Using a mobile Kibble balance as an educational tool

LF Mndebele, TG Mametja, AE Karsten, C Sonntag, M Sibisi

E-mail: lmndebele@nmisa.org

Abstract. In metrology, a Kibble balance is an instrument used by metrologists to realize the SI unit for mass. There are several physics principles used in the operation of this instrument – namely electromagnetism, classical mechanics, electrostatics, electricity, optics, materials science, and metrology. The basis of this investigation is on all these physics disciplines applied for the functionality of the Kibble balance. The National Metrology Institute of South Africa (NMISA) developed a miniature version of the Kibble balance with 3D printed mechanical parts, referred to as the Mobile Kibble Balance (MKB). This version serves the same purpose as a Kibble balance but has less accuracy and precision. Detailed, uncomplicated explanations for all the mechanisms involved in operating the MKB are given. This paper demonstrates the educational value of the MBK in teaching physics and promotes metrology in the community.

1. Introduction

The discussion begins with explaining what the Kibble balance is and how it functions.

Figure 1: NIST-4 (The United States of America Kibble Balance Model)

A Kibble balance (originally known as a Watt Balance) is an instrument used by metrologists to realize the kilogram with high accuracy. Like most balances, it needs a certain force to counter another force: Thus, an electromagnetic force induced in a current carrying coil emersed in a magnetic field is used to balance out the weight of a test mass. In this paper, the NMISA MKB is used to demonstrate the Kibble balance's core operation modes for better visualization and understanding. A discussion of the physics principles applied in the MKB and suggestions on how to integrate the instrument in modern education is also given.

2. NMISA's mobile Kibble balance and functionality

A mobile Kibble balance (MKB) serves the same purpose as a Kibble balance but is a much simplified and less precise version of it. The MKB is used to demonstrate how the actual Kibble balance realizes the kilogram or calibrates mass. In *figure 2,* the main components of an MKB system are depicted.

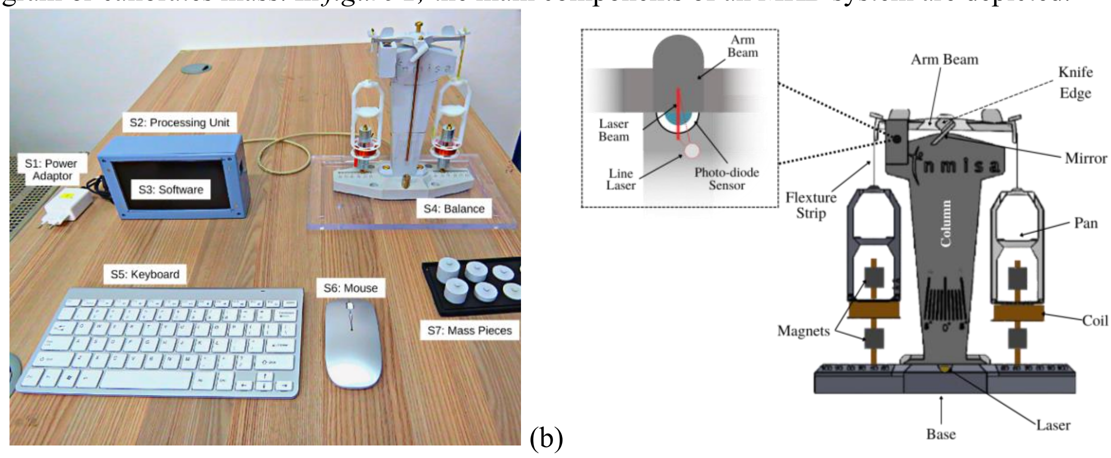
(a) (b)


Figure 2: (a) All components that make up the mobile Kibble balance system. (b) A labelled diagram of the balance.

There are two basic operation modes for the MKB – (1) weighing (or force) mode and (2) velocity (or calibration) mode. Before performing any measurements, a driver coil is chosen – this is the coil that will be supplied with current as needed per operation mode requirement. In the weighing mode, a test mass is placed on a pan attached to the coil with a current carrying wire emersed in a magnetic field (measurement coil). When energized, the measurement coil induces an electromagnetic force that counters the weight of the test mass. It would have been ideal to simply use $mg = IBL$ as a working equation, where I is the current needed to counter the test mass's weight, B is the magnetic field strength and L is the length of the wire. However, it is challenging to accurately obtain the B and L values during measurements.

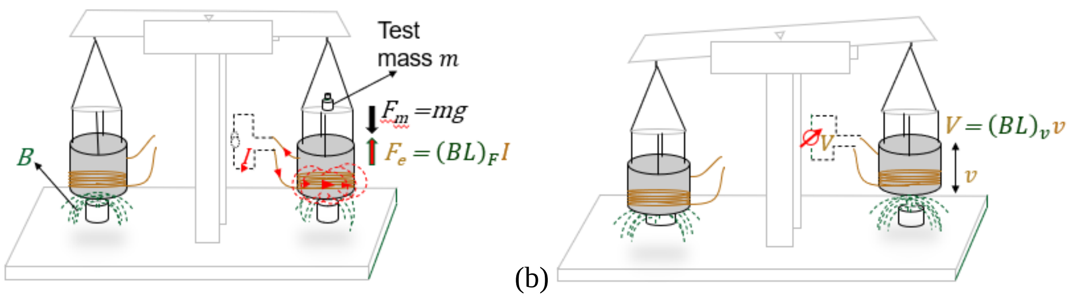
(a) (b)


Figure 3: (a) Illustrates the weighing mode of operation. (b) Illustrates the velocity mode of operation.

To take care of this we need the velocity mode. This is because it also has these quantities appearing in its working equation i.e., $V = vBL$ (from Faraday's law), where V is the induced voltage and v the speed of the coils. The velocity mode can be viewed as a second step in taking measurements with a mobile Kibble balance. Here, the driver coil is supplied with a sinusoidal signal that in turn makes the balance's coils alternate in a sinusoidal motion at constant speed v [2]. Voltage, V, is thus induced in the coils due to the change in magnetic flux as described by Faraday's law of induction [3].

In a final step the B and L are eliminated, using working equations obtained from the weighing and velocity mode i.e., $mg = IBL$ and $V = BLv$ to get $m \approx \frac{VI}{gv}$ where g is the earth's gravitational acceleration and m the mass of the test mass. The final approximation is only valid if one uses the same driver coil for the two modes [2]. Notice that this final expression is free of B and L as desired.

3. Physics Principles Applied in the Mobile Kibble Balance

This section is the meat of the investigation where the basic physics principles governing the operation of the MKB are clearly summarized (See the *appendix* at the end of this paper for a table summarizing the physics principles seen in the MKB's mechanical parts with their functions). These can then be used to teach or assess physics in an actual classroom.

Touching on classical mechanics, optics, magnetism, electrostatics, and metrology, this is an ideal 'toy' for a physics student. However, before recommending ways to integrate the MKB in a classroom, reasons why physics' teaching methods need to be improved are discussed.

4. Link to Education

With all the theorical implications above, it is now time to highlight reasons why including a MKB in a classroom would be effective and the specific areas in physics where improvements can be made. In a case study conducted by the University of Liverpool in 2003, the reason why fewer secondary students were interested in physics than in biology was investigated. This investigation involved 317 physics students from six comprehensive secondary schools in Liverpool [1].

The university used short questionnaires to collect data from the same sample of students. A closed-form item was used to ask if students found physics 'very interesting', 'boring' or 'neither interesting nor boring'. Next, in an open-form item, the students were required to substantiate their previous answer with any number of reasons. From that case study the specific areas in the discipline which the uninterested students expressed to be boring are evaluated [1]. *Disclaimer: we took interest in the following data (Tables 1 to 3) from a paper published by the University of Liverpool as cited in this section.*

4.1 Results from the case study

Table 1. A table with proportions of the students considering physics boring, interesting or neither

How students find physics	Males (%)	Females (%)	All (%)
Very interesting	8	4	6
Interesting	28	13	20
Neither interesting nor boring	26	25	26
Boring	20	29	25
Very boring	18	20	24

Table 2: A table with categories of reasons for why students find physics boring and the proportions

Category of reason	Percentage from sample (%)
Difficult/hard subject	48
Do not enjoy subject	30
Content of subject	20
Subject irrelevant	14
Subject too easy	11
Too little practical work	7
Subject repetitive/predictable	6

Table 3: A table with the specific content of physics found boring or interesting and their proportions

Specific content of physics found boring or interesting	Boring (%)	Interesting (%)
Mathematical aspects	15	12
Electricity	3	8
Energy	1	8
Forces	2	5
Solar system/universe	-	6
Circuits	-	4
Nuclear energy	-	3
Magnetism	-	3
Colour/spectrum	-	1

Note: Percentages may total more than 100% because individual students offered more than one reason and percentages may not total exactly 100% due to rounding. Total number of students who participated, n = 317.

4.2 Discussion of results from case study

As seen in *table 2*, about 49% of the 317 students found physics to be either boring or very boring. This alarming percentage alone would justify the need to improve the way in which teachers present physics in schools.

The University of Liverpool further investigated to see what the reasons were for students who found physics to be uninteresting. From the categories in *table 2,* one can see that the MKB has a chance in improving more than half of them; those being ‘Do not enjoy subject’, ‘Content of subject’, ‘Too little practical work’ and ‘Subject repetitive/predictable’.

These reasons only highlight the problems learners are facing in physics as a whole and not necessarily the concerns in specific areas of the study. Therefore, since physics is a multi-discipline field of study, the university then took the investigation a step further to get specific areas of physics that were uninteresting to students. According to *Table* 3, improvements by the MKB use can be made in ‘Forces’, ‘Magnetism’, ‘Color/Spectrum’ (Optics) and ‘Electricity’ (Electrostatics). If one considers these results and the summary from the *Physics Principles Applied in the MKB* section, it can be inferred that a substantial number of educational fields in physics can be touched upon by a single MKB instrument.

5. Prescriptions for integrating a MKB in modern education

This section discusses ways in which teachers can use the MKB in a modern classroom to enrich the physics learning experience. Analogous to having a human skeleton in a biology class or chemicals in a chemistry lab, an MKB can be a prominent teaching tool in a physics classroom. One of the key aspects of this tool is that it touches more than one area of the subject, thus making it multi-purpose in application.

5.1. Education levels recommended for MKB use

From the commencement of the study of physics it is important that students grasp its concepts properly. Hence it is recommended that the MKB gets integrated in a classroom from the first year of learning physics – grade 10 in South Africa. It can be used as an apparatus for experiments or a visualization aid for concepts to improve learning [4].

5.2. Possible experimental projects

As shown under the *Link to Education* section, the MKB has a great span over physics. One can only lack imagination when it comes to the physics projects that can be curated for students using the MKB. In this section, we suggest a few of these projects without imposing limitations to any other ones.

Proposed investigation	Description
Balancing forces (Classical mechanics)	In this project, students can explore the concept of weight using the balance and mass pieces. *Mass calibration (Application - Metrology);* Traditional calibration of mass (assigning mass values to mass pieces) can be an extra step for their investigation.
Current carrying coils (Electromagnetism)	The classic right-hand rule is a famous convention in physics, but truth be told it takes some imagination to visualize the result of what happens when we have a current-carrying conductor. This is where the MKB comes in. Electromagnetic force behavior can be studied using the coils of the balance. Balancing the electromagnetic force with a mass piece’s weight can be an addition to this project. Coil properties can also be investigated, such as the number of coils, wire thickness and wire material.
Magnetic field properties investigations (Magnetism)	Using the MKB’s magnets, students can study the properties of magnets and their of fields. This can be further visualized using the magnetic field lines sketches. The concepts of repulsion and attraction can also be seen.
Light reflection investigations (Optics)	**Warning: Lasers can lead to blindness; the right goggles must be worn as a safety precaution.** The MKB has lasers that can be used for optics observations like light reflection. The laser in the base (see *table 4, no. 7*) can also be used to study how light behaves in other media, for example light refraction.
Determining the experimental value of Planck constant (Application – Metrology)	As an application task, learners can work towards obtaining the Planck constant. The following may be the outline used when curating an investigation: From the weighing and velocity mode’s working equation ($mg = BLI$ and $V = BLv$ respectively). The Planck constant can then be approximated to be $$h = \frac{(BL)_w}{(BL)_v} h_{conv}$$ where $(BL)_w$ the value for (BL) from weighing mode, $(BL)_v$ the (BL) value from the velocity mode and h_{conv} is the conventional Planck constant i.e., $h_{conv} = 6{,}62607015 \times 10^{34}$Js, (Refer to *section 2* for description of symbols)

6. Conclusion

This paper has discussed the basic functions of the MKB and its potential for addressing the existing gaps in physics education. It was shown how using an MKB as a visualization tool or experiment apparatus can potentially facilitate the teaching and assessing of physics learners. The instrument is particularly advantageous because it explicitly handles multiple fields in physics which are relevant to school or undergraduate curricula. Lastly, since this is an instrument adapted from an actual instrument used in metrology (the Kibble balance), it does bring about awareness for metrology itself.

7. Investigation recommendations

There exists great potential for further study in this field. Additional research could include obtaining feedback from learners to assess the impact of the ideas proposed in this paper. A broader survey can be done to observe if the gaps found in the Liverpool case study apply to other school curricula in different regions. These are a few of many recommendations possible to scale up this investigation.

References

[1] Why aren't secondary students interested in physics?, *Department of Physics, University of Liverpool* **32**, 4 (2003); doi 0031-9120/040324

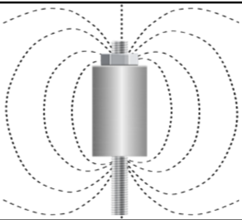
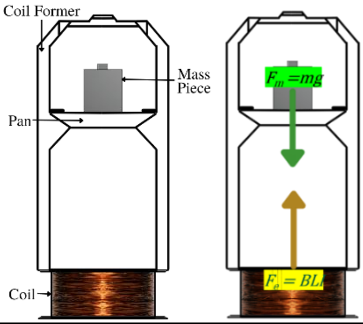
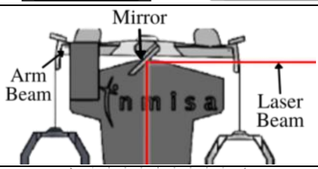
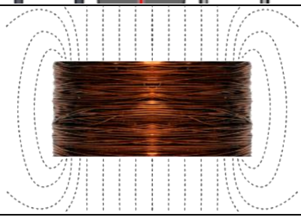
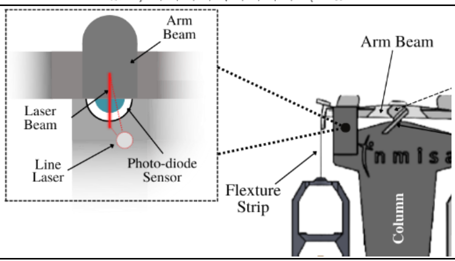
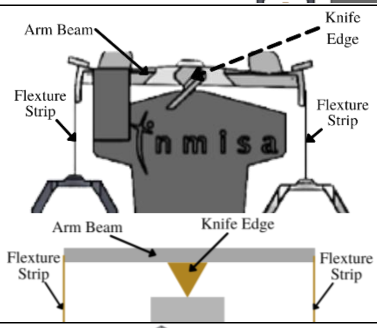
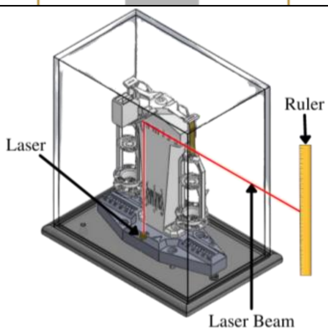
[2] A LEGO Watt balance: An apparatus to determine a mass based on the new SI, *American Journal of Physics* **83**, 913 (2015); doi 10.1119)/1.4929898

[3] Kinsler, Paul. Faraday's Law and Magnetic Induction: Cause and Effect, Experiment and Theory. *ResearchGate*. **2**. 148-161 (2020); doi 10.3390/physics2020009

[4] Shabiralyani, G., & Hasan, S. K. Impact of Visual Aids in Enhancing the Learning Process Case Research: District Dera Ghazi Khan. *Journal of Education and Practice*, 226-233 (2015).

Appendix

Table 4. A table summarizing the physics principles from the MKB mechanical parts with their functions

	Name	Part of the system	Function	Physics Principle
1.	Magnet		Provides magnet field to coils	Magnetism (Magnetic field)
2.	Coil former pans		Platform for mass pieces	Classical Mechanics (Forces)
3.	Mirror		Reflects laser light to measure ruler	Optics (Light reflection)
4.	Coil wires		Carry current and induce electric field	Electrostatics (Current carrying conductors)
5.	Line laser		System's equilibrium sensing	Optics (Light polarisation)
6.	Arm beam and knife edge		Designed for balance	Classical Mechanics (Forces)
7.	MKB		Mass calibration	Metrology (Physical Metrology)