euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

The development of a next-generation Kibble balance for the realisation of the unit of mass following the revision of the SI

Stuart Davidson[1], Ian Robinson[1], Peter Lovelock[1], Charlie Jarvis[1]

[1]National Physical Laboratory, Hampton Road, Teddington, Middlesex, United Kingdom, TW11 0LW

stuart.davidson@npl.co.uk

Abstract
In the near future it is proposed that the International System of Units (SI) will undergo a major revision which is due to be ratified in November 2018. The "new" kilogram will be related to the Planck constant and can be realised via the International Avogadro Coordination by counting the atoms in a silicon sphere or via the Kibble balance which realises the unit of mass with relation to quantum electrical phenomena. After the revision of the SI the need will be to routinely realise the kilogram for the maintenance and dissemination of the mass scale. To this end NPL is developing the next-generation Kibble balance. This paper describes the latest stages of this work including the use of a conventional balance to validate the application of a twisted pair weighing coil to eliminate alignment errors and the development of a "seismometer"-based balance to evaluate the use of flexure strips for the weighing and moving operations and electromagnetic tare of the weighing mechanism. A demonstrator instrument that shows the vision for the final balance, which can be produced in multiple units and scaled to realise different ranges of mass, has also been constructed. Finally, a vision for the wider application of this technology will be presented with particular focus on micro-force and micro-mass applications.

Kibble balance, kilogram, flexure strip, instrument

1. Introduction

In preparation for the redefinition of the kilogram NPL is developing a next-generation Kibble balance instrument which will allow NMIs around the world routine access to the SI unit of mass.

In November 2018 the International System of Units (SI) will be revised to define the seven base SI units in terms of a set of seven reference constants. The kilogram will be defined in terms of the Planck constant which will guarantee its long-term stability and, in theory, give independent access to the SI unit of mass for any laboratory with suitable apparatus. In practice the current iterations of the Avogadro and Kibble balance experiments are expensive to develop and complicated to use; they are essentially designed to measure the Planck constant rather than to produce routine access to the SI unit of mass following the redefinition. The new NPL Kibble balance will address this issue and the aim is to produce a cost-effective and user-friendly instrument which will allow NMIs direct and easy access to the new SI unit of mass at the level of parts in 10^8 which will be required for the dissemination of the mass scale to end-users.

2. Progress

2.1. Single-mode dual-phase operation

The measurement principle behind the Kibble balance is to equate virtual electrical and mechanical power [1] $mg = BIl$. A mass m, under local gravity g, is balanced by the current I in a coil within a magnetic field. In order to eliminate the need to measure magnetic field strength B and coil length l, the Kibble balance operates in two modes; a weighing mode ($mg = BIl$) and a moving mode ($V = Blu$). Field strength and coil length can thus be eliminated and mass m can be determined in terms of a fixed value of the Planck constant and measurements of gravity, velocity u, current, and voltage V (the latter two being traceable to quantum electrical units via the Josephson junction and quantum Hall resistance). While eliminating the need to measure B and l, the two mode operation means that the experiment is extremely sensitive to any change in the alignment of the coil in the magnetic field between measurement modes. Typical values of I, V, and u will be 50 mA, 10 mV and 1 mm/second meaning accuracies at the 10's pA and pV and better than 10 picometres are required to achieve an overall uncertainty of 2 in 10^8.

The new NPL Kibble balance employs a novel single-mode dual-phase operation [2] whereby the weighing and moving modes are common (although still carried out separately). A bi-filar (twisted pair) coil allows the independent measurement of current (during the weighing phase) and voltage (during the moving phase). This combined with a "seismometer"-type construction virtually eliminates the uncertainties due to coil misalignment.

The single-mode dual-phase operating principle has been validated using a conventional two-pan knife-edge balance and work is underway on a seismometer balance to develop and evaluate an electromagnetic tare system for the balance weighing mechanism and the flexure strips to support this mechanism.

3. Demonstrator Instrument

An instrument has been built to demonstrate and evaluate a "seismometer"-type Kibble balance with particular emphasis on the electro-magnetic tare and flexure strips. Figure 1 shows a section through the design showing the outer frame, weighing mechanism, magnets and coils, and flexure strips.

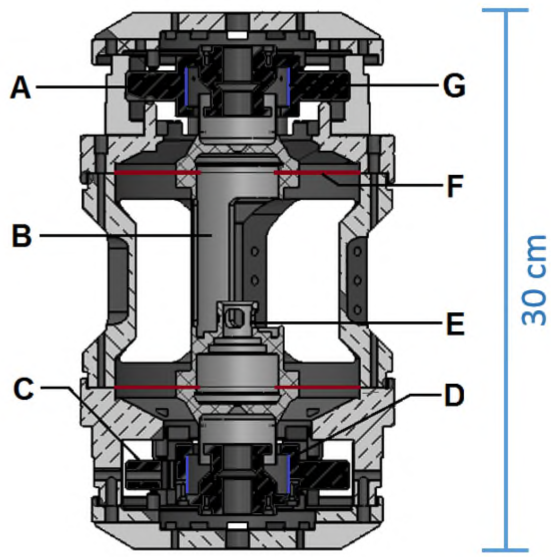

Figure 1. Section through Kibble balance demonstrator instrument A – Tare/drive magnet, B – Weighing mechanism, C – Weighing magnet, D – Weighing coil (blue), E - Weight holder, F – (Upper) flexure strip (red), G – Tare/drive coil (blue)

3.1. Magnets and coils

Twisted-pair coils have been constructed from self-bonding 0.19 mm diameter copper wire using a bespoke twisting and winding apparatus. Open rather than closed magnets have been used for ease of access but the design of the magnets, using finite element modelling, ensures that there are minimal losses and that the flux density is extremely linear over the range of motion of the instrument.

3.2. Flexure strip design

The design and construction of the flexure strips is critical for the new Kibble balance to be able to operate at the level of 1 part in 10^8. The flexures must be stiff in five degrees of freedom but must have high sensitivity in the other, vertical, direction to give the resolution necessary in the weighing mode. Additionally, the flexures need to accommodate the moving mode of the apparatus which requires at least 10 mm travel in the vertical direction.

Finite element analysis has been used to assess various designs for the flexure strips. Figure 2 shows two of the designs which have been evaluated.

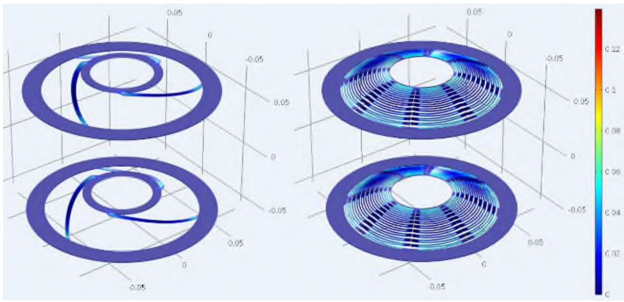

Figure 2. Finite element models for Kibble balance flexure strip designs (O/D = 20 cm)

The "open" design illustrated on the left of Figure 2 has been used for the construction of the demonstrator instrument. As a first iteration this design offer the best compromise between stiffness, z-axis sensitivity, and accommodation of movement. The flexures were made from 0.3 mm spring steel sheet which was spark eroded to the required form. Further iterations of the design employing different materials and 3-dimensional design features should further enhance the performance of the flexures.

3.3. Instrument fabrication

Figure 3 shows the finished Kibble balance demonstrator instrument. The majority of it is manufactured from aluminium but the central weighing mechanism has been made from PEEK to reduce its mass and to have lower magnetic permeability. The apparatus is operational and uses an optical linear encoder to measure the vertical motion, which will limit its performance to about 1 ppm. Nevertheless this will allow the software and control systems necessary for the final instrument to be developed.

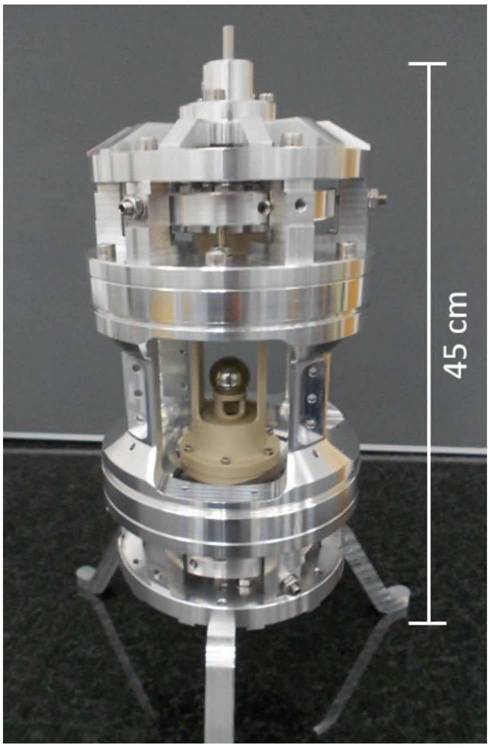

Figure 3. Kibble balance demonstrator instrument

4. Future work

The demonstrator instrument will allow the development of the control systems for the final instrument. A larger technology demonstrator is under construction which will facilitate more thorough evaluation of the electromagnetic tare system, the flexure strips, and the interferometer which will be used for displacement measurement in the final instrument. The aim is to complete the final instrument by 2020.

References

[1] Kibble B P, A measurement of the gyromagnetic ratio of the proton by the strong field method, *Atomic Masses and Fundamental Constants*, **5**, ed J H Sanders and A H Wapstra (New York: Plenum), pp 545–51, 1976

[2] Robinson I A, Simplified fundamental force and mass measurements, *Metrologia*, **53**, 1054–60, 2016

[3] Kibble B P and Robinson I A, Principles of a new generation of simplified and accurate watt balances, *Metrologia*, **51**, S132, 2014