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The Swiss Watt Balance: First Measurements

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Abstract

The Swiss Watt Balance is a new type of moving-coil experiment with a very compact design. The aim of the experiment is to link the unit of mass to fundamental constants with a view to a future redefinition of the kilogram. That means to express the kilogram in terms of the meter, the second and the Planck's constant, by equating electrical and mechanical power, with a relative uncertainty of $\leq 10^{-8}$. The main features of the Swiss design are a very compact construction and a strict separation between the moving and weighing parts of the experiment. In order to optimize all the key components of the set-up, they were separately tested and accurately characterized. An update on the optical velocity measurement and regulation system, on the permanent magnet and coil assembly assessment, and on the automation of the programmable Josephson voltage standard is given first. In addition, the mass comparator, the characterization of the 100 g gold mass standards, and the absolute gravity measurements are presented. In a second part, the description of a complete sequence of data acquisition is explained in details.

1. Introduction

The 21st Conférence Générale des Poids et Mesures (*resolution Nr 7 adopted in October 1999*) recommends that national laboratories improve the link of the unit of mass to fundamental constants. The ultimate goal of the improvements is to redefine the kilogram.

Among the existing proposals to realise the link of the unit of mass to fundamental constants, the concept of the Watt balance, proposed by B. Kibble [1], seems to be the most likely to achieve a relative uncertainty of $\leq 10^{-8}$ in the near future. Experiments of this kind are currently pursued at the National Physical Laboratory (NPL, UK), the National Institute of Standards and Technology (NIST, USA), and the Swiss Federal Office of Metrology and Accreditation (METAS, CH). A fourth Watt balance project recently started at the Bureau National de Métrologie (BNM, FR).

The Swiss Watt balance is composed of different modules: the mechanical apparatus, the magnet and coil assembly, the interferometer, the Josephson voltage standard, the mass comparator, the absolute gravimeter, and the drive and control electronics. The recent progress made in each of these modules will be described below.

2. System Characterisation

The principle and design of the Swiss Watt balance was previously described in [2] and [3]. Fig. 1 shows schematically the apparatus for both (a) the weighing part (force compensation) and (b) the moving part of the experiment.

For the force compensation, the main coil and the test mass are suspended to the mass comparator. The Laplace force induced by a stabilised current is used to compensate the gravitational force on the test mass (see Fig. 1a). Before the moving sequence, the coil is transferred from the suspension frame to the parallelogram. The velocity of the moving coil and the induced voltage are then measured during the moving part of the experiment (see Fig. 1b).

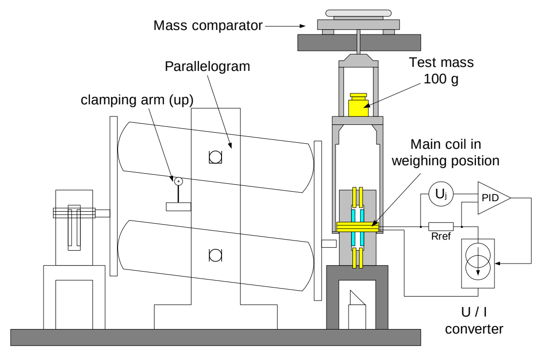
The detailed sequence of measurement is described in section 3.

2.1 The mechanical set-up

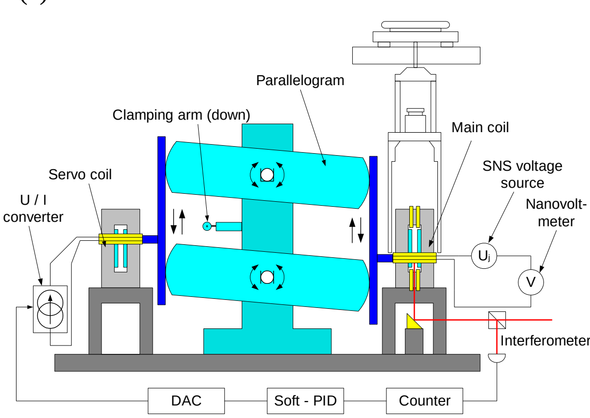
The mechanical construction, the mechanics and optics adjustments were finished and tested at the end of 2000.

2.2 Velocity Measurement and Regulation

During the moving part of the experiment, the velocity of the coil *v(x)*, typically 3 mm/s, has to be stabilised and then measured with a relative uncertainty of one part in 10^8. The measurement system is a Fabry-Perot interferometer formed by two flat mirrors and operating in reflection. The first fixed partially reflecting mirror is the reference. The second mirror is attached to the moving coil. The beam is emitted by a Zeeman-stabilized laser and spatially filtered by a single-mode, polarization-maintaining fiber.



(a)



(b)

Figure 1. Scheme of the Swiss Watt balance in the (a) force compensation and (b) moving part of the experiment (velocity and induced voltage measurement)

The beat signal due to the interference of the waves reflected by both mirrors is detected with the photo-detector. This Doppler frequency is measured by a counter board, and converted to the velocity information.

This information is used in a software implemented PID regulator to generate a feedback voltage, which drives the current source of the servo coil to maintain the velocity at the target value. The servo coil acts here as a force transducer.

A time interval analyser (TIA) with a resolution of 75 ps is actually used to log the time tags of the fringes with a relative accuracy of $<10^{-8}$. The measurement window of the digital voltmeter, measuring the induced voltage, is also logged through this TIA. During the post-processing of the results, time tags are converted to the velocity information, and synchronised to the measurement cycles of the voltmeter.

The influence of the relevant parameters of the optical system on the accuracy of the velocity measurement, such as mirror alignment, the curvature of the Gaussian beam, and the optimum reflectivity of the mirrors, has been extensively studied in [4].

2.3 Permanent Magnet and Coil Assembly

The magnet consists of 2 sets of SmCo permanent magnetic plates inserted between a rectangular steel yoke (Fig.2).

Steel plates of 1 mm thickness are placed on the gap side of the magnets to smooth the random variation of the magnetic field on the surface. This assembly provides a magnetic field of about 0.49 T in the 7 mm air gap between the magnets. The coil assembly consists of two parallel windings of 2000 turns each of a 0.1 mm diameter bi-filar copper wire, wound in an “8” shape to cancel the contributions of interfering AC magnetic fields. During all phases of measurement (see section 3), one of the two windings is driven by the weighing current (to reduce thermal and magnetic changes in the system). The induced voltage is measured across the second coil.

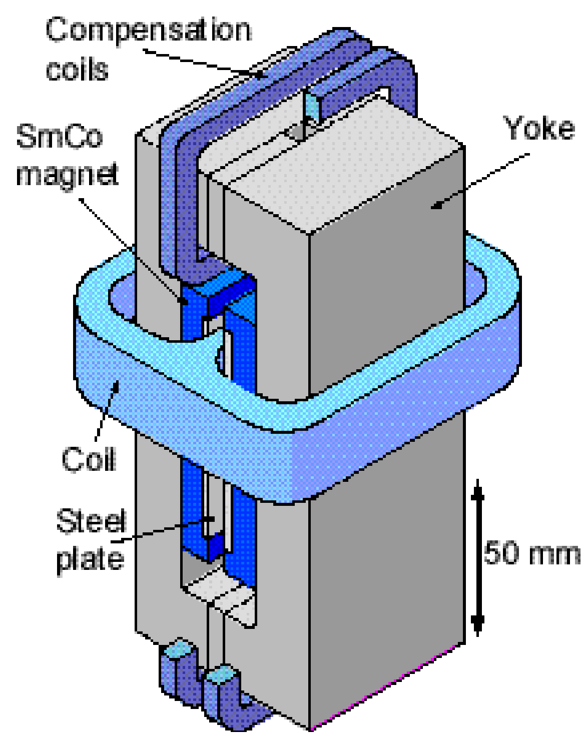


Figure 2. Scheme of the magnet and coil assembly with the compensation coils

The moving part of the experiment has been used to characterise the magnet and coil assembly. The magnetic flux variation (Fig. 3) along the air gap between the permanent magnets has been determined by measuring the ratio of the induced voltage *U(x)* to the velocity *v(x)* of the moving coil. The term $\partial\phi(x)/\partial x$ in equation (1) is the magnetic flux variation.

$$-U(x) = \frac{\partial\phi(x)}{\partial x}\frac{dx}{dt} \quad (1)$$

The results of the characterisation show that the magnetic field in the air gap depends not only on the remnant field of the SmCo permanent magnets, but also on the additional field produced by the weighing current in the main coil. As a result of this additional field, constant and linearly varying position dependent components are added to the field integral. The magnitude of these components depends on the polarity and the magnitude of the weighing current.

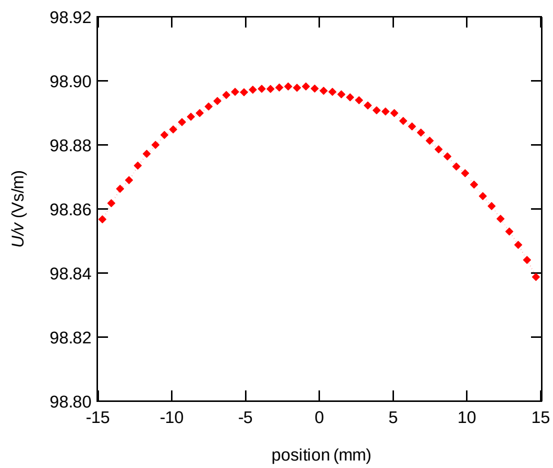


Figure 3. Magnetic flux variation measured with the main coil

The constant component induced by the additional field can be eliminated by a proper adjustment of a set of 2 compensation coils enclosing the yoke (Fig.2), which produces a magnetic flux in the counter-sense of the one produced by the main coil. The additional linear components cannot easily be eliminated. However they are not important as long as the field at the weighing position is kept constant during the weighing and the moving part of the experiment. This can be ensured by a proper definition of the measurement sequence, as explained in section 3.

2.4 The Programmable Josephson Voltage Standard

Recently, a new Josephson voltage standard based on a 1 V superconductor – normal - superconductor (SNS) Josephson junction array provided by NIST was implemented at METAS [5]. Such arrays are intrinsically stable and the switching time between voltage steps can be in the µs range. These two characteristics are particularly appropriate for the moving coil experiment. A comparison between the SNS and a conventional superconductor – insulator - superconductor (SIS) Josephson voltage standard was performed [5]. At a level of 1 V, the mean difference between the SIS and SNS voltage was 0.14 nV, with a one standard deviation of the mean of 0.34 nV. This corresponds to a relative difference of (1.4 ± 3.4) parts in 10^{10}. This result clearly shows that the SNS system is working perfectly with an accuracy that is one order of magnitude smaller than the target accuracy of our moving coil experiment. The SNS Josephson voltage standard will be directly used in the experiment as voltage reference for the induced voltage measurement *U(x)* and for measurement of the force compensation current.

2.5 The Mass Comparator

A custom-made flexure strip single pan mass comparator was installed in May 2001 (Fig. 4). Careful preparation made it possible to exchange the provisional mass comparator, initially used, with the new 2.2-kg mass comparator without any changes in the mechanical alignment of the system. The result of this exchange is a gain of a factor 1000 in the resolution of the mass comparator.

The following tests still have to be conducted before using the whole sequence of measurement described in section 3.

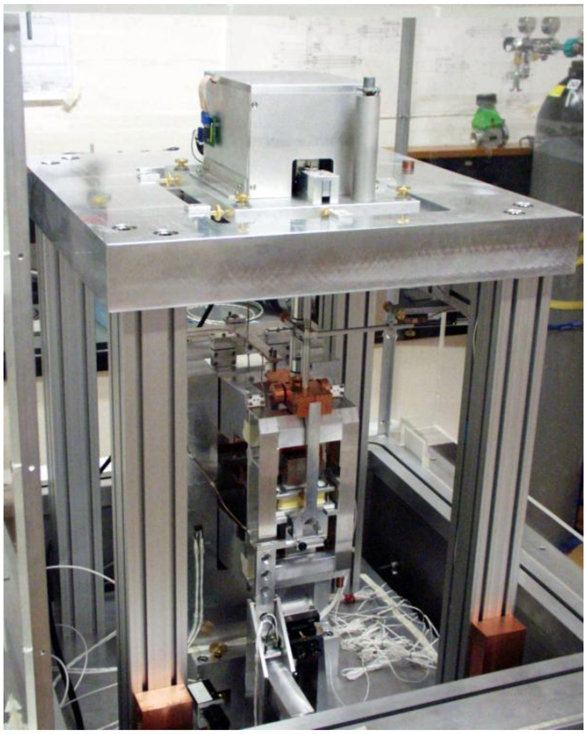


Figure 4. Watt balance with the new mass comparator on the top

The initial status of the mass comparator is a 50-g under load. As a consequence the exchange of two 50 g mass standards can be easily performed using the two mass lifters. This simple mass comparison will be first tested using the mass comparator only, with no external force compensation.

The force compensation itself will then be tested in order to characterise the mechanical stability of the suspension as well as the reproducibility of the mass comparator as zero detector. In this case, a current of about 4.9 mA is necessary in the coil to produce a force of $F = 0.5$ N.

These tests on the weighing part of the experiment will be performed first using the vacuum chamber as a classical airtight chamber and then under vacuum.

2.6 The Gold Test Mass

Five 100-g pure gold masses were produced at BIPM. Two of them were characterised at METAS (mass and volume) and will return at BIPM as reference for monitoring their stability. The mass and volume of the three remaining gold cylinders will be measured at METAS in summer 2001. Finally two of these three pieces will be calibrated against 100-g Pt-Ir standards at BIPM and thus directly linked to international kilogram prototype. The BIPM will also provide vacuum measurements of the mass difference of the same gold cylinders.

The METAS 1-kg vacuum mass comparator is actually used to check surface effects on the mass in air and vacuum, as well as the reproducibility of such air and vacuum measurements. These measurements will be performed on 1 kg copper artifacts of different surface area and covered by a 10 µm thick gold layer.

2.7 The Absolute Gravimeter

The new laboratory for the Watt balance experiment in the extension building at METAS is now finished. Five absolute gravity sites were defined and identified in this laboratory. The middle one is located at the final position of the test mass in the Watt balance experiment, and four are located outside the experimental area on two diagonals crossing the middle point.

These five absolute gravity sites were characterised for the first time between March and May 2001 using an absolute gravimeter. Three of the five absolute stations have absolute gravitational accelerations within $1.5 \cdot 10^{-8}$ m/s^2. The maximum deviation of the gravitational acceleration values between the five absolute sites is $\pm 7.9 \cdot 10^{-8}$ m/s^2, with a typical uncertainty of measurement of $1.5 \cdot 10^{-8}$ m/s^2. Long-term stability measurements and horizontal transfer determination between one of the four sites and the centre of the experiment will be performed until the end of 2001.

It is also important to measure gradients of the gravitational acceleration in order to densify the network around the Watt balance experiment, and to record and calculate the tide and loading coefficients. For this purpose a relative gravimeter was recently purchased, which will provide relative measurements at the 10^{-8} m/s^2 level.

3. The Sequence of Acquisition

The main measurement sequence contains 6 basic phases for weighing and induced voltage measurements. These basic phases are given in Table 1.

During the first phase the main coil (measurement coil) is translated up and down by the seesaw mechanism at constant velocity in the magnetic field. The first winding of the main coil is driven with a positive dc current (to insure a constant thermal load in the system). The second winding is used to measure the induced voltage $U_{ind} \cong 0.29$ V at v=3 mm/s. The coil velocity is measured at the same time using the Fabry-Perrot interferometer.

Table 1. Basic phases for the sequence of acquisition

1.	Field integral measurement with positive current in the coil
2.	Weighing (force compensation) with 100 g mass (F = +0.5 N) and with positive current in the coil
3.	Field integral measurement with positive current in the coil
4.	Field integral measurement with negative current in the coil
5.	Weighing (force compensation) without mass (F = -0.5 N) and with negative current in the coil
6.	Field integral measurement with negative current in the coil

For the second phase of measurement, the main coil is transferred from the seesaw mechanism to the mass comparator (suspension).

The mass comparator is initially underloaded by 50 g. As a consequence the loading of a 100 g reference mass on the suspension produces an overload of 50 g. The first winding of the main coil is driven with a positive current (weighing current). The generated Laplace Force compensates this overload and the mass comparator reads values on the realised equilibrium.

For the third phase the main coil is transferred back to seesaw mechanism and the measurements are identical to those of the first phase.

Phases 4 to 6 are performed with the roles of the coils reversed. In this case the 100 g test mass is removed from the mass comparator for the force compensation measurement. The Laplace force directly compensates the 50-g underload.

Finally phases 1 to 6 are repeated with the current in the second winding of the main coil.

Both field integral measurements before and after the weighing as well as time symmetry in the data acquisition are necessary to compensate the linear drifts.

Extended LabVIEW software was developed. A home-made macro language was specially created in order to be able to easily add commands and to change the measurement procedure. A special attention was also paid to record history of all tests and measurements.

4. Conclusions

The Swiss Watt Balance is now ready to perform full sequences of data acquisition. As much data as possible will then be acquired at constant pressure and under vacuum until the end of 2001 in the old METAS building where the experiment was initially built. Moving into the new METAS building is planned for the beginning of 2002.

This period of moving will be used to adapt or modify some mechanical parts and refine the measurement sequence.

5. References

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