National Physical Laboratory demonstrates 1 g Kibble balance: Linkage of macroscopic mass to Planck constant

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Mass is the only base unit, which is represented as a primary standard in the form of artifact for more than 125 years. International prototype of kilogram (IPK) is kept at the Bureau International des Poids et Mesures (BIPM), Paris and serves as the international standard of kilogram. It is made of 90% platinum and 10% iridium and as a cylinder of 39 mm diameter and 39 mm height. Replicas of the IPK are made of the same material and used at BIPM as reference or working standards and national prototype of kilogram (NPK), kept at different National Metrology Institutes (NMIs). NPK-57, kept at CSIR-National Physical Laboratory, is sent periodically to BIPM for calibration. NPK further is being implied through transfer standards of mass to provide unbroken chain of traceability for dissemination of mass to the user industries, calibration laboratories and legal metrology organizations, etc. of the country. According to a study, a drift of about 5×10^{-8} has been found between the IPK and a set of copies kept under similar conditions and with the present definition of kilogram, it is difficult to assign this drift to the IPK or copies of IPK[1,2].

To solve the problem of artifact-based definition of kilogram, kilogram in form of fundamental constant or atomic constant, for example Planck constant, has been redefined. The conditions for redefining kilogram in a form of time and artifact invariant are as follows:

- An accurate and precise measurement method with comparable uncertainty of measurement to the present system of definition (in order of few parts in 10^8 or better).
- An international consensus on the basis of values obtained from a sufficient number of independent experiments developed in different national laboratories or NMIs.

Redefinition of kilogram is utmost priority for the metrological community and has been confirmed by two resolutions of the CGPM in 1995 and 1999 respectively. Consistent efforts are underway for more than four decades and it is expected that redefinition of kilogram might be over by 2018.

Kibble reported the concept of Kibble balance in 1975 to provide linkage of macroscopic mass to the Planck constant. Kibble balance is a self-calibrating electromechanical balance and provides the measurement of mass, traceable in terms of electrical parameters. Development of Kibble balance was started in 1975 at NPL-UK by Kibble and Robinson. Later, NIST-USA and NRC-Canada have successfully demonstrated and developed Kibble balance for 1 kg with an uncertainty of measurement in order of 5×10^{-8} or better[3]. Kibble balance essentially consists of two modes: Force (static/weighing) mode and velocity (dynamic) mode. These two modes lead to the measurement of mass[4,5].

The force mode involves weight of a mass compensated by equivalent electromagnetic force

$$mg = BLI$$

or

$$BL = (mg/I), \quad (1)$$

where m is the mass, g the acceleration due to gravity, I the current flowing in the coil of wire length l, with magnetic field, B. BL represents the geometric factor.

The velocity mode involves moving of the coil in vertical direction with velocity v through the magnetic field. In this process, a voltage U is induced to the coil

$$U = BLv$$

or

$$BL = (U/v). \quad (2)$$

From eqs (1) and (2), we get

$$mgv = UI. \quad (3)$$

Both sides of eq. (3) have the units of power (Kibble), mgv represents the mechanical power and UI is the electrical power[4]. Hence, the efficiency, ε may be termed as

$$\varepsilon = (mgv/UI) \cong 1. \quad (4)$$

From eq. (3) after taking into consideration of Josephson Effect and Quantum Hall Effect, Planck constant, h is formulated as

$$h = (4mgv/(K_{\mathrm{J}}^2 - 90R_{\mathrm{K}}^2 - 90)UI). \quad (5)$$

Equation (5) reveals that Planck constant, h, is directly correlated to mass, velocity,

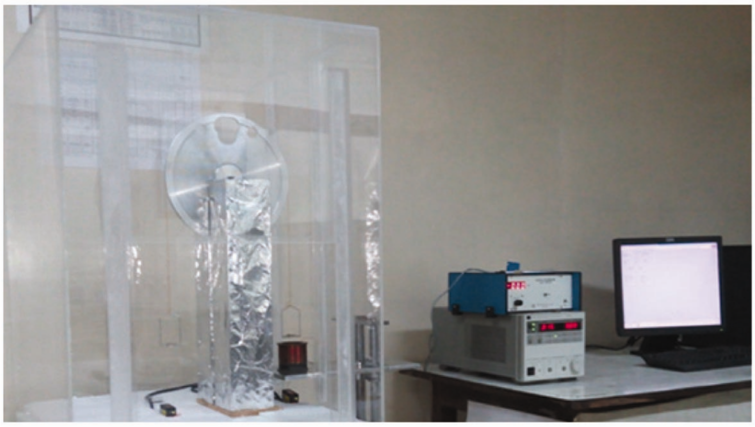

Figure 1. Experimental setup for the demonstration of Kibble balance principle.

induced voltage, current and the quantum constants. K_J–90 and R_K–90 are Josephson and von Klitzing constant respectively.

CSIR-NPL has started preliminary investigations for development of a Kibble balance. An experimental model has been successfully developed and established in the laboratory (Figures 1 and 2). An in-house wheel-based comparator made of aluminium has been designed and fabricated, which contains a wheel (diameter 300 mm, thickness 10 mm). The wheel is fitted with knife edge made of gun metal and placed over grove over the suitably flattened aluminium plate fixed to base. There are two pans of diameter 40 mm on either side of the wheel.

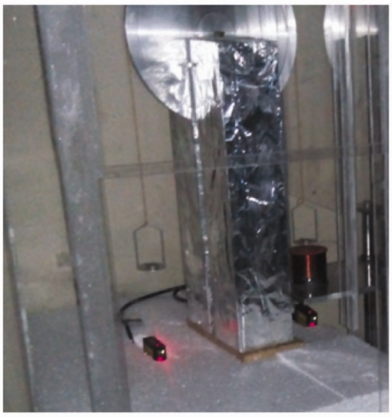

Figure 2. Balancing of weighing pan and monitoring through laser sensors.

A rare earth permanent magnet has been used to produce the magnetic field in 0.3 T range. The pans are adjusted in such a manner that both the pans are in balanced position initially.

The balancing of the pans is monitored through the industrial laser sensor with resolution of 0.001 mm or better. A coil of diameter 50 mm and height 60 mm, fabricated to serve as electromagnet, is placed under a pan and suitably positioned. A programmable DC power supply with resolution of 0.001 mA has been used to manipulate the current in accordance to the mass placed over the pan and balancing position. For movement of the coil with programmable and precision velocity, a servo motor-based system has been developed and the velocity of coil either upward or downward could be varied between 20 μm/s and 2.5 mm/s. The system has optical-sensor for the feedback to control the velocity of coil. The whole setup has been automated using LabView and the experimental setup has been completely automated. The setup has been experimentally evaluated for 1 g and Planck constant has been evaluated. A program has been coded in MATLAB for evaluation of uncertainty of measurement for 1 g Kibble balance experiment. There is deviation of up to 1% to the value of Planck constant calculated through experimental setup w.r.t. value obtained from CODATA. Uncertainty due to mass, current, velocity, induced voltage and acceleration due to gravity has been taken into consideration and uncertainty of measurement evaluated. Taking nominal factors into consideration regarding evaluation of the relative standard uncertainty associated with Planck constant, the associated uncertainty of measurement has been found up to 0.5% ($k = 1$).

CSIR-NPL has now geared up for the development of Kibble balance for 1 kg.

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