IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference
11 – 13 October 2022, Cavtat-Dubrovnik, Croatia

THE ARCHITECTURE OF THE NPL NEXT GENERATION KIBBLE BALANCE

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Abstract:

This paper provides an overview of the architecture of the NPL “Next Generation” Kibble balance. The balance is intended to realise SI mass in the 100 g to 250 g range with an ultimate target uncertainty of one to two parts in 10^8. It is intended to be simpler to build and operate than previous generations of Kibble balance with the aim of allowing many more laboratories to participate in the realisation of a global mass scale.

Keywords: Kibble balance; kilogram; SI mass realisation; Planck constant

1. INTRODUCTION

The recent redefinition of the kilogram removed the last artefact standard from the revised SI. The change eliminated a bottleneck in the system, as laboratories no longer need to have access to the International Prototype of the kilogram (IPK) to realise SI mass. However, to ensure that the world continues to enjoy a robust mass scale, laboratories are encouraged to make and compare independent realisations of mass from its new definition. With enough laboratories engaged in this process the mass scale would be unaffected by the temporary unavailability of a few contributors.

The Kibble balance [1] played a major role in the redefinition of the kilogram and provides a mechanism for realising the kilogram directly from its definition with no dependencies other than access to realisations of the metre and the second. Previous generations of Kibble balance were large, delicate, complex, difficult to build and difficult to operate. This acts as a discouragement to many laboratories who would like to take part in maintaining SI mass on a world-wide basis.

This paper describes the general architecture of the NPL “Next Generation” Kibble balance, shown in Figure 1. This work aims to provide NPL, and as many other laboratories as possible, with a simple means to make independent realisations of the kilogram from the new definition.

To achieve these aims it was necessary to consider a design that was simple and reproducible both in construction and operation. The design employs the ideas described in [2] and [3] which describe a balance consisting of a seismometer-like mechanism that guides a moving frame which is constrained to move freely only along its vertical axis. Circular coils, attached to the moving frame at top and bottom, are placed in the radial fields generated by two permanent magnets.

Figure 1: CAD rendering of the “Next Generation” Kibble balance showing the upper and lower magnets (A), the counterbalance masses (B), the mass lift (C), the interferometer (D) and the electronics enclosures (E)

One (tare) coil provides force for tare offset and motion control whilst the other (main) coil is wound as a bifilar pair. The balance operates in a single mode with two measurement phases. The current flowing in the tare coil is offset to compensate for half of the weight of the working mass. At any time one of the windings on the main coil carries a current which keeps the balance in equilibrium. The current associated with the weight of the working mass is measured in the weighing measurement phase. In the moving measurement phase the frame is moved and its velocity is measured along with the voltage generated in the free winding. The moving measurements are made with the working mass both on and off the balance and with the roles of the windings exchanged. With a knowledge of local gravity, the SI value of the mass can be determined. This method of operation eliminates several type B uncertainty contributions from the measurements.

This paper covers some of the major considerations which have determined the architecture of the balance including its mechanics, analogue electronics, digital electronics, and software. The work on the detailed designs and their implementation, some of which has been described in [4], is being carried out, in collaboration with NMISA (South Africa) and RISE (Sweden), by the members of the NPL Kibble balance team. It is intended that more of this work will be published, either individually or collectively, once the balance is assembled and operational.

2. GUIDING PRINCIPLES

The most important principle, guiding the whole design, is simplicity. All Kibble balances are complex machines but, by keeping many component parts simple and independent, the number of unwanted interactions arising as the machine is assembled can be minimised, allowing relatively straightforward validation of all parts of the apparatus [5]. This form of simplicity comes at a price and requires almost all the critical electronics to be custom-made. Symmetry is also a key part of the design: the magnet is highly symmetrical and the working mass is spherical. The mass is placed symmetrically between the magnets in both a magnetic and a gravitational null to minimise the corrections associated with unbalanced effects. The gravitational null simplifies the correction of gravimeter data to give the appropriate value of the free fall acceleration g at the centre of the mass.

Another principle guiding the architecture is the need for independence between copies of the balance. If such copies are statistically independent the uncertainty of a mass scale derived from an average of the results from an ensemble of n such copies, each with uncertainty u, will be $\sim u/\sqrt{n}$, limited by the amount of correlation between the residual type B uncertainties in the balances. For the electronic system the precautions described above can minimise such correlations. It is more difficult for the mechanics but, as the expected variations in mechanical tolerances will be about 0.01 %, it is a good indication that type B uncertainties are under control, if the balance can be dismantled, reassembled and necessary alignments made, with no significant shift in measurement results. Under these circumstances the measurement results from a particular balance may exhibit a small, but stable, offset from the “correct” result. Such offsets should be randomly distributed between balances, allowing the average results from an ensemble to behave as described above. Such an ensemble and the ensemble average, as embodied in one or more transfer masses, could be used to assist the discovery and elimination of small type B uncertainties, further improving the ensemble.

3. INITIAL DEVELOPMENT

Many of the principles guiding the construction of the balance were developed for the NPL Mk II Kibble balance [6] and its electronics have been updated for the “Next Generation” balance. This work is now in its final stages. The COVID-19 pandemic prevented much prototyping work but work on software and the design of both the magnet and the balance mechanics progressed. A simple CAD model, originally intended for 3D printing was extended to that shown in Figure 2. It included a workable load lock, mass lift/exchanger and mass storage system. After the pandemic the majority of the design was transformed into the manufacturable design shown in Figure 1. To keep the balance as simple as possible it is made with close tolerances and few adjustments. If initial tests on the balance determine that a particular adjustment is absolutely necessary, it can be incorporated into the design.

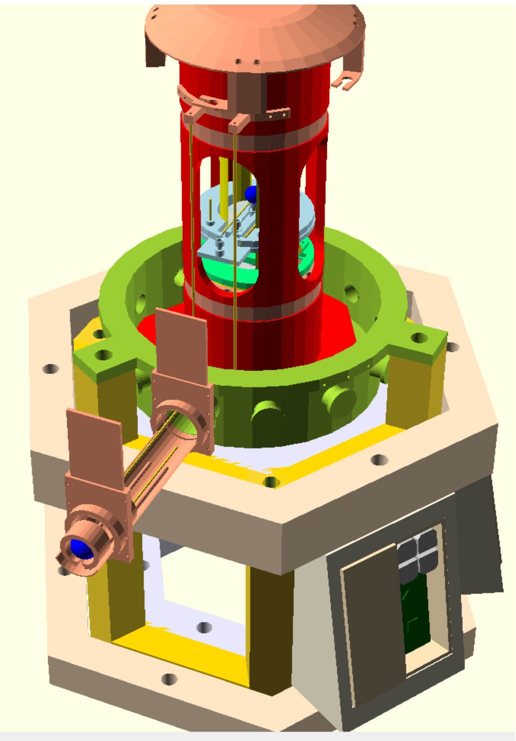

Figure 2: Initial CAD drawing showing the service well (green), support frame and magnets (red) interferometer (light green), the mass exchanger (light blue), electronics enclosures (grey) and the mass loading and storage system (salmon pink)

4. MECHANICAL ARCHITECTURE

4.1. Vacuum System and Support Structure

Operation of the apparatus in vacuum eliminates the corrections for the effects of air buoyancy on the mass and air refractive index on the laser wavelength. It also removes the effects of air currents and airborne vibration on the balance noise. This choice simplifies the measurement whilst increasing the complexity of the balance overall. The balance is placed in a two-part vacuum chamber. The service well provides electrical and optical feed through connections and a port is available for the future introduction of a mass loading/exchange system. The upper part can either be a glass or stainless-steel dome.

The balance is supported by the service well using a simple kinematic mount; however this may produce problems from vibrations arising from acoustic noise acting on the chamber. The design allows the balance to be supported using legs bolted to the floor. Vacuum bellows can then be used to isolate the balance from the chamber vibrations.

The pumping system consists of a turbo pump connected to the service well using a vibration isolator. Both the turbo pump and its backing pump have been chosen for their low vibration characteristics.

The support frame also houses six temperature-controlled enclosures, shown in blue in Figure 1, containing most of the electronic instrumentation for the balance.

4.2. Balance Components

Outer frame: The outer frame of the balance supports the magnets, the interferometer and the mass lift. It needs to be mechanically stiff, to prevent mechanical resonances disturbing the functioning of the balance control servos but needs to allow access to the moving frame. Simulation of the present design predicts an acceptable first resonant frequency above 80 Hz.

Guidance mechanism: The mechanism which guides the motion of the moving frame is a critical part of the design. It must supress motion in all but the vertical direction and must have a low spring constant in the vertical to provide sufficient weighing resolution when using the interferometer as a position detector. It must not be sensitive to the mass being either on or off the mass pan and should not exhibit any form of hysteretic behaviour.

Two very different flexure-based mechanisms have been designed. One is based on a disk flexure which has the advantage of simplicity, but the disadvantage that this requires extreme stability of the whole tare system as the weight of the inner frame must be supported by a force generated by a current flowing in the tare coil. This would dissipate several watts in the coil which would heat the tare magnet. The second mechanism is a parallel motion linkage which contains several small flexure hinges. This has the advantage that it can include masses to balance the weight of the inner frame but may suffer from hysteretic effects. The balance has been designed to accommodate both forms of guidance which will be investigated as part of the commissioning process.

Inner frame: The movement of the frame is guided by the upper and lower guidance mechanisms. It is made as light as possible and contains the mass pan, a retroreflector for the laser interferometer and mounts for autocollimator and position sensor reflectors.

Magnets: The balance is intended to be easy to assemble and disassemble. This precluded closed magnetic circuit designs. A symmetrical design like that of the magnet used in the NPL Mk II balance [7] was adopted as it offers many advantages in reducing unwanted variations in the parameters of the coil as it moves vertically in the gap. The magnet poles are made from a 50 % iron and 50 % nickel alloy which exhibits a very high permeability.

A disk of gadolinium/samarium/cobalt (GdSmCo) magnetic material is placed between the upper and lower inner poles. The material displays a very low temperature coefficient of remanence of 11 ppm$\cdot$K^{-1}. To enhance the temperature stability of the magnetic material it is shielded from heat flow from both the environment and the coils. The temperature of this material is measured via a hole in the centre of one pole. This measurement allows millikelvin-level temperature control of the magnetic material via a nested servo which adjusts the temperature of the magnet baseplate. This should provide a magnetic field stability at the part in 10^8 level. The compromise that has been made to achieve this stability is a reduced radial flux density of 0.2 T.

Working masses, mass lift and mass pan: The working masses for the balance are spherical, to ensure accurate, consistent, positioning. The balance is designed to accommodate masses of differing densities in the range from 100 g to 250 g. This allows a build up from 200 g or 250 g to 1 kg, using a conventional mass comparator, with little increase in uncertainty. The mass lift provides three hard domed support rods which are raised and lowered by a simple vertical slide mechanism using a piezoelectric motor and a linear potentiometer for position feedback. This provides precise control of the position of the mass and avoids the generation of excessive heat near a sensitive part of the apparatus. The mass pan consists of three hardened rods connected to the inner frame forming a triangular support for the mass close to the centre of the apparatus.

Coil assemblies: Both tare and main coil assemblies are wound on PEEK formers. Each consists of two coils spaced apart so that they are centred in the two pole gaps of the magnet. These coils are connected in series opposition which makes the unmounted assembly insensitive to external fields but, due to the opposing signs of the magnetic fields in their respective pole gaps their contributions to force or voltage generation add. The tare coil assembly is wound with a single conductor to maximise the copper in the coil volume which minimises the heat generated in the coil. The main coil assembly is wound with a bifilar winding which provides the two measurement coils. Each coil assembly mounts onto the moving part of the guidance mechanism.

Choice of BL product: The product of magnetic flux density B and coil length L (BL product) of the coil and magnet was chosen to be 150 T·m to keep the maximum voltage across the 100 Ω main resistor R within the range of a 1 V Josephson Junction array. The voltage across R when weighing a mass m (weight mg) of 250 g, offset by a 125 g tare, is $mgR/2BL$ = 0.8 V. The power dissipated in the coil and the main resistor remains small to avoid heating of the magnet and excessive power corrections to the value of the resistor. The coil voltage, when the inner frame is moving at u = 1 mm·s^{-1}, is BLu = 150 mV which can be measured reasonably easily. In the future, once the uncertainties of the first balance have been assessed, it would be possible to investigate increasing the BL product. A factor of two increase would allow 500 g to be measured and a factor of four would increase that to 1 kg. It would also increase the voltage measured in the moving phase by factors of two and four respectively. However, the coil resistance and inductance would increase significantly, which will have a detrimental effect on the performance of the balance, so it is not certain that such changes would provide a significant advantage.

Interferometer: The homodyne interferometer is fed from an external stabilised laser using a vacuum compatible polarisation maintaining fibre. It uses a cube beam splitter which incorporates a Downs-Raine beam splitter coating [8] producing offset sine and cosine signals from the optical detectors. To eliminate possible systematic errors in the velocity measurement caused by electrical crosstalk, two sets of detectors are employed, as in the MK II balance: one set supplies the signals to operate the position and velocity control system [6], the other set provides the input for the frequency measurement.

Laser vertical: The interferometer incorporates a mechanism for the determination of the verticality of the interferometer laser beam. A motorised slide allows a retroreflector or a liquid pool to be placed in the beam path. The angles of the reflected beam are measured. The orientation of the interferometer is adjusted by two piezoelectric motors to align the laser beam to the vertical by bringing the two pairs of measured angles into agreement. The adjustment needs to be made to about 30 µrad. The choice of material for the mirror is not straightforward. A liquid metal would be ideal as it forms a first surface mirror but needs to be safe and stable. A seemingly good choice - gallium - has problems with surface oxides. Vacuum oil is a possibility but its low reflectivity and the chance of spurious returns from transmitted light make it less attractive. We are collaborating with RISE on the choice of this material.

5. ELECTRICAL INSTRUMENTS

Temperature controller: The NPL Mk II Kibble balance used the laboratory air conditioning for precise (4 mK) temperature control [6] but this is impractical for a balance that is intended for operation in many countries. Parts of the balance would benefit from this level of control, requiring direct acting temperature control systems. In collaboration with NMISA we have developed a relatively simple, low-cost, temperature controller using a Raspberry Pi computer and a modified commercial temperature measuring unit. Four of these devices are employed to control: the temperature of the two magnets, the electronics enclosures and the main measurement resistor. The devices operate autonomously but are connected to the experiment control computer via a local Ethernet to allow parameters to be set and log files transferred.

Electronics enclosures: To make the system compact and easy to maintain most of the electronics are placed near to the balance in six enclosures fixed around the base. This allows most cables to be kept short enhancing the effectiveness of shielding and minimising: resistance, capacitance, inductance and thermal EMFs. This also reduces the number of cables required to link the balance to the rest of the apparatus. The enclosures can provide double shielding [5] for critical electronics and will be temperature controlled using circulated air. Maintenance is simplified by hinging the enclosures along their top edge allowing them to be raised to the horizontal for easy access.

A temperature control unit incorporating a fan, filters and a heater circulates air through pairs of enclosures connected in series. One of these enclosures will have the temperature of its inner metallic shield controlled at the millikelvin level by adjusting the temperature of the circulated air. The enclosures lose heat evenly to the surrounding air avoiding "hot spots" in the vicinity of the balance.

Power supply: To avoid line frequency magnetic fields near to the balance all the nearby electrical circuits are dc powered. To avoid low frequency magnetic fields, arising from currents flowing in the power cabling, power is distributed using shielded twisted pair cables. The loop areas of other circuits, near the balance, such as the magnet heaters, will be minimised for the same reason.

Critical electronics: To ensure that the system remains simple the critical electronic subsystems of the balance must be electrically isolated both from one another and from the controlling computer. This is achieved using the optical-fibre-ring data bus [9] and a commercial dc power source which uses techniques derived from [5]. This eliminates unexpected and unwanted interactions between the instruments and other parts of the apparatus simplifying the overall operation of the balance. The optical fibre data bus also provides a way of testing and minimising interference generated by the digital parts of the critical measurement circuits [9].

Support electronics: Other parts of the electronics, such as temperature controllers, barometers and piezoelectric motor controllers do not need such stringent isolation and use conventional dc power supplies, along with USB and Ethernet connections.

Voltage reference: The system requires a programmable Josephson junction array as a voltage reference. The bias source for the array is the same as that described in [10] allowing the array to be programmed identically to a simple DAC. The bias source can be used for daily tests to optimise the segment currents of the array, measure the effective resistance of the array segments and compare all the segment voltages by activating them sequentially in opposition.

Main resistor: The ideal resistor for sensing the current in the weighing phase would be a Quantum Hall Resistance (QHR) array as it operates as an ideal resistor linking directly to the Planck constant and the elementary charge. But it is not readily available everywhere. In the absence of such a resistor the balance has been designed to operate with a very high quality, extremely stable, 100 Ω resistor. The resistor will require regular calibration and its value must not be affected by transport to and from the QHR-based measurement system. A portable, battery-powered, temperature-controlled enclosure has been built to allow this to be achieved.

Voltmeter: Two voltages need to be measured: that across the main resistor in the weighing phase and that across the open coil in the moving phase. These voltages are in the range 0.1 V to 0.8 V and need to be measured with a resolution and accuracy at the nanovolt level or below. The Josephson Junction array provides the underlying accuracy by opposing almost all the voltage to be measured, requiring the measurement of the remaining few hundred microvolts to 1 ppm uncertainty. In the weighing phase the timing of the voltage measurements is not critical but, in the moving phase, the voltage and velocity must be averaged over the same period to enable the elimination of noise, arising from ground vibration, which is correlated between the two signals. This requires that the voltmeter input bandwidth be higher than normally encountered in most nanovoltmeters. This problem was addressed in [6] by the construction of a composite pre-amplifier with the necessary characteristics of nanovolt-level noise and stability and kilohertz bandwidth. An improved version of this amplifier is being built which will feed a custom-built charge balance voltmeter which integrates its input continuously and provides integrals of the input voltage between optical triggers from the fringe frequency counter.

Nanovolt switching: The apparatus requires an automated switching system, with at least nanovolt-level stability, to carry out its measurement tasks. The entire switching circuit will be updated from that described in [6] to use a copper-clad aluminium circuit board. The nanovolt-level circuits will be opened and closed using gold wires mounted on small circuit boards driven by latching solenoids.

All these circuits will be temperature controlled to stabilise residual thermal EMFs. The Josephson array voltage is set to keep the input to the voltmeter within its linear range using data from the servo systems. This avoids saturating the sensitive preamplifier which may affect its offset. The inevitable small switching transients and thermal EMFs will be given time to settle.

Counter: The velocity is derived from the interferometer output frequency. To suppress any effects from intensity changes of the laser, the offset sine and cosine electrical outputs of the interferometer are subtracted, and then fed to a comparator to provide clean transition signals to the counter. The apparatus uses a Carmel Instruments BI221 counter modified, by the manufacturers, for connection to the optical fibre ring [9], to provide electrical isolation. The counter provides continuous back-to-back measurements of transitions on its input and provides an optical trigger pulse to both the voltmeter and position measurement system [6] whenever it samples the time of a particular transition for frequency measurement.

6. DIGITAL PROCESSING

The computing system must provide real-time digital control of the balance facilitating the reconfigurable digital servos which are required during all the phases of its operation. The system must be reliable, maintainable, real-time, open, simple, small, flexible and powerful but does not need to be particularly fast. To meet these needs a specialised type of computer has been built, using a single board computer with a PC-104 bus to restore the original interface mechanism for the optical fibre ring data bus [9]. It is, once again, part of the I/O bus of the computer ensuring that read/write operations are atomic and execute within 5 µs. This simplifies mixed real-time and user space access to the ring and makes hardware access easy to understand, use and validate.

To meet the needs for reliable open and maintainable operation the balance software runs under Centos 7 Linux with CERN real time extensions. Most of the experiment is controlled using the custom programming language: Nessus-2, which is based on Postscript, a Forth-like language, which is compact and has a very small, extremely regular, syntax. The language is implemented as a multi-tasking interpreter with a shared dictionary of commands and variables. It is written in the compiled language Modula-2 with some C and C++. This system ran the NPL MK II balance, the whole system is small and works well. Although Modula-2 is an extremely good language for the construction of reliable, maintainable code its support has diminished. Despite this, open source Modula-2 compilers are still readily available and if, in the future, it is desired to translate it into another language, exhibiting both a good structure and high quality, Ada 2012 is an excellent candidate.

Although much of the required code already exists, robust code can be written and updated quickly. New facilities are coded as a set of Modula-2 routines and made permanently available as Nessus command words. This encourages rapid and complete testing. Complex tasks can be built from simple, tested, building blocks - all of which are always accessible. Commands can be added to the interpreter at any time without interrupting its operation. Key variables in the system can be output in real time as voltages at the interrupt period (currently 1 ms) and displayed on an oscilloscope encouraging comparison with external signals such as the voltage output from an external accelerometer.

To achieve the aim of complete separation of the calculation of results from their acquisition the apparatus will use external programs for all such calculations. The files used to transfer data will be written as simple ASCII text and will have a common style. The precise format of each type of file is controlled to allow all the files to be read and analysed using a broad range of software.

7. SUMMARY

The first balance of this type is being manufactured and will guide the production of further balances. Further details of the status of the balance will be presented at the conference.

8. ACKNOWLEDGEMENT

This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the UK's National Measurement System programmes.

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