What is the best displacement transducer for a seismic sensor?

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Abstract—This paper presents a development of a seismic sensor for the future Compact Linear Collider (CLIC). Sensor in which three different types of sub-nanometre displacement transducers have been integrated: a Fabry-Pérot interferometer, an optical encoder and a capacitive transducer. This sensor allows us to compare the resolution of all the transducers under the same conditions, thus enabling us to verify the most suitable transducer for a seismic sensor. The best resolution of 28.8 pm was achieved with the optical encoder. This in combination with ease of installation makes it an ideal candidate for a seismic sensor for CLIC.

Keywords—seismic sensors, displacement transducers, sub-nanometer resolution

I. INTRODUCTION

A problem of vibration isolation is very important in majority of big scientific projects and field of high precision engineering. For the CLIC, the cross section of beams at the interaction point will be an ellipse of 40 nm by 1 nm. Such extremely small dimensions are necessary in order to achieve the required luminosity [1]. The beam size of 1 nm in the vertical plane puts extremely high demands on vertical stability of the final focusing magnets as well as the quadrupoles of the delivery lines. The required stability levels are shown in Table 1. Such a high level of stability cannot be achieved by a passive isolation only and there are studies on the active isolation (stabilization) of the magnets already [2]-[4]. One of the main limitations of active isolation, however, is the resolution of the seismic sensors used in the control loop. It is therefore necessary to use a very high resolution sensors and to be able to measure this parameter accurately.

Table 2 shows the main requirement to a seismic sensor for CLIC. Desired resolution in rms $R_{\text{rms}}$ is integrated from an amplitude spectral density (ASD) in the bandwidth of interest as:

$$R_{\text{rms}}(f_{\text{min}}) = \sqrt{\int_{f_{\text{min}}}^{f_{\text{max}}} \left( \frac{\text{ASD}(f)}{\sqrt{\text{Hz}}} \right)^2 \, df}$$

Because $f_{\text{min}}$ for CLIC is equal to 1 Hz, all the rms values in this paper apply to this frequency.

Available state-of-the-art seismic sensors have limited bandwidth or resolution when compared to these requirements [5] and none of them is suited to work in the harsh environment of particle colliders, which is characterized by high radiation and magnetic fields. It is therefore imperative to develop such a sensor.

Research has been conducted in this field and sensors with different types of displacement transducers implemented have been developed [6]-[7]. Some of these sensors almost satisfy the requirements shown in Table 2. Because there is no unified methodology for the measurement of sensor resolution, it is difficult to validate the results obtained by these studies. In addition, when sub-nanometre resolution is required, all possible sources of uncertainty such as mechanical design, ambient environment, power supply stability and data acquisition system need to be taken into account. However, measurement uncertainty is almost never stated in publications on this subject and thus there is ambiguity between the results and it is difficult to compare them.

II. MECHANICAL DESIGN AND TRANSDUCERS

A. Mechanical body

To overcome this ambiguity, a new sensor design is proposed, as shown in Figure 3. It implements three different sub-nanometer displacement transducers within the same mechanical body. The sensors body, which was originally developed for a different study at LAPP [13], was redesigned in order to fit all the transducers. These measure relative displacement between a sensor housing and a mass, which is suspended on a membranes (springs). This simple mass-spring system creates a mechanical harmonic oscillator (second order high pass filter), which represents a basis of all seismic sensors. Characterization of the parameters of this oscillator is necessary when an actual ground motion needs to be evaluated [5]. This, however, is not the aim of our study and only the relative displacement is considered to evaluate performance of transducers themselves.

A mass-locking mechanism is implemented in order to lock the relative motion of the mass and thus enabling us to measure the transducers self-noise. This is especially important because noise divided by a sensitivity equals to the resolution.

$$\text{Resolution} = \frac{\text{Noise}}{\text{Sensitivity}}$$
TABLE I. RMS STABILITY REQUIREMENTS FOR THE CLIC MAGNETS.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Final focusing magnets</th>
<th>Main beam quadrupoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>0.2 nm &gt; 4 Hz</td>
<td>1.5 nm &gt; 1 Hz</td>
</tr>
<tr>
<td>Lateral</td>
<td>5 nm &gt; 4 Hz</td>
<td>5 nm &gt; 1 Hz</td>
</tr>
</tbody>
</table>

TABLE II. MAIN REQUIREMENTS TO A SEISMIC SENSOR FOR CLIC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>1 – 200 Hz</td>
</tr>
<tr>
<td>Resolution</td>
<td>≤ 0.1 mm rms@1 Hz</td>
</tr>
<tr>
<td>Range</td>
<td>10 µm</td>
</tr>
<tr>
<td>Others</td>
<td>Insensitivity to magnetic fields, radiation resistance</td>
</tr>
</tbody>
</table>

B. Transducers implemented

Required resolution below 0.1 nm puts the main constraint on the transducers that can be chosen. 10 µm of working range are sufficient because very weak vibrations will only be measured. Moreover, if a transducer is used in a closed loop, even lower range is enough. Contactless working principle and resistance to magnetic field are also required. This has led to a selection of the following three transducers:

- Optical encoder.
- Fabry-Perot interferometer.
- Capacitive displacement transducer.

with their principal parameters listed in Table 3.

The optical encoder consist of a sensing head, a linear scale with 250 nm signal period grating and a control unit. The scale is glued directly to the mass and the sensing head is attached to the housing (Fig. 1b). A simple kinematic adjustment system was designed in order to properly position the head with respect to the scale. This makes installation and alignment of the encoder fairly easy. A quadrature signal is the only option of the output for the encoder and two twisted pairs of leads provide a differential sine and cosine signals.

The interferometer consist of a control unit where all the electronic and optic is embedded. An optical fiber which is connected to the unit on one side and terminated with a collimating sensor head on the other, serves as a sensing element. The head is installed into the sensor in working distance of ~4 mm from a mirror which is glued to the mass (Fig. 1a). Simple system of screws allows to adjust position of the head with respect to the mirror. The controller provides different types of outputs and the quadrature signal is used again for a convenience.

The capacitive transducers consist of two plates with high level of flattens and a control unit. One of the plates is mounted directly on the mass and the other is mounted on a tilt platform TTN80 by NEWPORT (Fig. 1c). This platform allows fine alignment of one of the plates with respect to the other. This is necessary because a nominal working gap between plates is just 20 µm and having diameter of 10.7 mm, there is no room for misalignment. Control unit measures a capacitance between plates and translate it into voltage which is then proportional to displacement with sensitivity of 2 µm/V.

III. DATA ACQUISITION AND PROCESSING

A 24 bit, low noise ADC produced by Institute of Mine Seismology (IMS) is used for data acquisition. It was selected because of its very low self-noise and integrated antialiasing filter. The self-noise at 24 kHz sampling frequency is only 2.4 µV and its ASD (converted to displacement by sensitivity of capacitive transducer) is plotted together with transducers self-noises in Fig. 4. This is especially important for the capacitive transducer because its self-noise is specified by manufacturer to be 11 µV. For quadrature signals, the low noise ADC is not required.

![Fig. 1. Cross-section of the seismic sensor under the development. Positions of a) Fabry-Perot interferometer, b) optical encoder and c) capacitive transducer are depicted (left). Assembled sensor with all transducers installed (right)](image)

TABLE III. PARAMETERS OF DISPLACEMENT TRANSDUCERS AS SPECIFIED BY MANUFACTURERS.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Interferometer</th>
<th>Encoder</th>
<th>Capacitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>attocube</td>
<td>Magnescale</td>
<td>Queensgate</td>
</tr>
<tr>
<td>Type</td>
<td>IDS3010</td>
<td>BH25 + BE10</td>
<td>NXB2</td>
</tr>
<tr>
<td>Resolution (µm)</td>
<td>44</td>
<td>18.2</td>
<td>22</td>
</tr>
<tr>
<td>Bandwidth (Hz)</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>200 nm/2π</td>
<td>250 nm/2π</td>
<td>2 µm/V</td>
</tr>
<tr>
<td>Output signal</td>
<td>Quadrature</td>
<td>Quadrature</td>
<td>±10V</td>
</tr>
<tr>
<td>Power supply</td>
<td>12 V</td>
<td>5 V</td>
<td>±15 V</td>
</tr>
</tbody>
</table>

![Fig. 2. Example of quadrature signals produced by interferometer and encoder (left). Quadrature signals converted to Lissajous figures (right)](image)
The transducers are directly connected to the individual channels of ADC. Their signals are sampled at 24 kHz and stored to a hard drive. The data are processed in MATLAB subsequently as follows:

- Quadrature signals from interferometer and encoder are normalized in amplitude and converted into Lissajous figures as shown in Fig. 2. This is done by plotting sine and cosine as components to x and y axis respectively. Ellipse fitting algorithm is then used [12] to reconstruct phase which is proportional to displacement with the respective sensitivities as listed in Table 3.
- Signal from the capacitive transducer is directly proportional to displacement via its sensitivity.
- After all the signals are converted into displacement units, the rms values are calculated. First, the pwelch function with default parameters is used to obtain ASDs as a square root of power spectral densities (PSDs). Using equation 1, the rms values are calculated from ASDs.

IV. EXPERIMENTS AND RESULTS

In order to assess the transducers resolution and sensitivity, two different experiments were performed:

- In the first experiment, the sensor was excited by random ambient vibrations with amplitudes well above the self-noise level of the transducers. This test should reveal if all the transducers work properly and if sensitivities match the specifications. Theoretically, all the results should be the same in this case.
- The mass was locked by a locking mechanism in the second experiment, preventing it from a relative motion with respect to the housing, and thus allowing us to measure the resolutions of the transducers.

Measured signals in time domain with corresponding ASDs are shown in Fig. 3 and Fig. 4 respectively. Results of the first experiment show that there is a very good agreement between all the transducers. Detailed view of time domain signals in Fig. 3, however, shows a small difference in amplitudes. This is clearly visible in Table 4 where results of both experiments from a one minute measurement are compared on the basis of the rms values. Small difference of 0.17 nm between the interferometer and the encoder leads to an assumption that it is the capacitive transducer which has 1% higher sensitivity than specified. This can be explained by linearity error from imperfect alignment of sensing plates.

![Fig. 3. Displacements measured in time domain with individual transducers after ambient vibration excitation. Detailed view shows difference in measured amplitudes (top). Corresponding ASDs (bottom).](image1)

![Fig. 4. Self-noise (resolution) of individual transducers measured when mass is locked (top) and their corresponding ASDs with self-noise of ADC as an equivalent for capacitive transducer (bottom).](image2)

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Interferometer</th>
<th>Encoder</th>
<th>Capacitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st experiment - ambient vibration excitation (nm)</td>
<td>221.29</td>
<td>221.46</td>
<td>223.82</td>
</tr>
<tr>
<td>2nd experiment - resolution (pm)</td>
<td>69.3</td>
<td>28.8</td>
<td>39.8</td>
</tr>
<tr>
<td>Resolution specified by manufacturers (nm)</td>
<td>44</td>
<td>18.2</td>
<td>22</td>
</tr>
</tbody>
</table>

TABLE IV. RMS VALUES MEASURED BY INDIVIDUAL TRANSDUCERS.
achieved specified values. All the values were roughly 1.6 times higher. This is could be caused by residual vibrations of the mechanical system which are visible from ~4 Hz up to ~50 Hz in ASDs in Fig. 4. The mass locking system probably didn’t work well because of the heavy mass (5kg) and therefore its weight will be reduced in the future.

V. CONCLUSIONS AND FUTURE WORK

A seismic sensor design that allows to compare performance of a three different types of sub-nanometer displacement transducers under the same conditions has been proposed and experimentally demonstrated. It was shown that all transducers can reach required resolution of 0.1 nm. The best resolution of 28.8 pm was achieved with the optical encoder. This in combination with ease of installation makes it an ideal candidate for a seismic sensor for CLIC. It can be installed into geophones and convert them into high resolution seismometers or it can work in a closed loop inside a broadband seismometers thus increasing their resolution even further.

In addition to the transducers installed already, a multi-pass Michelson interferometer is currently being implemented to the sensor. It is designed to have a sensitivity at least one order higher than the Fabry-Pérot interferometer used in this study and similar level of noise. Referring to equation 2, this should lead to further increase in resolution.

Acknowledgment

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