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The INRIM electrostatic balance to implement the new SI definition of the mass in the milligram range

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Abstract

The realisation of the kilogram in the new SI can be implemented in several ways. The solution proposed by INRIM is based on an electrostatic balance operating in the milligram range. Due to the relative weakness of the electrostatic force compared to the 'magnetic' force (used in the Kibble balance), this type of balance is well suited for measuring small masses. On the other hand, small masses today suffer from a degradation of uncertainty due to the number of steps from the kilogram. For these reasons, there is a strong interest both in the scientific and in the metrological community for the realisation of a balance dedicated to masses below one gram. The electrostatic balance developed at INRIM is based on measuring the capacitance of a parallel plate capacitor to which the mass is hung. The objective of such instrument is to achieve a relative uncertainty of 10^{-4} for masses in the milligram range. Based on the experience gained with a previous prototype, a new mechanical structure of the device has been realised. A software for automating the measurements and the data acquisition has been developed in LabVIEW. A FEM model of the balance allowed to simulate the electric field between the capacitor plates and to obtain the relationship between the capacitance and the electrode distance. The paper describes the new set-up and reports the main results obtained in an intensive measurement campaign.

SI definition of the mass, electrostatic balance, parallel plate capacitor

1. Introduction

The new definition of the kilogram adopted in 2018 [1] is based on fundamental constants and its realization can be implemented in several ways [2,3]. The technique proposed by INRIM is based on an electrostatic balance operating in the milligram range. The paper describes the main aspects of the renewed set-up and its characterization.

2. INRIM electrostatic balance

The first prototype of INRIM electrostatic balance to measure small mass standards up to 1 g is described in [4]. Based on the gained experience, a second set-up based on a state of the art mass comparator and a capacitor made by two gold parallel plates has been realised. The mass comparator is the Ultra-microbalance UMX2 manufactured by Mettler-Toledo (measuring range 2 g, resolution 0.1 µg). The capacitor is made by two parallel plates made of glass: one plate is fixed to the pan of the balance, while the second is fixed to a piezoelectric actuator facing the first plate. In order to reduce the roughness of the plates, a gold film was deposited on the plates by sputtering in INRIM laboratories devoted to nano-fabrication of devices. A picture of the capacitor plates is shown in Fig.1. A portable magnifying camera is used to align the system and to assess the parallelism of the plates.

The working principle of the electrostatic balance is the equivalence between the gravitational force from a test mass, F_g, and the electrostatic force from a capacitor, F_e. Hence, the fundamental measurement equation is

$$F_g = mg\left(1 - \frac{\rho_{air}}{\rho_m}\right) = F_e = \frac{1}{2}\frac{\partial C}{\partial z}V^2 \qquad (1)$$

where m is the mass, g is the gravitational acceleration, ρ_{air} is the air density, ρ_m is the mass density, C is the capacitance, z is the distance between the capacitor plates and V is the voltage difference applied to the plates.

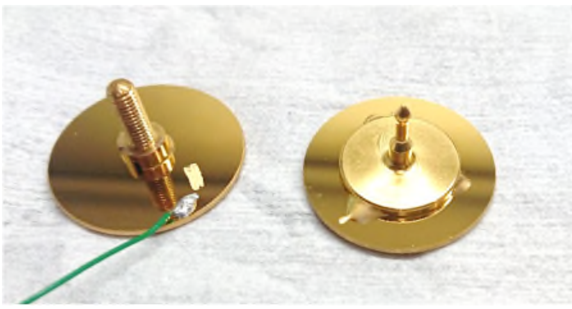

Figure 1. Picture of the capacitor gold plates manufactured in INRIM

The measurement procedure is divided in several steps. The first step is the measurement of the spatial gradient of capacitance, dC/dz, and the calculation of this quantity at a particular distance, d_0. Then the mass to be calibrated is loaded and a voltage is applied to the plate in order to compensate the gravitational force. A high accuracy Andeen-Hagerling 2500A capacitance bridge is used to measure the capacitance between the plates. A linear piezoelectric actuator manufactured by Physik Instrument, model PI-P753.2, is used to set the distance between the plates. The voltage applied to the capacitor is measured by an Agilent 3458A voltmeter. All the measurement are traceable to INRIM standards.

3. Mechanical characterization of the balance

A mechanical characterization of the mass comparator was performed before using it in the electrostatic balance set-up.
First of all, an Attocube laser interferometer was used to characterize the plate displacement caused by the load. The laser beam was directed through a fibre towards the plate fixed to the pan of the balance, as shown in Fig. 2. Then the balance was loaded with increasing mass standards and the corresponding plate displacements were measured by the interferometer. As expected from a good mechanical system, the plate displacement is linearly proportional to the load over the entire measuring range, as shown in Fig. 3.

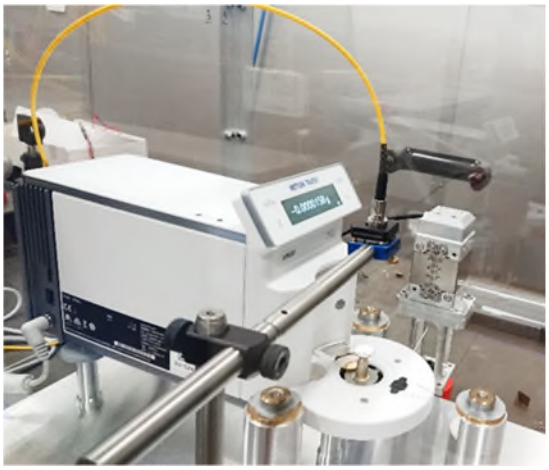

Figure 2. Picture of the interferometric set-up for the characterization of the mechanical properties of the balance

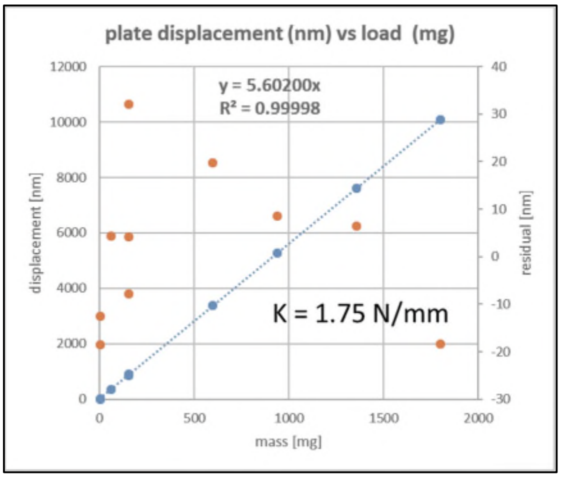

Figure 3. Left axis: linear dependence of the plate displacement on load (blue dots). Right axis: residuals from the linear fit (orange dots)

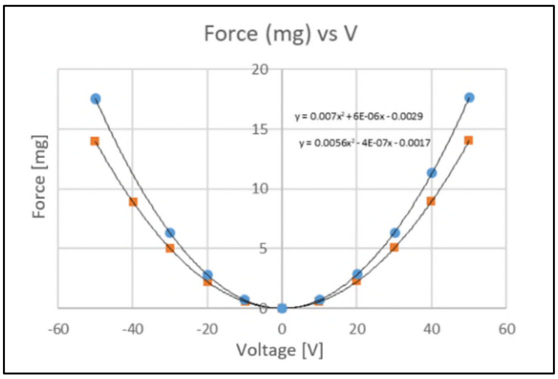

Figure 4. Force values measured by the balance as a function of the voltage applied to the capacitor at two different distances between the capacitor plates

Then the second plate fixed to the piezoelectric actuator is mounted facing the first plate and parallel to it at a distance of about 200 µm to form a capacitor. As second test on the mass comparator, an increasing voltage is applied to the electrodes while the force measured by the mass comparator is recorded. According to theory, the measured force has a second order behaviour with respect to the voltage, as shown in Fig. 4.

4. Measurement automation

In order to avoid the presence of an operator and reduce the thermal drift, a software for automating the procedure and the data acquisition has been developed in LabVIEW.
The program is able to manage the entire measurement cycle. Indeed, it allows to load and unload the mass standard. It communicates with all instruments to acquire data from the balance, the voltmeter and the capacitive bridge.
It allows to drive the piezoelectric actuator in selectable steps in order to measure the capacitance at different distance between the plates and to evaluate the spatial gradient of capacitance, dC/dz, as shown in Fig. 5.

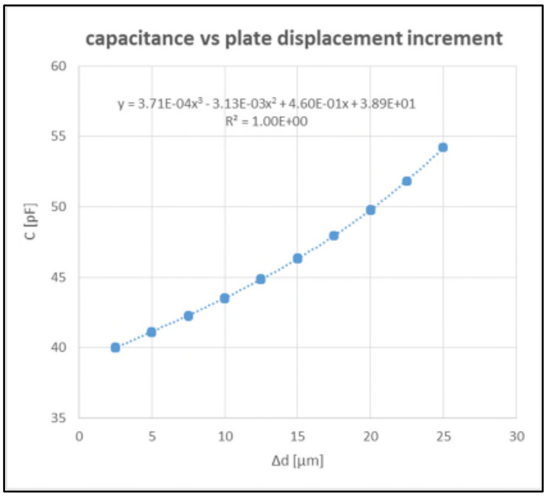

Figure 5. Capacitance values measured as a function of an increment of the distance between the capacitor plates

Finally, it controls a NI daq device USB-6356 to generate an analog voltage which is amplified and sent to one of the capacitor plate to compensate the load with the electrostatic force.
This automation will enable the measurements to be repeated many times in order to lower the statistical uncertainty.

5. Conclusions

A new prototype of an electrostatic balance based on gold parallel plates has been realized at INRIM to measure small mass standards in the milligram range. The mechanical performance of the system was extensively tested and a software for automating the measurement procedure was developed. With this new set-up, we foresee to achieve a relative uncertainty level of 10^{-4} for masses up to 100 mg.

References

[1] Proc. of the 26th meeting of the CGPM (2018)
[2] Robinson I A and Schlamminger S 2016 *Metrologia* **53** no. 5, pp. A46-A74
[3] Fujiiet K et al. 2016 *Metrologia* **53** no. 5, pp. A19-A45
[4] Pisani M, Malengo M, Santiano M, Saba F, Torchio D 2019 *IEEE Trans. Instrum. Meas.* **68** no. 6 pp. 2223-2228