Progress of Surface potential measurement using a torsion pendulum

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1. Introduction

- The metal is widely used for making test mass in precision measurements.
- In the idealized case, the isolated conductor is an equipotential body with the same potential over its surface.
- In fact, impurities and microcrystal structure will lead to a nonuniform dipole layer formed on the metal surface. When two metallic surfaces at finite distance, the force or torque on each of them will produce.
- The temporal and spatial variations in surface potential is one of the largest contributors of noise in precision measurements, such as LISA, GP-B, Test of Newtonian Gravitational Square Law and so on.
- Investigate the surface potential on test mass carefully is significant.
1. Introduction

Kelvin probe is an efficacious way to measure the distribution of surface potential. It is a non-contact, non-destructive vibrating capacitor device measures potential difference between a conducting specimen and a vibrating probe tip.

Kelvin probe measurements is a null measurement technique. The potential $V_b$ electrically connects the sample and tip. The surface potential will be found by recording the output signal as a function of $V_b$ and fitting the data to find the value of $V_b$ where the signal passes through zero.

• Its sensitivity could achieved 1mV/Hz$^{1/2}$.

Measure surface potential by torsion balance [2]

Electrostatic torque

\[ N = \frac{1}{2} \frac{dC}{d\theta} (V - V_{SP})^2 \]

Resolution \(30\mu V/\text{Hz}^{1/2}\)

- The torsion balance is widely used for measuring all kinds of weak force, because of its high sensitivity.
- The average surface potential and its temporal variations has been measured by University of Washington base on torsion balance.
- Their result shows that this scheme could measure the value of potential accurately.

2. Modeling and error analyze

- A scheme has been proposed for measuring distribution of surface potential base on electrostatic controlled torsion balance.

- The apparatus consists of a source conductor (5mm × 5mm × 5mm), pendulum (100mm × 40mm × 8mm), gravitational compensator, two pair of electrodes and a series of translational stages.

- The source conductor with voltage $V_s$ could be moved relative to surface of pendulum. The voltage of feedback $V_f$ will reflect the value of electrostatic torque between source conductor and sample in the appropriate regions.

$$
\tau_{PE} = -\frac{1}{2} \frac{C_p l_p}{d_p} (V_s - V_{TM})^2 \\
\text{Electrostatic torque}
$$

Goal: $10\mu V/Hz^{1/2}$

$$
\delta\tau_{\text{measure, min}} = \frac{C_p}{d_p} (V_s - V_{TM}) l_p \delta V_{TM, \text{min}} \approx 7.1 \times 10^{-14} \text{Nm} / Hz^{1/2}
$$
2. Design and Error analysis

Major factors effecting the resolution:
- Thermal noise of fiber.
- Resolution of capacitive sensor.
- Fluctuation of voltage applied to pendulum, electrodes and source conductor (SC).

![Graph showing thermal noise, voltage of feedback, voltage applied to SC, and capacitive sensor over frequency](image-url)
3. Experimental apparatus

Apparatus is made up of a source conductor, pendulum, gravitational compensator, electrodes, magnetic damping, translational stages and other fixtures.
3. Experimental apparatus

**Thermal noise of free pendulum**

- Resolution of capacitive sensor: $6 \times 10^{-7}$ pF/Hz$^{1/2}$

**Noise of electrostatic actuator**

- Torque sensitivity of system: $7 \times 10^{-14}$ Nm/Hz$^{1/2}$

**Torque sensitivity of apparatus is able to achieve our goal**
4. Measurements: Static mode

Measurement of surface potential with static mode
1. DC voltage $V_{DC}$ applied to source conductor
2. Record the torque of feedback with different $V_{DC}$. 
3. The surface potential will be found by fitting the data to find the value of $V_{DC}$, where the signal equals to extremum.

\[
\tau_{PE} = \frac{1}{2} \frac{\partial C_p}{\partial \theta} (V_{DC} - V_{TM})^2
\]

Surface potential $V_{TM} = (1.6904 \pm 0.0018) \, V$
4. Measurements: Static mode

Resolution of measuring surface potential

\[ \tau_{\text{feedback}} = \frac{1}{2} \frac{\partial C_p}{\partial \theta} (V_{\text{DC}} - V_{\text{TM}})^2 + \tau_0 \]

\[ \delta V_{\text{TM}} = \frac{d_p \delta \tau_{\text{measure}}}{C_p (V_{\text{DC}} - V_{\text{TM}}) l_p} \]

A measurement of surface potential fluctuations.
The spectrum is white at \(15 \mu \text{V}/\text{Hz}^{1/2}\) for frequencies above 0.03 Hz.
4. Measurements: Scan mode

Source conductor

Test mass

The electrostatic torque

\[
\tau_e = \frac{\partial W_e}{\partial \theta} = \frac{1}{2} \left[ \sum_{i=1}^{n-1} \left( \sum_{j=i+1}^{n} C'_{ij} (V_i - V_j)^2 \right) + \frac{1}{2} \sum_{i=1}^{n} C'_{is} (V_i - V_s)^2 \right]
\]

Total charge on the \(i\)th electrode

\[
Q_i = \sum_{j=1}^{n} C_{ij} (V_i - V_j) + C_{is} (V_i - V_s)
\]

Total charge on the source conductor

\[
Q_s = \sum_{i=1}^{n} C_{is} (V_s - V_i)
\]

Modulation voltage applied to source conductor

\[
V_s = V_{DC} + V_{AC} \sin(\omega t)
\]

\[
\begin{align*}
\text{DC} & \quad \tau_{e_0} = \frac{1}{2} \left[ \sum_{i=1}^{n-1} \left( \sum_{j=i+1}^{n} C'_{ij} (V_i - V_j)^2 \right) \right] + \frac{1}{2} \sum_{i=1}^{n} C'_{is} \left( (V_i - V_{DC})^2 + \frac{1}{2} V_{AC}^2 \right) \\
1\omega & \quad \tau_{e_\omega} = -\sum_{i=1}^{n} C'_{is} (V_i - V_{DC}) V_{AC} \\
2\omega & \quad \tau_{e_{2\omega}} = -\frac{1}{4} \sum_{i=1}^{n} C'_{is} V_{AC}^2 \\
\end{align*}
\]

\[
V_{tm} = \frac{\sum_{i=1}^{n} (C'_{is} V_i)}{\sum_{i=1}^{n} C'_{is}} = V_{DC} + \frac{\tau_{e_{2\omega}} V_{AC}}{4 \tau_{e_{2\omega}}}
\]

A weighted average over all potentials on sample.

The output could express an average potential over local regions which are face to source conductor.
4. Measurements: Scan mode

Modulation voltage applied to source conductor

\[
V_s = V_{DC} + V_{AC} \sin(\omega t) \quad V_{AC} = 1.0V \quad V_{DC} = 1.5V
\]

\[
V_{tm} = V_{DC} + \frac{\tau_{e_1} V_{AC}}{4\tau_{e_2}\omega}
\]

Power spectrum of torque feedback

The amplitude of \( \tau_{e_1} \) and \( \tau_{e_2} \) will be obtained by fitting. The fitted equation is expressed as follow.

\[
\tau_f(t) = \tau_e(t) = \tau_{e_1}\cos(\omega c t) + \tau_{e_1}\sin(\omega c t) + \tau_{e_2}\cos(2\omega c t) + \tau_{e_2}\sin(2\omega c t) + \ldots + d_0 + d_1 P_1(t)
\]

\[
\tau_{e_1} = \sqrt{\tau_{e_1} \sin^2 + \tau_{e_1} \cos^2}
\]

\[
\tau_{e_2} = \sqrt{\tau_{e_2} \sin^2 + \tau_{e_2} \cos^2}
\]
4. Measurements: Scan mode

- The variation of surface potential over time (11 days) is less than 0.5 mV.
- Measuring distribution of surface potential with scan mode shows that our apparatus could obtain the distribution of surface potential and experimental data had good repeatability.
- The experimental data with different scanning steps reflect more details in distribution of surface potential.
- The variation of surface potential over time (11 days) is less than 0.5 mV.
5. Summarize

- Design and install our apparatus for measuring, whose resolution achieves to our goal.
- Measuring the value of surface potential with static mode.
- The spatial variations in surface potential could be obtained by apparatus depend on scanning mode.
- Researching for elements which may influence the variations in surface potential is our focus in the next step.
- Investigating the charge management base on our apparatus will be carried out in the future.
The End
Thanks for your attention!