A variety of "astatic" suspension designs are used in seismometers to obtain low resonance frequencies in a compact volume. [8].

The NLC inertial sensor uses a (non-astatic) leaf spring design with the unconventional feature that the spring is pre-bent to be flat under gravity load. The flat spring results in a high transverse mode frequency for a low fundamental frequency.

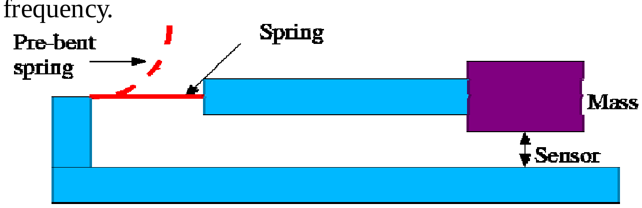

Figure 1: Pre-bent suspension spring

The fundamental resonance of the suspended mass has a relatively high Q (to reduce thermal noise) resulting in an enhancement in motion at resonance relative to low frequency motion. Rather than design a position sensor with high dynamic range, most high sensitivity seismic sensors use feedback to control the position of the suspended mass.

In most commercial feedback seismometers, the feedback element is magnetic. For the NLC inertial sensor, which must operate in a strong external field, an electrostatic pusher is used for feedback. Approximately 70V applied over a 300 micron gap provides sufficient force to control the mass position.

A variety of feedback algorithms can be used in the NLC inertial sensor DSP based feedback system. A conceptually simple one which will be used for initial sensor testing is to use feedback to maintain the mass position fixed relative to the sensor frame, and use the applied force as the acceleration signal.

SENSOR MECHANICAL / ELECTRICAL

The 40 gram Tungsten test mass is mounted on a 15cm long aluminium cantilever. The suspension spring is BeCu, pre-bent by 90 degrees to be flat under gravity load. The spring is operated at high stress (~75% of yield) to maximise the higher mode frequencies (as a result of ANSYS simulations).

The high stress in the spring results in creep which is compensated by a non-magnetic "picomotor" [9] that moves the spring support on a flexure mount. Creep measurements at SLAC indicate that the adjustment range will provide a ~20 year creep lifetime

The sensor is expected to be extremely sensitive to temperature changes in the suspension spring, with a10^{-8}C change corresponding to the theoretical thermal noise at 0.1Hz. The change in spring stiffness due to temperature is common to all mechanical suspension designs, and in most low high sensitivity seismometers is mitigated by the use of springs with a small variation of K with temperature. Unfortunately these compensated materials are ferromagnetic, and unsuitable for our application. [10].

The NLC inertial sensor design includes a series of "thermal low pass filters" to reduce short timescale temperature variations of the support spring. The housing and spring are gold plated to reduce temperature changes due to thermal radiation. Thermal effects are expected to be the ultimate limit to low frequency performance of the sensor.

Table 1: Sensor Specifications

Test mass	40 grams	Design
Resonant f	1.46 Hz	Measured
Resonant Q	~50	Measured
Thermal Noise	$2.5x10^{-10}M/s^2/Hz^{1/2}$	Theory
Electrical noise	$10^{-10}M/s^2/Hz^{1/2}$	Calculated

The calculated electrical noise, assuming 100mW RF drive power, the estimated coupling, and a 10dB amplifier noise figure is less than the mechanical thermal noise. It is believed that 1/f noise in the mechanical system, rather than electrical noise will dominate the low frequency noise.

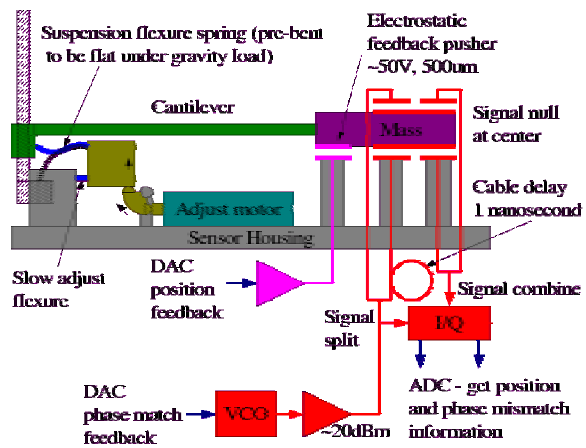

Figure 2: NLC inertial sensor block diagram

A capacitive sensor is used to measure the position of the test mass. An RF signal at ~450MHz is applied out of phase to two capacitive gaps on opposite sides of the test mass. When the mass is centered in the gap, the net voltage induced in the mass is zero. The induced voltage is capacitively coupled to the detection electronics.

Any mismatch in the drive gap capacitances results in a stable offset in the mass position for null signal. Any mismatch in the 180 degree phase shift between the two drive signals is corrected by changing the frequency of the oscillator.

The detection electronics amplifies the signals in low noise RF amplifiers, then uses an I/Q mixer to detect the vector components of the induced signal. DSP based feedback is used to null the I signal by adjusting the mass position, and the Q signal by adjusting the frequency.

The sensor components are mounted in a 18cm x 11cm x 6cm stainless vacuum chamber. Under atmospheric pressure, the mechanical Q is reduced from 50 to approximately 4 due to air viscosity in the narrow gaps. In addition, the vacuum provides thermal insulation, and prevents noise due to convection currents.

Figure 3: Sensor mechanics installed in vacuum chamber

PERFORMANCE TESTS

Mechanical construction of the first sensor is complete and testing has begun. The feedback system has not yet been commissioned for this sensor.

The NLC sensor is mounted on a 30 Ton shielding block, isolated from the ground by elastomeric supports. Two Streckheisen STS2 seismometers are also mounted on the block to provide reference and calibration signals. The raw output from the sensor is shown in figure 4.

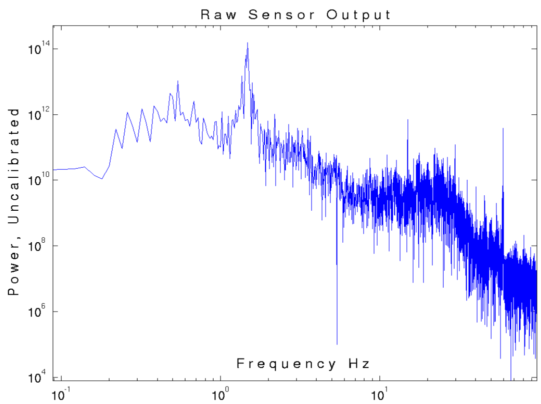

Figure 4: Sensor power spectrum

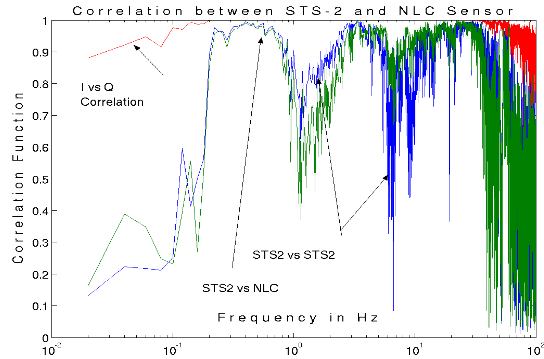

Figure 5: Correlation between STS-2 seismometers, STS2 vs NLC sensor, NLC I vs Q output

The correlation function between the two STS-2 seismometers, and between a STS-2 and the NLC sensor is shown in figure 5.

The data does not yet indicate the noise floor of the NLC sensor; however the correlation between the sensor and a STS2 is good down to 0.2Hz, indicating that it is able to measure motion in the test lab down to this frequency.

PLANS

After the feedback is activated, the sensor response will be compared to a STS-2 seismometer in a seismically quiet location at SLAC. If the noise floor meets the NLC requirements, production of additional sensors will begin in late 2003.

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