KBTM

Kibble Balance: Electrical Measurements

Ian A. Robinson, NPL

20 November 2025

Kibble Balance Technical Meeting
special session "knowledge transfer"
20 November 2025, BIPM

Introduction

This is a general talk on electrical measurements in the context of NMI level Kibble balances.

- **For industrial level kibble balances the problems are either:**
- Generally easier for uncertainties where the stability of conventional electrical standards allow long times between calibrations but particular measurement needs may require innovative solutions.
- Increasingly difficult as uncertainty requirements make it difficult to find sufficiently stable conventional standards at a cost that meets industrial needs.
- **I will try to cover some of the techniques that are common to most balances and also, in some cases describe what I do and why I do it.**

Weighing 1

In a conventional Kibble balance, we balance the weight *Mg* of a mass *M* against the force generated by a current *I* flowing in a coil of length *L* in a magnetic flux density *B* giving $Mg = BLI$

The current is measured by passing it through a resistor *R* and measuring the voltage *V*.

In a high precision measurement, we use a four terminal resistor to avoid errors due to lead resistance.

We also arrange to make an M/2 tare offset to the balance so that the mass is measured as the difference between equal and opposite currents –I/2 and +I/2 when the mass is removed or added to the balance.

Weighing 2

This has two main advantages the power $R\,I^2/4$, dissipated in the resistor, is constant and the linear part of the effect of the current on the magnetic flux density B is eliminated.

In some balances the weighing current is adjusted by a servo system to keep the balance at a designated position. In others the current is kept constant and force differences are monitored by a mass comparator.

An NMI level balance needs to be able to resolve changes in the weight of the mass to a few parts in 10^9. This requires a low noise current source, precise, low bandwidth, voltage measurement and a stable resistor.

The servo system must be carefully designed to minimize the effects of balance drift and external vibration.

Weighing 3

Some advantages can be obtained by adopting a variant of the approach originally suggested by BIPM. This employs two separate coils derived from a twisted pair or bifilar winding. This allows one coil to carry the weighing current whilst the other can be used for the moving measurement.

Electrically this has a number of advantages:

The weighing current flows in the resistor at all times stabilizing its temperature.

Measurements of *BL* can be made with the mass up or the mass down and no assumptions need to be made about the effect of the current on the magnetic flux density *B*.

Moving 1

BIPM

In the moving part of the experiment the coil is moved up and down with a measured velocity *U* and the voltage generated, $V = BLU$, is measured.

In a conventional balance this is done with the weighing current removed and the measured *BL* product is applied to weighings both with mass up and mass down.

In a 2-coil balance the appropriate measurement of *BL* is applied to the appropriate weighing measurement, easing the need for accurate tare mass setting to obtain equal and opposite currents for mass up/down.

Ground vibration causes significant noise in both the velocity and the voltage signals. However, the noise is correlated, and, with care, the correlation can be used to reduce the noise in the measurement result.

Moving 2

The need to ensure that the correlation in the velocity and voltage measurements can be exploited requires that the bandwidth of both measurement channels is greater than that of the significant vibrational noise signals and that the signals are measured at the same time.

This is relatively easy for the velocity measurement but is more difficult for the voltage measurement.

The voltage measurement usually requires nV level measurements and most nanovoltmeters do not have a high bandwidth.

This problem does not exist in the joule balance as the corresponding measurements are taken with the balance halted.

Numbers

To put some values on this:

Consider a balance intended to weigh 0.5 kg with a BL product of 500 Tm

This corresponds to a current change of 10 mA which if measured using a 100 ohm resistor would give a voltage change of 1 V.

For a measurement resolution of 1 part in 10^9 this voltage needs to be measured to 1 nV. As vibrational noise is present the measurement has to be made over an extended period.

If the coil moves at 1 mm/s it generates a voltage difference, between up and down motion, of 1 V but, if there is vibration of 0.001 mm/s, there will be around 1 mV of noise on the measurement. But the resolution is still required to be 1 nV. Achieving this requires careful use of correlation.

Electrical Isolation and noise

The aim of the electrical measurements is to achieve uncertainties approaching 1 nV/V.

To do this it advisable to ensure that the instrumentation not only has a low measurement noise but also is not susceptible to external interference and generates little electrical noise and interference.

This can be achieved by:

- Proper isolation and shielding: both power and data.
- Keeping mains power sources away from sensitive parts of the balance – use dc power distribution.
- Checking for ac fields in the laboratory

Voltmeter: Main Voltmeter

BIPM

The main voltmeter usually measures voltages in the weighing and moving phases of the measurement. It is usually an integrating voltmeter as this generally gives a good noise performance.

I will discuss two forms of integrating voltmeter:

- The multi-slope integrating voltmeter e.g the Keysight 3458A
- Charge Balance voltmeters e.g the Thaler ADC 180.

Voltmeter: Multi Slope

These voltmeters work by using a capacitor to integrate a current proportional to the input voltage for a fixed time and then reducing the integral to zero using a series of fixed currents for measured times.

These voltmeters are very versatile, highly linear and have good noise characteristics.

But the voltmeter is only sensitive to its input during the integration time which wastes measurement time.

To avoid this either two or three voltmeters are used in sequence to maintain continuous measurement.

Voltmeter: Charge Balance

This form of voltmeter integrates its input continuously. A reference voltage is switched on and off for timed periods to keep the integrator switching rapidly between two fixed levels. The voltmeter can be read whenever the integral reaches a particular one of the two levels.

This form of voltmeter has a high resolution and is reasonably linear. It is not easily available but is far simpler than the multi slope approach. It has a disadvantage that its response to a trigger can be delayed by around 200 µs.

Voltmeter: Triggering

In the moving measurement it is important to take the velocity and voltage measurements over the same period.

This means that either the voltmeter must trigger the counter or vice versa.

The multi slope voltmeter usually triggers the counter at the start and finish of its integration period.

For the charge balance voltmeter a trigger signal is generated by the counter at each edge of its gate. This causes the voltmeter to store the state of its counters at the next available time, usually within 200 µs of the trigger. This allows the average voltage over a time which is close to the counter gate time to be calculated.

Voltmeter: Voltage Reference

For measurements with very low uncertainties it is necessary to employ a voltage reference which uses the Josephson effect

This produces a voltage that depends only on *h*, *e*, a chosen number *n* and the frequency of the microwaves used to illuminate an array of Josephson junctions kept a temperature close to 4 K.

As conventional voltmeters drift considerably it is possible to calibrate them against such a reference to maintain the desired accuracy.

Another approach is to use the reference to oppose most of the voltage to be measured this just leaves a small voltage which can be measured with a reduced relative uncertainty. This approach is often favoured.

Voltmeter: nanovolt Amplifiers

If most of the voltage to be measured has been opposed by a Josephson reference there is a considerable advantage to be gained by amplifying the resulting difference voltage before measurement.

A nanovolt amplifier can be used for this task but most such amplifiers have a limited bandwidth.

This is not a problem for weighing measurements, but for moving measurements the limited bandwidth can compromise the correlation between the velocity and the voltage measurements.

By a careful combination of a low bandwidth nanovolt amplifier and a conventional amplifier it is possible to produce a nanovolt amplifier with a suitable bandwidth and extremely low 1/f noise.

Voltmeter: signal switching

The signal paths in the balance need to be altered, under computer control, to select coils and select the input to the voltmeter.

This needs to be carried out without compromising the nV level measurement needs of the balance.

This requires automated switches that do not produce large varying thermal EMFs when they switch.

Ideally copper to copper contacts, if possible with a gold plating, should be employed to reduce varying thermal EMFs in the critical measurement system.

Shielded twisted-pair cables with silver-plated copper conductors can work well to connect the sensitive parts of the balance.

Weighing Measurement: Current Source

The source needs to be low noise and low drift.

The acceptable level of noise and drift is dependent on the application.

- **Tare source**
- Moving drive and flexure stiffness compensation
  - **Range small so generally ok**
- Tare offset
  - **Range large so needs care to ensure that drift can be eliminated in the data fitting**
- **Main source - used in a servo loop or as a fixed current**
- Needs low enough noise and stability to avoid compromising the measurement. The stability is more critical in a system employing a mass comparator, but in one employing a servo it must exhibit noise less than that caused by vibration.

Weighing Measurement: Resistor

The resistor converts the current passing through the coil into a voltage which is measured by the voltage measuring system.

In many balances the current through the coil and resistor is controlled by a servo system which keeps the position of the coil constant this will generate noise due to ground vibration .

The measurement noise appearing across the resistor is composed of the noise generated by the servo system, the noise of the current source and the noise of the resistor.

Most Kibble balances use conventional resistors but it is now possible to use a Quantum Hall Array to produce a suitable resistor for weighing measurements.

Weighing Measurement: Conventional resistor

Conventional resistors consist of a metallic resistance element arranged to minimize the imperfections which are always present.

- Temperature sensitivity
- Power sensitivity
- Long term drift and instability
- Humidity and pressure sensitivity
- Shock sensitivity

It is often required to control and measure the temperature of the resistor to ensure that it can be calibrated reliably so that the uncertainty of the overall result is not compromised.

Weighing Measurement: QHR array

The imperfections of conventional resistors can be eliminated using a QHR array.

These have none of the imperfections listed for conventional resistors.

However their use requires thought:

- It is necessary to ensure that the array is properly quantized.
- The array operates at cryogenic temperatures, often requiring cooling systems which generate vibration.
- They require relatively high magnetic fields to be generated in the cryostat.
- They are costly both to buy and operate.

Temperature Control

A number of parts of the apparatus may require precise temperature control:

- The magnet(s)
- The conventional resistor
- The electronics – current sources and voltage measurement system.

The resistor may require a portable temperature control system if it is to be carried between the Kibble balance laboratory and the QHR based measurement system.

Weighing Measurement: Servo

The servo system required for weighing depends on the mechanism associated with the addition and removal of the working mass.

Some balances use a physical stop to prevent excess movement of the balance as the mass is added or removed. Such balances should only need a simple Proportional, Integral, Derivative servo to maintain position while taking data.

Other balances use the servo to maintain position during addition and removal of the mass. During this process the servo needs to react rapidly to changes in force and is often made sensitive to acceleration. However, whilst taking data the servo needs to be similar to the one described above.

Weighing Measurement: Data collection

BIPM

During data collection the voltmeter will usually be set to take relatively long (1 s or more) averages of the resistor voltage.

The data which will usually be taken is:

- Data to allow the resistor voltage to be derived from the voltmeter measurement: Josephson array settings, preamplifier settings.
- Time of measurement to allow linking to gravity data e.g. Modified Julian Date (MJD)
- Position data
- Balance state: mass up/down, coil in use …

Moving Measurement: Servo

BIPM

The aim of the servo for the moving measurement is to maintain the coil at the desired velocity. This can be done by servoing directly to velocity or by servoing to a point moving at the desired velocity.

Often it is necessary to allow the servo to follow a particular movement profile to ensure that the balance is treated gently and no unwanted motions are set up by the acceleration or deceleration of the coil.

Moving Measurement: Measurement optimisation

If a nV amplifier is in use along with the programmable array it is possible to use velocity data from the servo to set the array to continuously null the voltage from the coil. This allows the preamplifier to remain connected between the coil and the array without it being overloaded. This avoids either the unwanted effects of overloading the amplifier or the switching transients that would otherwise have been needed to protect the amplifier from overload.

When measurements are about to be taken the array is set to a fixed voltage to avoid errors due to the unpredictable transient voltages generated while the voltage of the array is changing.

Moving Measurement: Data collection

During data collection the voltmeter will usually be set to take averages of the resistor voltage over periods from line period to 1 s.

The data which will usually be taken is:

- Data to allow the resistor voltage to be derived from the voltmeter measurement: Josephson array settings, preamplifier settings.
- Counter data corresponding to the present voltage measurement.
- Time of measurement to allow linking to the weighing data
- Position data for the start and end of each measurement
- Balance state: mass up/down, coil in use …

Conclusion

It is relatively difficult to get the absolute best out of the electrical systems required for the Kibble balance.

However it is possible to achieve extremely good results in many different ways and all of the Kibble balance groups have done this.

The nV level target for voltage measurements is achievable with care and attention to detail.

This is an area where all the problems have solutions. It is often just a matter of correct implementation and ensuring that all the interactions between the parts of the electrical measuring system are properly understood and controlled. This will give confidence that the system can, and will, produce low noise results with the desired uncertainty.

Thank you.

ian.robinson@npl.co.uk