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General Considerations for building a Kibble Balance

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Introduction

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This is a big subject

I will look back at the development of the balance and the uses to which it has been put to help understand its future development.

I aim to cover most of the forms of balance and then home in on NMI balances as they are the most relevant to this community.

I will try not to be prescriptive but I will make my preferences clear and give the reasons for them.

However I must emphasise that many perfectly operational balances have been built by not following any of the routes that I prefer.

History: pre 1990

Bryan Kibble developed the first Kibble balance to meet a pressing need: he did not want to work on the Current Balance!

So the first Kibble balance was aimed at replacing the current balance to unify the measurement of voltage across the world.

Bryan had many contacts at NIST, including Dr Ed Williams, and they also started building a balance.

The Kibble balance played a major role in unifying voltage measurement allowing the CCE to fix a conventional value of the Josephson constant $K_{J\text{-}90}$ in 1990.

It can be seen that the first balances were aimed at scientific and metrological progress.

History: 1990 -2019

The second generation of balances aimed to lay the groundwork for the redefinition of the kilogram, by linking mass to a fundamental constant: the Planck constant *h*.

This was enabled by the discovery of the Quantum Hall Effect which allowed electrical power to be measured in terms of the Planck constant and time.

Once again this meant that the balances were aimed at scientific/metrological progress although with a much more difficult target of at least 2 parts in 10^8.

The advantage was that many more laboratories were joining in with the work and this effort led to the redefinition of the kilogram in 2019.

The future: post 2019 (1)

Once the redefinition had taken place the emphasis changed.

The balances that measured the Planck constant now work to provide the world with a stable mass scale and that is now the task of future balances operating at NMI level.

This means that Kibble balances are becoming routine measurement instruments.

Kibble balances can now be split into two classes:

- NMI level instruments
- Industrial level instruments

The future: post 2019 (2)

NMI level instruments work at the lowest uncertainties. They are still extremely difficult to build and operate, they require access to gravimeters and quantum standards and are extremely costly.

Industrial level instruments are aimed at measuring mass, force or torque, using conventional electronics with emphasis on ease of use and low cost, both to build and operate.

I do not have time to talk about Kibble balance based force and torque measurements. But they are being made, for example, in the US, Japan and Germany.

Usage

For most mass metrology, conventional mass standards will continue to be used. Conventional masses are stable, low-cost and easy to understand and use.

Mass comparators will continue to be used to compare mass standards as they too are relatively simple to operate and do not require expensive support equipment.

NMI level Kibble balances will be needed to realise mass from its definition and maintain the world's mass scale.

They will also support very low uncertainty measurements of masses well away from the values of 100 g, 200 g, 500 g and 1000 g. This is perhaps a niche application but should not be forgotten.

Ensemble operation and Independence

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The world is moving to the point where Kibble balances will be authorised to make independent determinations of SI mass.

This is important for local measurements but there are gains, both in uncertainty and reliability, to be made from operating balances in an ensemble.

If the balances can be shown to be statistically independent the uncertainty of their average, embodied in a stable transfer mass, will be lower than that of any single balance.

The balances should be constructed and programmed to encourage investigations into their correct operation to underpin the assertion of independence from other balances in the ensemble.

Construction

As we are no longer in a pure research phase it is unlikely that funding for research on a particular balance will increase.

This may make it difficult to retain good researchers.

However the complexity of a Kibble balance demands a good understanding of its operation.

In this situation it is important that balances are constructed to be open, reliable and as simple as possible within the limits of correct operation.

There needs to be good support available to detect and diagnose problems.

Simplicity and Symmetry

I feel that it is important to keep the balance and its support systems as simple as possible.

This can reduce workload as if there is only one instrument doing a particular job only one calibration is necessary.

It makes it easier to analyse problems as there are fewer places for them to hide.

There is a limit to simplification as sometimes a more complex solution will give advantages in the elimination of an error mechanism.

Sometimes it is possible to take advantage of symmetry in the design of a Kibble balance. For example the mass can be placed in a gravitational and magnetic null between two magnets placed symmetrically above and below it.

Isolation and Shielding

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The Kibble balance depends on the accuracy of its electrical measurements but it is a complex electro-mechanical instrument.

To ensure that the balance functions correctly, it is necessary to eliminate unwanted electrical interactions between each electrical part of the balance, the environment, all the other parts and the controlling computer.

This requires high quality dc and ac isolation of each part using appropriate shielding and a power supply which blocks both dc and ac leakage from the mains.

The computer interface should be fully electrically isolated and the environment should generate very low level ac magnetic fields.

Software

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The software of the balance is often overlooked.

Again simplicity is the key. Ideally the controlling software should be small and fully understandable, allowing any high level action to be traced to the lowest level in the computer.

The software for acquiring the data should not used to process it. A defined textual interface should be used. This allows testing of the analysis code and inspection of the textual data to look for problems.

The balance often runs for days at a time. The ability to interact with it and check, or correct, its operation at any time is very valuable.

It is an advantage if the software and hardware is published using free or open source licences so there are no hidden parts.

Research

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Whilst we are moving into a time when there may be less research on the NMI level balances, because funding may be reduced and many parts of the balance will have been optimized, however there are still reasons to perform research:

- **To maintain expertise on the balance and its operation.**
- It is very hard to maintain a high level of expertise without interesting research.
- **To improve the analysis of the data.**
- AI techniques could be applied to the large amounts of data generated by a Kibble balance and that may lead to improvements in the operation of the balance.
- **To research into better conventional voltage sources and other techniques which have applications outside the Kibble balance.**

Industrial Balances

Kibble balances which have uncertainties above 50 ppm would be relatively easy to manufacture at low cost, using conventional references.

These would operate with very small masses where the uncertainties or difficulties associated with conventional mass metrology make their construction and use attractive. MEMS techniques and electrostatic operating methods can be applied in this area.

It is possible to make industrial balances with uncertainties between 50 ppm and those of NMI level balances. NIST, PTB and the Technical University of Ilmenau have worked successfully in this area.

It is always necessary to consider that a conventional mass can be a good, and cheap, competitor to a Kibble balance in the industrial space.

NMI level balances

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These are balances intended for the realization of mass in the 100 g to 1000 g range aiming for uncertainties of 2 parts in 10^8 or better.

At present conventional mass comparators can relate those standards of lower mass to the kilogram with little affect on the overall uncertainty.

NMI level balances are difficult to make, requiring extreme care to ensure that all the components of uncertainty are accounted for.

They require access to Quantum Hall and Josephson standards along with an absolute measurement of free fall acceleration.

The remainder of this talk will be concerned with an overview of NMI level balance techniques. The details will be given in other talks today.

Primary input/measured quantities

$$M = V_m\, V_w / (R\, g\, u)$$

Mass M is now measured by the apparatus in terms of its definition

Velocity u is measured from the frequency produced by the interferometer measuring the position of the mass carrier and the known wavelength of the laser.

The free fall acceleration g is measured by an absolute gravimeter using the same techniques as the velocity measurement.

Voltages V_m and V_w are measured in terms of frequency, h and e using a Josephson Array.

Resistance R is measured in terms of h and e using a Quantum Hall Effect resistance standard.

Big or Small

Kibble balances have traditionally come in a range of sizes from multi storey machines to machines occupying much less than a cubic metre.

Larger balances often have larger magnets and can measure masses of 1 - 2 kg. Smaller balances are often optimized for smaller masses.

Larger balances use more material, can be more costly and require larger vacuum pumps and lifting equipment. But they can have advantages in ease of both access and modification.

The size of the balance should be considered along with other aspects of the balance, as a poor choice can make the balance difficult to access and modify, slowing down the development work.

Kibble Robinson Theory (KRT)

KRT extends the original theory of the Kibble balance and shows that a balance, which uses the same mechanism for weighing and moving, is immune to a number of coil alignment/motion errors.

This will be explained in more detail in a later talk

It influences the choice of how to build Kibble balances.

Balances that do not conform to the needs of this theory work perfectly well but require alignment tests and adjustments to ensure that all the error terms, eliminated in a conformant balance, are small with respect to the target uncertainty.

Choice of weighing mechanism

There are four main choices of weighing mechanism: the mass comparator, the beam (or wheel) balance, the seismometer style balance or the pressure balance.

The mass comparator uses flexures for weighing and has an excellent sensitivity however it has a restricted movement range and it is difficult to adapt it to move as well as weigh. This usually dictates a separate moving mechanism and thus it cannot take advantage of KRT.

The remaining balances can take advantage of KRT but each has its own set of advantages and disadvantages as a weighing and moving mechanism.

Laboratory

Considerable thought should be given to the choice of laboratory.

- Minimal slowly varying magnetic fields (magnet dependent)
- Minimal ac magnetic fields
- Away from sources of vibration
- Very good temperature control
- Stable solid floor
- Low gravity gradients
- Good facilities for isolating noisy pumps and compressors.
- Lots of space

Vacuum or air

The presence of air affects the masses via air buoyancy and the laser wavelength via the refractive index of air.

It is possible to run in air but it requires extremely good measurements of the properties of the air in the apparatus.

One group (UME) in Turkey eliminates the refractive index effects using a local vacuum for the interferometer.

Most groups choose to eliminate these problems by operating the whole balance in vacuum.

This has an added advantage of eliminating the noise caused by air convection over the surface of the balance.

Magnets

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The coil needs to be suspended in a relatively strong magnetic field.

Originally NIST used the field generated by a current in several superconducting coils but this made the balance very big and required considerable amounts of liquid helium. All other balances use permanent magnets to generate the field.

The BIPM style magnet is popular. It is a closed design and has to be split to introduce or remove the coil. It has the considerable advantage that it shields the coil from external magnetic fields.

Another design is the NPL design which uses two coils in a symmetrical manner in opposing fields. The design is open which allows easy introduction of the coil but it is sensitive to external fields.

Moving coil or moving magnet

Many balances use the original form of a moving coil with a fixed magnet.

A number of balances use a moving magnet. This has a number of advantages:

- It is relatively easy to move the magnet in a controlled manner.
- Makes it easy to use a mass comparator for weighing.

But it has disadvantages:

- Cannot take advantage of KRT
- Must ensure that external magnetic fields do not affect the internal magnetic field.

Position and velocity

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All Kibble balances use calibrated interferometers for measuring position and velocity.

There is a choice between heterodyne and homodyne interferometer.

Some balances use more than one interferometer to allow angles to be measured as well as vertical position. This can allow imperfections in the coil motion to be corrected.

The velocity measurement must be made along the gravitational vertical so the beam(s) must be adjusted to be vertical.

Voltage measurement

The balance needs to measure both the coil voltage and the resistor voltage with an uncertainty approaching 1 part in 10^9.

This can be done directly by a voltmeter which is calibrated frequently against a Josephson junction reference, or by opposing the majority of the voltage to be measured with the Josephson reference and measuring the difference with a voltmeter or nanovoltmeter.

Moving measurements require special treatment as, to eliminate vibrational noise from the measurement, the frequency and voltage measurements need to be synchronized.

Weighing measurements are not so critical.

Weighing Resistor

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The weighing current is measured by passing it through a stable resistor and measuring the resulting voltage.

The resistor can either be a conventional resistor or a Quantum Hall Array. A Quantum Hall Array is the best choice but is expensive to obtain, requires cryogenic cooling and generates a magnetic field.

A conventional resistor needs to be temperature controlled to maintain its stability.

If the resistor is carried to be calibrated the temperature control system needs to be portable and carefully designed so that the value of the resistor does not depend on details of its location, as this can lead to errors which are very hard to detect.

Conclusion

The design of a Kibble balance often requires sensible compromise.

For example: excellent low vibration environments can be found in many isolated areas of the world but we choose not to build balances there for many reasons both technical and human.

This means that we work in non ideal vibration environments, employ methods to reduce its influence and try hard not to generate more vibration from the pumps and compressors needed for the work.

I hope that this short introduction gives an idea of some of the choices that can be investigated to produce a balance which will meet the needs of its designers and operators.

Remember: simplicity and symmetry.

Thank you.

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