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Design of the new METAS watt balance experiment Mark II

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Abstract
The kilogram is the last unit of the international system of units (SI) still based on a material artefact, the international prototype of the kilogram (IPK). The comparisons made in the last hundred years have clearly revealed a long-term relative drift between the IPK and the official copies kept under similar conditions at the Bureau International des Poids et Mesures. A promising route towards a new definition of the kilogram based on a fundamental constant is represented by the watt balance experiment which links the mass unit to the Planck constant $h$. For more than ten years, the Federal Institute of Metrology METAS has been actively working in the conception and development of a watt balance experiment. This paper describes the new design of the Mark II METAS watt balance. The metrological characteristics of the different components of the experiment are described and discussed.

(Some figures may appear in colour only in the online journal)

1. Introduction
The kilogram definition still corresponds to the one formulated more than a hundred years ago. It is the last base unit in the International System of Units (SI) based on a material artefact, the International Prototype of the Kilogram (IPK). The IPK is a platinum–iridium cylinder (Pt 90%–Ir 10% in mass) machined in 1878 with a diameter equal to its height of 39 mm. In addition to IPK, six official copies were realized and these are kept under the same conditions at the Bureau International des Poids et Mesures (BIPM) in Sèvres (France). All member states of the Metre Convention have the right to a copy of the IPK, often referred to as the national prototype of the kilogram. To survey the stability of the whole system, three international comparisons between IPK and the national copies have been carried out since 1880. The results of these comparisons have clearly shown a variation of the mass of the different prototypes in time [1]. Unfortunately, it is not possible to attribute the drift to IPK or to the copies. The mean drift of the official copies relative to the mass of the IPK has been estimated as $0.5 \mu g$ year$^{-1}$. Since it is now possible to compare two 1 kg mass standards made out of the same material at the level of $1 \mu g$, the instability among the national mass prototypes is a major contribution to the final uncertainty. The instability of the mass unit has also a direct influence on the realization of the mole, the candela and the ampere and, thus, on the whole set of electrical units.

This situation is unsatisfactory, and it is now accepted by the metrology community that the mass unit will be redefined as soon as the conditions fixed by the Resolution of the 24th CGPM [2] are met.

To ensure the long-term stability of the mass unit, the new definition should be linked to a fundamental constant of nature with a relative uncertainty of the order of $10^{-8}$. Over the last decades, several experiments have been attempted to realize the new definition [3, 4]. Up to now, in addition to the Avogadro experiment, which links the kilogram to the mass of a fundamental particle [4], the most successful approach has been the watt balance proposed by Kibble in 1975 [5]. The principle of this experiment is to link the mass to the Planck constant $h$ by a virtual comparison of the electrical power to the mechanical power. Recognizing that with a definition linking the kilogram to the Planck constant, the SI system would gain in stability, the Resolution of the CGPM [2] states that the
new definition of the kilogram will be based on a fixed value of the Planck constant. To ensure the credibility of the new definition it is imperative that the Planck constant is determined with different experimental approaches. This can be achieved as well with the watt balance experiment as with the Avogadro project [6].

A number of watt balances are now in operation around the world [7,8]. More than fifteen years ago, the development of a first watt balance experiment started at the Federal Institute of Metrology, METAS (Switzerland). After several years of continuous improvements, systematic characterization and thorough investigations, a final result for the Planck constant was published [9]. With this result, the apparatus reached its technical limits, and it was decided to redesign the main part of the experiment in close collaboration with universities (Laboratoire de Systèmes Robotiques, LSRO, from the Ecole Polytechnique de Lausanne, EPFL), research institutes (Centre Européen de Recherche Nucléaire, CERN) and industrial partners (METTLER TOLEDO).

2. Watt balance principle

The concept of the watt balance has been intensely discussed elsewhere [3,7,8]. The experiment is carried out in two steps with the same experimental setup: the static or weighing mode and the dynamic or induction mode (figure 1).

In the static mode, the force generated by a mass \( m \) placed in the local gravity field \( g \) is balanced by the vertical component of the electromagnetic force produced by a current \( I \) flowing in a coil immersed in a magnetic field of flux density \( \mathbf{B} \). The electromagnetic force can be expressed by

\[
\mathbf{F} = I \cdot \oint \mathbf{a} \times \mathbf{B},
\]

(1)

where \( d\mathbf{l} \) is the elementary conductor length of the coil.

In the dynamic mode, the coil is moved vertically at a velocity \( v \) through the magnetic flux \( \mathbf{B} \). This motion induces a voltage \( U \) across the coil that can be expressed by

\[
U = \oint (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{l} = -\oint (d\mathbf{l} \times \mathbf{B}) \cdot \mathbf{v}.
\]

(2)

If the magnetic field and the mechanical dimensions of the coil are strictly identical in both modes, and under the hypothesis that the coil passes through its weighing position during the velocity mode with the same orientation, the combination of both modes leads to the expression

\[
U \cdot I = m \cdot g \cdot v.
\]

(3)

The experiment thus allows a virtual comparison of the electrical and the mechanical power. Using the expressions for the Josephson and quantum Hall effects, equation (3) can be rewritten as

\[
m = C \cdot \frac{f_j \cdot f'_j}{g} \cdot h,
\]

(4)

where \( C \) is a dimensionless calibration factor, \( f_j \) and \( f'_j \) are the Josephson frequencies used during the static and the dynamic phases and \( h \) is the Planck constant. The watt balance experiment thus relates the unit of mass to the metre, the second and the Planck constant.

3. Basic experimental requirements

As described above, a virtual comparison between the mechanical and the electrical power is theoretically possible only if the physical characteristics of the magnetic field and the coil are the same in both modes and if the coil passes, in the dynamic mode, through the same position it had during the static phase. The level at which these requirements are satisfied directly defines the metrological performance of the experiment and implicitly the uncertainty associated with \( h \).

Figure 2 shows the main parameters that must be aligned during both phases of the experiment. In the static phase, the electrical force \( \mathbf{F} \) must be aligned with the mechanical force which is oriented along the local gravity field \( \mathbf{g} \). In this phase, the measurement strategy is very similar to the scheme used in mass calibration [9]. The sequence consists in a weighing with a current injected in the coil producing a downward force equivalent to the half of the weight of the test mass followed by a weighing with a reversed current producing an upward force and the test mass placed on the pan. In both weighing steps, the rest force has to be estimated with a relative uncertainty better than \( 10^{-8} \). The determination of the current is made through

Figure 1. Principle of the watt balance experiment. Static mode: the electromagnetic force acting on the current-carrying coil is balanced against the weight of the test mass. Dynamic mode: the coil is moved in the vertical direction through the magnetic field and the induced voltage is measured.
the voltage drop across a calibrated resistor connected in series with the coil. This resistor is calibrated against a quantum Hall resistance and the voltage drop is measured against a programmable Josephson standard [10].

In the dynamic phase, the coil is moved with a velocity $\vec{v}$, along the vertical direction given by $\vec{g}$. To minimize the voltage induced by lateral motions, the coil must be guided by an appropriate stage along its trajectory. The measurement of a velocity with an uncertainty better than $10^{-8}$ can be achieved with interferometer techniques under the condition that the laser beam is aligned with the trajectory of the moving body [11].

Finally, the ‘link’ between both phases of the experiment is the position in space of the coil that must be strictly identical. To ensure this condition, all orientation angles given in figure 2 must be smaller than $\sim 100 \mu$rad.

4. New METAS design

The first watt balance developed and operated at METAS during the last 15 years reached its metrological limits [12]. Based on this experience, the main components of the METAS watt balance experiment are newly designed in collaboration with external partners. A new translation stage is developed in association with the laboratory of robotics of the EPFL, a completely new monolithic load cell is realized by METTLER TOLEDO and a high-precision magnetic circuit is constructed in cooperation with the group of Magnets and Superconductors of CERN.

The general view of the new design, presented in figure 3, shows the main components of the experiment. At the top, the driving stage will move the coil during the dynamic mode. The translation stage is placed just under the driving system and has the primary function of guiding the coil along the vertical. Inserted in the driving stage, the comparator holds the complete suspension. The suspension goes through the magnetic circuit and supports the coil and the mass pan. The advantage of placing the mass pan at the lowest point of the suspension is that all components will see the same forces during both steps of the static phase of the experiment.

4.1. Driving stage

The driving stage is used, during the dynamic phase of the experiment, to move the translation stage, with the comparator and the complete suspension at a velocity of a few mm s$^{-1}$. Special attention must be paid to the design of this stage to minimize its impact on the quality of the translation stage.

The conception of the driving stage is based on the working principle of a Sarrus linkage [13] and is presented in figure 4. To each arm of the linkage, two mobile masses are attached. By adjusting the position of these masses, the stiffness of the translation stage and the weight of the complete suspension can be compensated to minimize the translation force. In this way, the maximum force that must be produced by the motor can be reduced to approximately 30 mN. This
allows the use of a voice coil motor that is well suited for a precise regulation of the velocity.

To evaluate the influence of the translation stage on the quality of the guiding device, the straightness of the output is measured. Figure 5 shows that the deviation from verticality in the $x$ and $y$ directions is better than $2 \mu m$.

4.2. Translation stage

One of the central points of any watt balance experiment is the mechanism used to translate the coil along the vertical direction. This part of the experiment determines the quality of the dynamic mode, but also, depending on the design, the reproducibility of the static mode. A 13-hinge translation stage was chosen and developed. The working principle of such a translation system, sketched in figure 6, is based on two parallelograms moving in the same direction, but ‘head to foot’. The mobile output stage is linked to an intermediate stage by a coupling lever. By an appropriate design, the circular motion of the output stage can be compensated by the asymmetric motion of the intermediate stage [14]. A detailed description of the design of the translation stage can be found in [13].

Figure 7 shows the first prototype that has been developed and manufactured. The total output stroke is $40 \text{ mm}$ and the hinge thickness is $155 \mu \text{m}$ with a radius of $50 \text{ mm}$. The deformation angle of the hinges is $\pm 5^\circ$.

To evaluate the straightness of the vertical trajectory, the lateral position of the outlet was measured with an interferometer when the table was displaced vertically up and down. During this measurement the translation stage was uncharged and it was moved with a linear motor over a pulley system. The results of these measurements, illustrated in figure 8, show a peak to peak straightness of $190 \text{ nm}$ in $x$ and $40 \text{ nm}$ in $y$ for a displacement of $\sim 35 \text{ mm}$. The difference between the up and down motions is less than $10 \text{ nm}$.

To evaluate the dynamic behaviour of the translation stage, an extensive frequency analysis is carried out. The measured eigenfrequencies of the mechanical structure are summarized in table 1.

The lowest frequency that has been measured is $0.6 \text{ Hz}$ in the vertical direction. This frequency corresponds to the natural frequency of the mobile output stage from the translation mechanism. Because the output stage will be driven by a regulation loop with a much higher sampling rate, this frequency will never be excited. All other frequencies of the translation stage are in a domain that is much higher than the translation frequency in the dynamic mode of the experiment. Effectively, in the dynamic mode, the up and down movement will be performed at a frequency of the order of $0.05 \text{ Hz}$, which is 10 times lower than the lowest eigenfrequency of the translation table.

4.3. Force cell

In the new concept, the residual force in the static phase will be measured with a load cell integrated in the translation stage (figure 9).
Figure 8. Straightness measurement of the 13-hinge translation stage. The dashed and solid lines represent the \( x \) and \( y \) deviations measured during an up–down motion.

Table 1. Summary of the measured eigenfrequencies of the translation stage.

<table>
<thead>
<tr>
<th>Eigenfrequencies / Hz</th>
<th>( x )</th>
<th>( y )</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1 )</td>
<td>142.5</td>
<td>72.5</td>
<td>0.6</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>342.5</td>
<td>122.5</td>
<td>140</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>492.5</td>
<td>302.5</td>
<td>965</td>
</tr>
<tr>
<td>( f_4 )</td>
<td>882.5</td>
<td>432.5</td>
<td>—</td>
</tr>
</tbody>
</table>

Since the mass comparator is integrated in the displacement system, severe requirements in terms of mass and dimensions have to be met. The use of existing instruments turned out to be impossible. The low mass, a new adjustable interface to the motion mechanism, the vacuum compatibility, the robustness of the control loop and the low sensitivity to external disturbances were among the most important challenges in designing the new load cell.

After evaluating different solutions, the monolithic approach was identified as the most promising one. The result of an intensive design phase was a complete new innovative load cell design. Using proven components and the Monobloc approach, a prototype of the comparator was manufactured. The first comparator prototype behaved close to the expected simulation results, and with some optimizations the expectations are fulfilled. The load cell impressed with speed, sub-microgram repeatability with the typical measurement procedure, low hysteresis (\( \sigma = 0.29 \mu g \)) and very highly repeatable thermal behaviour.

In the context of the watt balance experiment, the comparator is not used in a traditional way and the orientation of its working axis is very important. In standard applications for the determination of mass, any systematic error introduced by a misalignment of the working axes from verticality is automatically cancelled by the substitution procedure and an appropriate calibration step. To adjust the orientation of the load cell, a special tool is developed and is presented in figure 10. The orientation system is the interface between the translation stage and the load cell. By means of two differential screws, the cell can be tilted around its output point with a stroke of 5 mrad and a resolution of a few microradians [13].

4.4. Magnet assembly

The new design of the magnet assembly consists of two main parts: the magnetic circuit and the orientation table.

4.4.1. Magnetic circuit. The adopted design, presented in figure 11, is a closed cylindrical geometry. The main advantage of this type of geometry is its insensitivity to external magnetic fields. The magnetic field is produced by two SmCoGd permanent magnets placed on both sides of the kernel with the same poles facing each other. The adjustment of the magnets to the kernel and the centring of the magnets–kernel assembly to the yoke are ensured by two bronze centring rings to guarantee a parallelism better than a few micrometres along the 50 mm gap height, which is 8 mm wide. Theoretically, this circuit should deliver a magnetic flux density of 0.6 T in the gap with a vertical relative homogeneity of \( 10^{-5} \) over a 20 mm region centred in the gap height.
A major contribution to the global uncertainty of the experiment is linked to the temperature dependence of the field produced by the permanent magnets. The temperature coefficient of common SmCo magnets is around −360 ppm K$^{-1}$. In order to reduce the temperature influence, two directions are pursued: the use of a SmCoGd permanent magnet, with a temperature coefficient around −10 ppm K$^{-1}$, and the use of a ‘magnetic shunt’ in parallel to the magnetic circuit can drastically reduce the temperature coefficient of the system. In the new design, a ‘shunt’ made of an Fe–Ni alloy is inserted in the centre hole. The working principle of this passive temperature compensation is based on the magnetic behaviour of the Fe–Ni alloy that has a Curie temperature of 55 $^\circ$C. This implies that at room temperature its magnetic polarization is strongly temperature dependent (figure 12). Consequently, when the temperature of the magnetic circuit increases, the polarization of the shunt will decrease and less magnetic flux will go through the shunt. Conversely, when the temperature of the circuit decreases, the polarization of the shunt increases and more flux flows through the shunt.

To verify the feasibility of this compensation, a demonstrator is designed and experimentally characterized.

The design of the demonstrator is presented in figure 13. In this conception, the two SmCoGd permanent magnets are placed in series to generate a homogeneous magnetic flux of 0.3 T in the central gap. During the experiment, the magnetic circuit was placed in a climatic chamber and a temperature excursion, varying from 15 $^\circ$C to 25 $^\circ$C, was performed with 5 $^\circ$C steps. At each step, a stabilization time of 1 h was respected before measuring the magnetic field. The measurement of the magnetic field was carried out with a NMR probe stabilized at 20 $^\circ$C and placed in the gap. The temperature stabilization was realized with a copper plate placed in the gap and connected to a thermal bath.

With this experimental setup, it was shown that by ‘shunting’ the permanent magnet with cylinders of different wall thicknesses, the temperature dependence of the circuit can be inverted (figure 14). Based on this approach, the temperature coefficient of the circuit can theoretically be eliminated [15].
4.4.2. Orientation table. To satisfy the conditions described in section 2, the magnetic field must be radial to the magnetic axis of the coil. To adjust the orientation of the magnetic field, a special orientation tool was developed.

The orientation table, presented in figure 15, is an inverted double gimbal in which the flexures are replaced by two pairs of zirconium spheres placed in grooves between each stage of the gimbal [13]. With this concept, the four degrees of freedom ($x$, $y$, $\theta_x$ and $\theta_y$) can be adjusted with two pairs of differential screws. To determine the absolute position of the magnet, these four parameters are measured, respectively, with two interferometers and an autocollimator. In this way, a determination of the position with a resolution of a few micrometres in the $x$–$y$ plane can be ensured as well as a few microradians in the $\theta_x$ and $\theta_y$ angles.

4.5. Coil suspension assembly

The coil suspension assembly, presented in figure 16, is an essential part of the experiment. A central tube composed of two parts connected together with an aluminum articulation forms the skeleton of the suspension. The upper end is connected to the load cell with a second gimbal (not shown), and the lower part goes through the magnetic circuit to support the mass pan and the hexagonal plate holding the coil. With the help of the two articulations, it will be possible to distinguish between a lateral force and torque acting on the coil during the static phase [16].

In the static phase, an electromagnetic force of 5 N is generated with a current of approximately 7 mA flowing in a wire of total length 1.1 km, immersed in a magnetic flux of 0.6 T. The wire diameter of 250 µm is a compromise between weight and power dissipation. The air coil of 1836 windings has a mean diameter of 200 mm, a height of 21 mm, an electrical resistance of 458 $\Omega$ and an inductance of 1.23 H. The coil is pinched between two rings and attached to the central tube by six legs mounted on a hexagonal plate. This plate is then rigidly attached to the central tube. The mechanical behaviour of the suspension during both phases of the experiment is analysed and optimized with the help of finite element simulations.

5. Conclusion

The basic requirement for a new definition of the kilogram is a reliable evaluation of the Planck constant $h$. Until now, the published values of $h$ are not in agreement within their uncertainties [17]. The origin of the discrepancies between the published values may be due to systematic errors in the experimental setups. To solve this problem, new experiments with different approaches have to be developed around the world involving the best experts for each part of the conception. The approach taken by METAS is to develop a new watt balance experiment in strong collaboration with specialized partners coming from high technology industry, research institutes and universities [18].

The preliminary results obtained for the main parts of the experiment are very promising and should allow one, in the near future, to reach the expected relative uncertainty of a few parts in $10^8$ [19].

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