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Towards a simplified Kibble balance to realise mass in the new SI

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Abstract

In 2018, as part of the planned reformulation of the SI, it is intended to redefine the kilogram in terms of a fixed value of the Planck constant h. This will allow the world to build a robust and egalitarian mass scale, but only if sufficient laboratories are able to realise mass from the new definition. Current implementations of the techniques for doing this are extremely expensive, difficult to duplicate, and painstaking to operate. NPL has proposed improvements to one such technique: the Kibble (or watt) balance, which was originated at NPL in 1975. These improvements have the potential to reduce significantly the cost and complexity of both building and operating the balance. To demonstrate the technology and test the viability of the essential improvements, we are presently building a small capacity (100 g - 250 g) Kibble balance based mechanically on a conventional knife edge balance. A second technology demonstrator will be built to test the viability of a Kibble balance based on a "seismometer" mechanism. This will use the same flexures for both weighing and moving and will incorporate a highly stable electromagnetic "tare" system to allow any mass m, within the working range of the balance, to be weighed without the need for an $m/2$ "tare" mass. In collaboration with industry and other laboratories around the world, we intend to produce a next generation Kibble balance which will be relatively simple, both to manufacture and to use, to encourage more laboratories to participate in the realisation of the redefined SI unit of mass, using this readily-scalable improved technique.

SI, kilogram, redefinition, watt balance, Kibble balance

1. Introduction

In 2018, as part of the planned reformulation of the SI, it is intended to redefine the kilogram in terms of a fixed value of the Planck constant h. To realise the benefits of this change, many national laboratories must be able to realise mass from the new definition but existing implementations of the techniques for doing this are extremely expensive, difficult to duplicate, and painstaking to operate. The UK's National Physical Laboratory (NPL) has proposed improvements to one such technique: the Kibble (or watt) balance, which was originated at NPL in 1975. These improvements have the potential to reduce significantly the cost and complexity of both building and operating the balance.

2. Improvements to the Kibble balance

The conventional Kibble balance [1] is an experiment which equates virtual electrical and mechanical power in two separate modes. In the weighing mode, a measured current I is passed through a coil placed in a strong magnetic field B.

The generated force opposes the weight mg of a mass m in the gravitational field of the earth at a point where the local gravitational acceleration is g. At equilibrium we can write $mg=BlI$ where l is the length of the wire in the field. In the moving mode, the current and mass are withdrawn and the coil is moved at a set velocity u through the magnetic field, generating a measured voltage $V=Blu$. If it is assumed that the term Bl remains constant between the two modes, we can eliminate it to give the Kibble equation $VI=mgu$. A combination of the Josephson and quantum Hall effects allows electrical power VI to be measured in terms of the Planck constant h and frequency and so, if the numerical value of h is fixed, the Kibble balance can determine mass in terms of measurements of length and time. This highly-simplified analysis ignores a large number of issues and existing Kibble balances require complex and time-consuming adjustments to eliminate the effects of unwanted forces, torques, and motions associated with the coil. However, it has recently been shown that these effects can be eliminated in a Kibble balance having a common moving and weighing mechanism [2].

If all the motions of the coil are precisely determined by the vertical motion of the mass pan $u_{z'}$, [2] shows that it is possible to express the weighing equilibrium as:

$$mg = -I\left(\frac{\partial\Phi}{\partial x}\frac{\partial x}{\partial z'} + \frac{\partial\Phi}{\partial y}\frac{\partial y}{\partial z'} + \frac{\partial\Phi}{\partial z}\frac{\partial z}{\partial z'} + \frac{\partial\Phi}{\partial\theta_x}\frac{\partial\theta_x}{\partial z'} + \frac{\partial\Phi}{\partial\theta_y}\frac{\partial\theta_y}{\partial z'} + \frac{\partial\Phi}{\partial\theta_z}\frac{\partial\theta_z}{\partial z'}\right) \quad (1)$$

and the moving voltage as

$$V = -u_{z'}\left(\frac{\partial\Phi}{\partial x}\frac{\partial x}{\partial z'} + \frac{\partial\Phi}{\partial y}\frac{\partial y}{\partial z'} + \frac{\partial\Phi}{\partial z}\frac{\partial z}{\partial z'} + \frac{\partial\Phi}{\partial\theta_x}\frac{\partial\theta_x}{\partial z'} + \frac{\partial\Phi}{\partial\theta_y}\frac{\partial\theta_y}{\partial z'} + \frac{\partial\Phi}{\partial\theta_z}\frac{\partial\theta_z}{\partial z'}\right) \quad (2)$$

If the terms in brackets in equations 1 and 2 do not vary between weighing and moving modes, we can combine 1 and 2 to give:

$$mgu_{z'} = VI \quad (3)$$

Under perfect conditions, the effects of imperfections in the alignment of the coil, which give rise to non-vertical forces and torques, are eliminated but the cancellation may not be perfect if, for example, the coil moves slightly between weighing and moving modes. In [2] this was addressed by using a "seismometer" mechanism that was free to move vertically but constrained in all other motions.

In practice it is not possible to achieve perfect rigidity but it has been shown in [3] that, by winding the coil with a bifilar twisted pair winding, it is possible to combine the weighing and moving modes into a single mode, avoiding the force changes and associated motions associated with the change of mode.

This, and the other changes described in [3], have the potential to make the technique highly immune to misalignment which will make Kibble balances easier to construct and operate and allow them to scale to other mass ranges.

The proposed changes are fairly radical and NPL will initially build two ``technology demonstrators'' to identify and solve any problems before designing a next generation Kibble balance.

3. Technology demonstrators

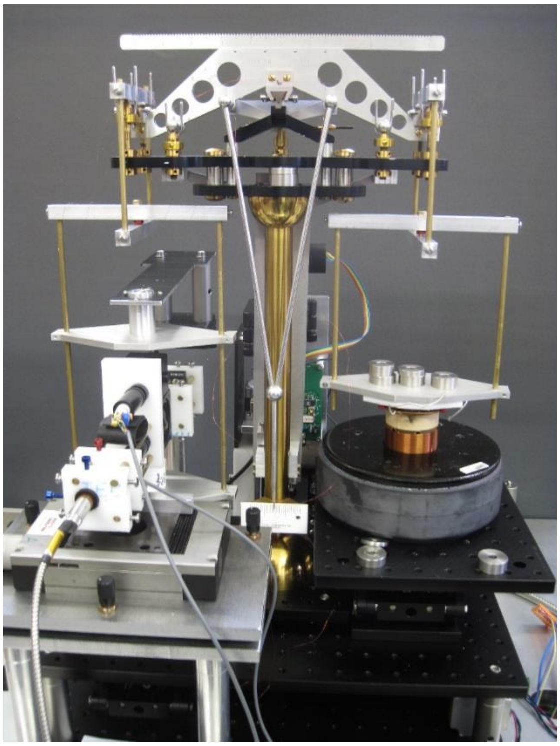

Figure 1. Technology Demonstrator 1

The first technology demonstrator, shown in Figure 1, uses a conventional knife-edge balance and is intended to validate the new form of combined moving and weighing mode Kibble balance.

The second technology demonstrator, shown in Figure 2, will be used to test the construction techniques needed to produce a Kibble balance based upon a "seismometer" mechanism. Novel flexures will be needed to provide motion of the coil over many millimetres of travel whilst providing sufficient sensitivity for precise weighing. In addition it is intended that the weight of the moving frame, shown as the light coloured parts in Figure 2, will be supported electromagnetically. This will require extreme stability from both the magnet and the current source providing the current to support this weight.

Figure 2. Technology Demonstrator 2

4. The next generation Kibble balance

The results from the work on the technology demonstrators will provide the basis for the design and construction of the next generation Kibble balance. It is intended that this work will be carried out by NPL in collaboration with other national measurement institutes and industrial partners, leading to a design that can be manufactured relatively easily to produce a balance that will be capable of measuring SI mass at the level of parts in 10^8.

4. The future

In the future we hope to take advantage of the scalability of the new technique to produce balances that can measure small masses and forces related directly to the SI definition of mass.

References

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[2] Kibble B P and Robinson I A 2014 *Metrologia* **51** S132.

[3] Robinson I A 2016 *Metrologia* **53** 1054-60.