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Automation of Demonstrational Model of 1 g Kibble Balance Using LabVIEW at CSIR-NPL

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A demonstrational model of Kibble balance has been designed and fabricated at CSIR-NPL. This paper details the software developed in LabVIEW that has been developed for its testing and operation. The software performs instrument control and automation, data acquisition and signal processing, real-time display of measurement status, and finally stores the measurement data for record and further analysis. The developed software provides a highly flexible platform for conducting the various functional tests with the experimental design of the balance. It has been successfully used to investigate the performance accuracy of the balance design by collecting data while operating it in both static and dynamic modes. The results helped pinpoint inherent design errors, both mechanical and electrical, that need to be eliminated for improving the weighing accuracy of the balance.

Keywords: Kibble balance; Kilogram redefinition; LabVIEW; Data acquisition; Automation

1 **Introduction**

In the new SI definition of the kilogram, the unit of mass is realized in terms of the Planck constant h, employing the Kibble balance[1-4]. The Kibble balance is a highly complex and sophisticated equipment. Developing such a system involves substantial investments, including financial, supporting infrastructure, and a very high level of scientific and technical expertise. The lack of necessary expertise and resources is a stumbling block for many National Metrology Institutes (NMI) worldwide to establish this facility. Due to this fact, only a very few NMIs have been able to implement the Kibble Balances in their countries[5-10]. An NMI needs the Kibble balance for making traceable measurements of mass standards with the lowest possible uncertainties. To cater to this need with the minimum, monetary and technical resources, one option is to develop the Kibble Balance suitable for masses well below 1 kg[11-14]. CSIR-National Physical Laboratory (CSIR-NPL), the NMI of India, is one such laboratory considering this option[15].

At CSIR-NPL, a demonstrational setup of a Kibble balance using readily available commercial components for a mass value of 1 g has been designed and fabricated. This work commenced keeping the focus on two main objectives. One was to create a setup that can suitably demonstrate the Kibble balance basic principle for academic purposes. The other was to use it as a test model to investigate specific electrical and mechanical design requirements necessary to develop a Kibble balance for masses in the range of 1 g to 10 g. The fabrication was carried out employing an indigenous design keeping the hardware configuration as simple as possible. While the design was completed by ensuring its correct functionality as a balance, verifying the balance performance accuracy was a matter that had to be done through actual measurements. Given this fact, the automation of the system was essential, and developing the necessary software programs was crucial. In the present work, LabVIEW was used to create all the required programs to automate the measurements and carry out necessary signal processing. The focus of software development was to obtain a sufficiently good mass measurement result with the experimental model. The implemented software solutions helped to achieve the envisaged goal to a great extent.

LabVIEW is a graphical programming language designed mainly for software development in engineering and scientific applications[16]. LabVIEW contains an extensive array of ready-to-use built-in functions that can perform many operations, including instrument automation, testing, signal generation, data acquisition, signal processing, analysis of acquired data, display and store the results. The key advantage

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of LabVIEW is that all these activities can be implemented in the same programming environment. Several investigators have mentioned the use of LabVIEW for software development in their Kibble balance design and operation, however without giving any details thereof [11,17-20]. This paper presents essential aspects of the software developed in LabVIEW to make measurements and testing of demonstrational Kibble balance setup implemented at CSIR-NPL. Brief descriptions of the basic principle of Kibble balance and the hardware of the experimental setup hardware design are also presented.

2. Instrumentation

2.1 Basic Principle of Kibble Balance

Kibble balance is essentially an electromechanical device used to realize the SI unit of mass, the kilogram, in terms of the Planck constant h in the new SI[21]. The Kibble balance, originally known as the Watt balance, was invented by Dr. Brayan Peter Kibble to realize the ampere in terms of mechanical units[22,23]. It works by balancing the gravitational force on a mass by an upward electromagnetic force (Lorentz force) generated by a current-carrying coil immersed in a magnetic field. The two forces can be represented mathematically by the equation $mg = BLI$, where m is the mass, g is the acceleration due to gravity, B is the magnetic field strength, L is the wire length of the coil, and I is the current through the coil. In the working of the Kibble balance, this is known as the weighing or static mode of the balance. In practice, determining the value of BL with the required accuracy is a difficult task. To avoid this, another mode of operation, viz., the dynamic or velocity mode of operation, has been incorporated into the working of the balance. In this mode, the balance is operated without the mass in the pan with the coil current turned off. The coil is then moved vertically with a known velocity ($\boldsymbol{v}$) in the same magnetic field, which generates a voltage ($\boldsymbol{U}$) across the coil given by $U = BLv$. Combining the two modes gives $mgv = UI$, which essentially equates mechanical power to electrical power, and this was the reason for its original name, "Watt balance". So the main parameters for measurement are the voltage and current. To realize the kilogram in terms of h, through the Kibble balance, the voltage and current measurements are made using quantum phenomena based electrical standards through the Josephson and quantum Hall effects[5-7,24]. However, for a simple experimental setup like the one used in the present work, *in situ* quantum measurements are well beyond its scope.

2.2 Construction of the Experimental Model of 1g Kibble Balance at CSIR-NPL

The schematic of the 1 g Kibble balance setup designed and fabricated at CSIR-NPL is shown in Fig. 1. The mechanical design consists of a wheel based balance with two identical pans of 40 mm diameters. The wheel is made of aluminum with a diameter of 300 mm and a thickness of 10 mm.

The wheel is pivoted on a horizontal central knife-edge support, which rests on two pillars. The wheel remains in equilibrium, with both the pans freely hanging down by cords symmetrically on either side. The wheel rotates to allow the pans to move vertically up and down, corresponding to the load placed on the pans. To restrict the wheel motion within a small range so as to maintain it within safe limits, an arresting mechanism has been mounted symmetrically on the wheel. One of the pans is marked as the mass pan, below which the Lorentz force coil is suitably placed. The coil is made of copper wire, wound tightly over a wooden hollow cylinder, with a suitable number of turns and coil dimensions as required for the experiment. The wooden cylinder's inner diameter is chosen such that the mass pan could move vertically up and down through the coil with sufficient clearance all around. A permanent magnet with a magnetic field of the order of 0.3 T is placed on the mass pan, which traverses axially in the coil. The electronics include a GPIB programmable current source Keithley 6221 DC and AC current source to supply precisely known current to the coil and a multifunction data acquisition (DAQ) card to acquire the measurement data and generate control signals for the balance using a PC. A laser module has been used

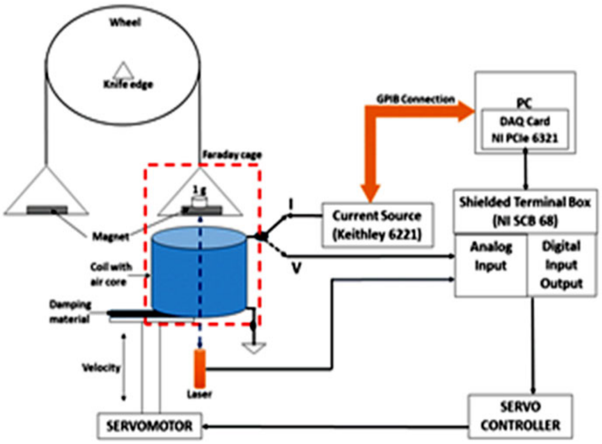


Fig. 1 — Block schematic of 1 g demonstrational model of Kibble balance at CSIR-NPL

to optically monitor the position of the pan and determine the balance condition in the static mode accurately. A programmable servomotor-based arrangement has been used to move the coil vertically upward and downward in the magnetic field at precisely known speeds for the velocity mode measurements. The arrangement consists of a platform on which the coil is placed, and the coil is moved up and down in the magnetic field by the vertical movements of the platform.

3 **Software Development**

The Kibble balance involves precision electrical measurements. The weighing accuracy of the balance depends on how perfect the design is for its proper electrical and mechanical performance. Implementing a perfect design at the first instance itself is a daunting task without complete and correct knowledge of all the required electrical and mechanical design parameters pertaining to the balance. Tests and measurements become necessary to know for sure whether the designed balance is performing at the desired level in both the static and dynamic modes. To carry out such measurements manually is a tedious job. Therefore, automation with proper application software becomes the preferred choice to operate the balance, collect necessary data and analyze its performance under the different test conditions. With the right kind of application software, it will be possible to save time and minimize the amount of instrumentation required for the job while offering flexibility in performing the measurements in both static and dynamic modes of the balance. The application program has been implemented as two modules based on operational requirements, each for the static and dynamic modes.

3.1 Automation Program for Static Mode Measurement

The program has to perform the following major tasks:

a) Automate the working of the current source.
b) Arrive at the exact value of coil current required for balancing the weight in the pan.
c) Continuously monitor the displacement of the pan from its position of balance by measuring the laser sensor's output.
d) On reaching the position of balance, record the current and laser reading.

The current source is operated using GPIB port which is programmed in LabVIEW using the VISA VIs. The program is made to work in a feedback loop to increase or decrease the coil current in finite steps depending on the direction of displacement of the weighing pan till it gets back the starting position of balance. The displacement of the pan is measured by the output of the laser module and monitored as a voltage signal by the DAQ. The iterations for the coil current are implemented in a While Loop.

Several practical aspects have been taken into account in the design of the program to make it more efficient. The foremost among them is setting an error limit for the determination of the position of the balance by the program. As the coil current can be varied only in discrete steps, it is seldom possible to reach the exact value for the starting position of balance by the iteration. In the program this is taken care of by specifying an error limit in approaching the balance position. This error value is very crucial for concluding the While Loop in a reasonable number of iterations. The interval between iterations is another important factor. Once a current is applied, the pan needs to stabilize in its new position before its displacement can be measured correctly. So the program is made to have necessary time delays between iterations. Yet another consideration is the need for properly reading the output of the laser sensor. The electronic output of the sensor contains random fluctuations, and the programming is done to average a number of readings every time to obtain more accurate position values. If the set current is smaller than that required for attaining the balance condition, the program will work to increase the current and vice-versa. The programming is done to use different current steps, one for the increment and another for the decrement. This is necessary to avoid unending loops that will otherwise execute back and forth in case the current in iteration is getting decreased or increased, below or above that is required for balance from the previous iteration. To speed up the iteration and minimize the measurement time the program initially provides the option for increasing or decreasing the coil current in larger steps. Further, on nearing the balance condition, the program is designed to reduce the step size to iterate at smaller current steps to achieve a much finer balance condition.

The flowchart for the program is shown in Fig 2. The program input variables are the laser reading for the balance condition (which corresponds to the rest position when both the pans are empty), the initial coil current, its incremental step size and the position error limit. To know the real-time status, a front panel display is provided for coil current and laser readout.

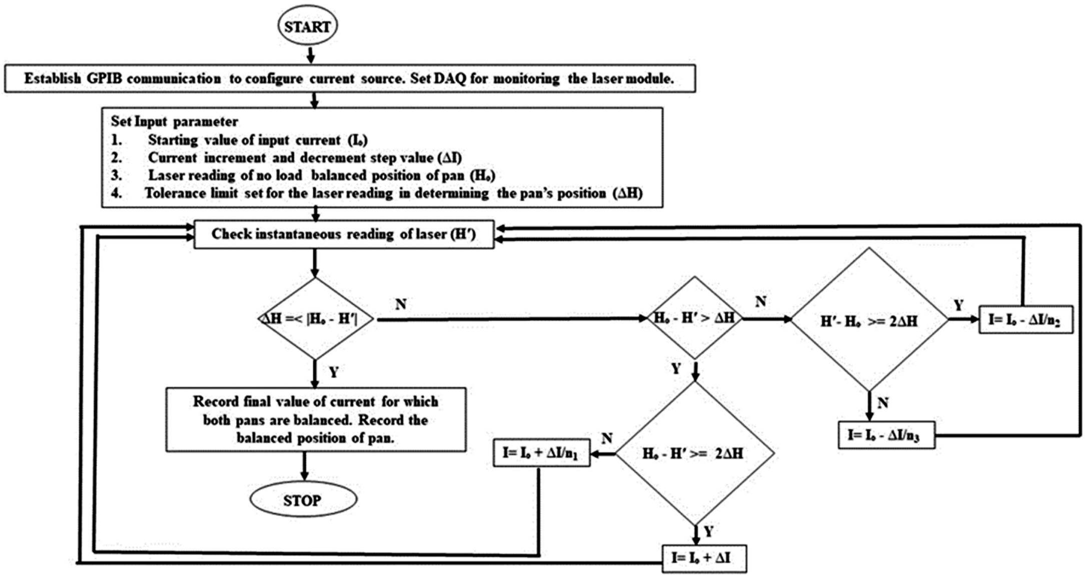
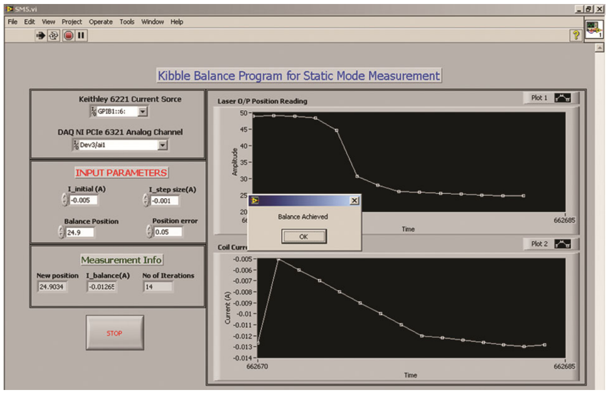


Fig. 2 — Flow chart for the static mode of measurement. Here, n1, n2, and n3 are divisional factors for ΔI to iterate at lower I and avoid an unending loop.



Keithley 6221 Current Sorce: GPIB1::6:

DAQ NI PCIe 6321 Analog Channel: Dev3/ai1

INPUT PARAMETERS

I_initial (A): -0.005

I_step size(A): -0.001

Balance Position: 24.9

Position error: 0.05

Measurement Info

New position: 24.9034

I_balance(A): -0.01265

No of Iterations: 14

Fig. 3 — Front panel display of static mode of measurement showing real-time graphical displays of laser reading indicating the pan position (upper panel) and current iteration values (bottom panel). On nearing the balance position, the program reduces the current step size for iteration to achieve an accurate balance position.

On achieving balance, the program stops, and the iteration values of the current and laser readings are recorded and saved into a file for data analysis. A snapshot of the program front panel is shown in Fig. 3.

3.2 Automation Program for Dynamic Mode Measurement

From a programming point of view, the tasks to be accomplished are:

a) Configure the required analogue input (AI) channel of DAQ to measure the coil voltage.
b) Configure the required digital input/output (DIO) channels for generating control signals for the servomotor to move the coil at known vertical velocities in the magnetic field.
c) Acquire and save the measured data.

Configuring the AI channel for the coil voltage measurement is straightforward. The servo-controller needs a logic signal to control the rotational speed of the motor. For this the counter function of the DAQ is programmed to output a square wave signal on the selected DIO channel. The rotational speed of the motor and hence the speed with which the coil platform moves depends on the frequency of this signal. So it is convenient to fix the coil velocity in a measurement by choosing the signal frequency. As the induced voltage depends on the coil velocity, it is made as a primary input parameter in the program. The program will calculate the frequency using the motor parameters and accordingly the DIO will supply the required signal. Two other logic signals required for the motor, viz., an ON/OFF control for its start/stop and a direction control for moving the platform UP or DOWN are also generated in the DIO.

The purpose of the dynamic mode measurement is to estimate the value of BL, which is equal to U/v. An appropriate value for v in the measurements is crucial for best results. However, it will be very difficult to find one standardized value for v to carry out the measurements. Therefore, the best option lies in making the measurements at several v values to get a more accurate estimate of the BL. With this in mind the data acquisition program has been designed to measure the same amount of data irrespective of the value of v for a given coil trajectory by scaling the data sampling rate in proportion to v. This ensures acquiring data points equally spaced along the coil trajectory at all coil velocities to facilitate easy comparison of measurements from different velocity sweeps. The program is made to automatically choose the appropriate sampling rate and number of data points to acquire using the coil speed and trajectory inputs. Their values will be displayed on the front panel during the program run, which can be used for confirmation and record. During the velocity sweep, a graphical display is used to provide real-time monitoring of the voltage profile. It is observed that the coil voltage is corrupted by the interference of stray signals in the operating environment; some post-acquisition signal processing has been included in the software design that helps to retrieve clean signals from the measured data. This includes mainly low pass filtering and curve fitting methods. An FFT module has also been included to obtain the frequency components of the interfering signals, which would be useful for diagnostic purposes and to plan corrective measures.

The measurement data are saved into a worksheet file for record and further analysis. Since it is essential to repeat a measurement several times, the file saving module has been designed to save repeated measurement data into the same worksheet file. The data file will be updated on every new measurement by saving the latest data into a new column in the same worksheet file as explained in (Ref 25)[25]. This will make available a single file for a set of identical measurements for easy comparison and analysis. The flowchart for the program made in LabVIEW is shown in Fig 4. A screenshot of the program's front panel display is given in Fig. 5.

4 Performance and Test results

Extensive measurements were carried out to verify the functioning of the software programs and the balance. The balance was set up on a very sturdy platform in a laboratory with well-regulated environmental conditions. It was housed in an enclosure to reduce any air currents from affecting the weighing and located away from other instruments to minimize the chances of interference from any nearby electric and magnetic sources.

In the dynamic mode, induced coil voltages were measured at different coil velocities, and the polynomial fit generated smooth profiles. The fit's accuracy is ascertained by the very small standard error of the regression, and it was critical for the successful recovery of the desired signal from the noisy environment. A combined plot of the profiles obtained from measured voltages for five different coil velocities is given in Fig. 6. In these measurements, the distance is counted from the bottom of the magnet, which remains stationary. At the start of the measurement (D = 0), the magnet was inside the coil with its base at the level with the bottom end of the coil. The coil winding height is 60 mm, and the magnet has a thickness of 9 mm. A simplified sketch of the coil-magnet arrangement is shown in Fig. 7. to aid the explanation. The profiles shown are from measurements taken by moving the coil

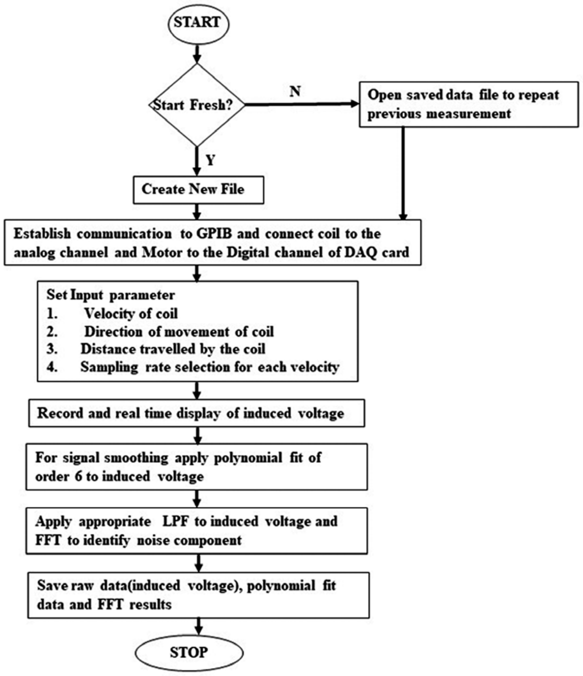
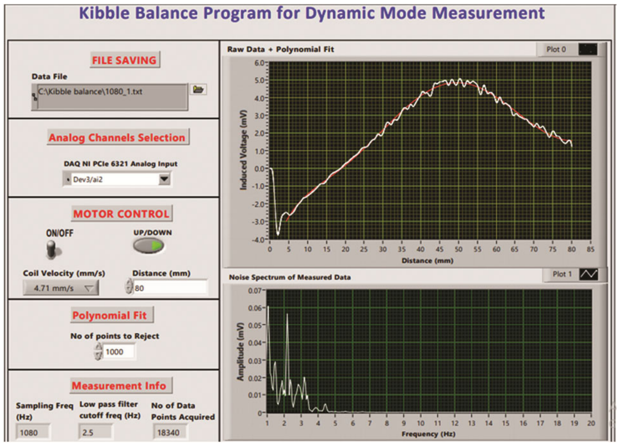


Fig. 4 — Flowchart for dynamic mode measurement



Data File: C:\Kibble balance\1080_1.txt

DAQ NI PCIe 6321 Analog Input: Dev3/ai2

Coil Velocity (mm/s): 4.71 mm/s

Distance (mm): 80

No of points to Reject: 1000

Sampling Freq (Hz): 1080

Low pass filter cutoff freq (Hz): 2.5

No of Data Points Acquired: 18340

Fig. 5 — LabVIEW program's front panel display of Dynamic mode of measurement. The top panel graph shows the induced coil voltage profile after low pass filtering along with a smooth polynomial fit. The bottom graph shows the FFT of the noise in the data. It shows the signals due to motor-induced vibrations and oscillations of the pan.

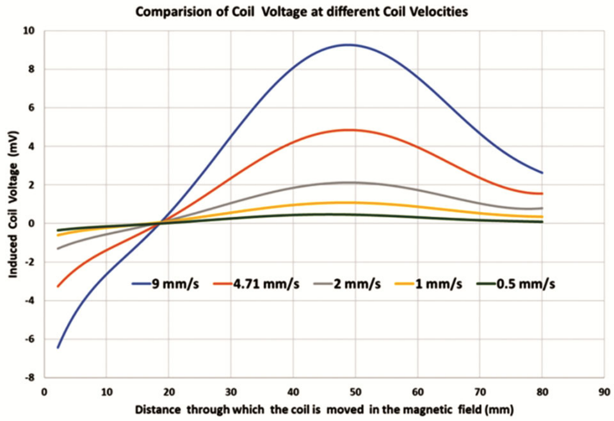


Fig. 6 — Comparison graph of induced voltages at five different coil velocities.

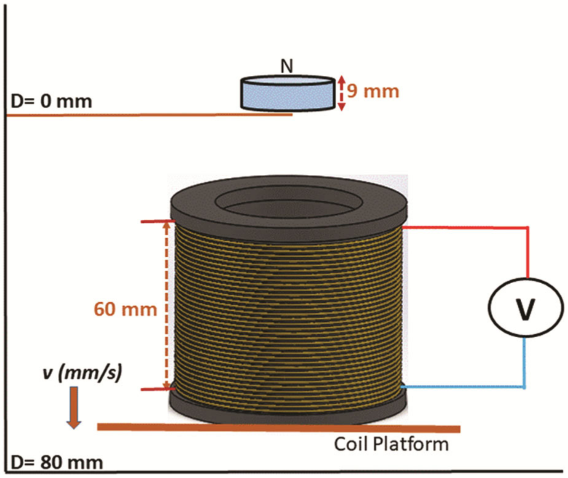


Fig. 7 — Figure depicting Coil-Magnet configuration in velocity mode measurements for the graphs shown in Fig.6. At the start of the measurement, the bottom of the coil winding was at level with the bottom of the magnet (D=0). The measurements were made by moving the coil through a height of 80 mm down at different constant speeds. This distance is the X-axis of Fig.6.

Table 1 — Calculated ***BL*** values corresponding to the peak voltages of the 5 different velocities

v (mm/s)	U (mV)	*BL* = U/v (T m)
0.5	0.51	1.022
1.0	1.03	1.026
2.0	2.06	1.030
4.71	4.82	1.024
9.0	9.16	1.018

down at the given vertical velocities through a distance of 80 mm. As we can see, the profiles show identical characteristics, with peak values occurring at the same location in terms of the positions of the magnet and coil.

The shape of the profile can be understood very well by visualizing the coil's trajectory in the magnet's field. The induced voltage depends on the projected area of the coil and the change in magnetic flux. For the magnet that has been used in the present study, the magnetic field varies over the coil trajectory. Assuming that the coil area did not change and the magnetic field was perpendicular to the coil's plane, the profile shape reflects the rate of change of the magnetic flux seen by the coil along the coil path during a velocity sweep. For a coil of area, A and N turns in a magnetic field B, the voltage produced $= -NA\frac{\delta B}{\delta t}$. For the coil moving with a constant velocity v, the voltage generated can be obtained as $U = -NA\frac{\delta B}{\delta z}v$, where $\frac{\delta B}{\delta z}$ is the vertical gradient of the magnetic field along the coil trajectory, and the smooth profile is in excellent qualitative agreement with this situation.

Many measurements were made at different coil velocities, which provided very consistent voltage measurement results with curve fitting. From these voltage profiles, *U/v* can be calculated to get reasonably good estimates of *BL*. As the field was not uniform along the trajectory, *BL*'s value varies with the coil and magnet's relative positions. The profiles contain an almost flat region at the peak, and the value of *BL* can be determined at these points with a relative accuracy of better than ± 1 %. The values of *BL* calculated at the voltage peaks at the different coil velocities are given in Table 1, which shows excellent agreement in these values, which is a significant result. It should validate the curve fitting method adopted in dealing with noisy data.

One of the essential considerations for static mode measurements is the *BL* value, as the coil current required for the balance condition depends on it. In the present setup, the *BL* value depends very much on the coil and magnet's relative positions, and this information is available from the dynamic mode measurements. Before running the program for static operation, some initial settings are required, which include: (1) choosing a convenient value of *BL,* (2) without the weighing mass in the pan and coil current, aligning the magnet along the axis of the coil and position it for the chosen *BL* value and, (3) recording the corresponding laser reading which provides the reference position of the pans for mass balance. Fine scale-markings provided along the coil's inner wall helped position the magnet at different known distances accurately.

The test measurements were carried out for a mass of 1 g. The precision current source Keithley 6221 has been used to generate the coil current. For this use, the current source has been calibrated over the DC current ranges traceable to the primary standards at CSIR-NPL. As described earlier, the software program makes the current source supply the necessary current by working on a feedback loop. As the number of iterations needed to obtain mass balance depends on the initial input current, the iteration process's efficiency can be significantly improved by properly selecting this value. Better precisions can be achieved by using smaller increments. Using the dynamic mode measurements, it was possible to estimate the values of current required for the mass balance at different coil positions (or equivalently, *BL* values). A sample plot of this estimate is shown in Fig. 8 for a 1 g mass. This data is used to set the initial current to a value close to that predicted for balance, which helped the program arrive at the desired current in a few iterations. As mentioned in the software description, the current was initially increased in relatively larger steps (in the range of 100 µA). On approaching the equilibrium position, finer current increments of the order of a few microamperes were used so that excellent precision measurements could be obtained. In this way, it was easy to get the desired current value with an accuracy of ± 20 µA in a small number of iterations. Still, better results (to within ± 5 µA) can be obtained by suitably fine-tuning the program input quantities, particularly the position error limit and current iteration step sizes. However, this will take more time and iterations to reach the position of balance. To test whether the operation of the balance is satisfactory or not the balance operation using the software, measurements were carried out at a few selected *BL* values, and the measured currents obtained for balance are plotted in Fig. 8. The current values from the static mode are reasonably close to those predicted by the dynamic mode measurements.

5 Discussion

Using the developed software, we conducted preliminary tests and demonstrated the functional validity and capabilities of balance's design. From the results presented, the functional performance of the balance can be considered satisfactory. It must be mentioned that the hardware was fabricated based on an untested design, carried out with very modest objectives. The developed software allowed operating the balance under different test conditions to collect data that can help us to identify the design deficiencies of the balance in its present form. The main advantages of the software-based testing were that it minimized the amount of time and instrumentation required for the job.

These test measurements helped to pinpoint a few specific issues with the hardware design that was affecting the performance of the balance. The data so generated showed some major noise sources in the setup based on which certain specific remedial measures could be applied. The remedial measures included both hardware and software solutions. The coil has been found to pick up RF signals in the operating environment and it is stopped by enclosing the coil inside a faraday cage. The servo-controller

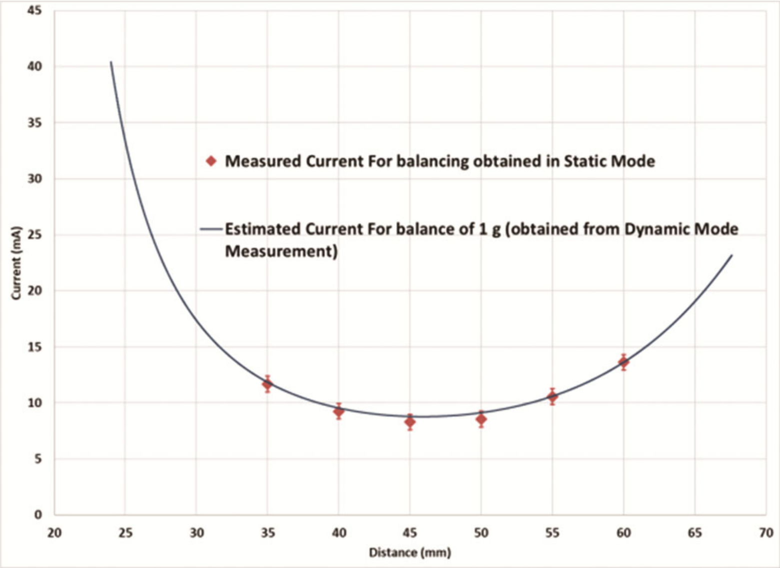


Fig. 8 — Comparison plot of measured and estimated coil currents to balance a mass of 1g.

has been found to be an internal source of RF noise and it is solved by using an RF filter in the controller unit with proper grounding arrangement. The vibration of the coil platform during motor operation was another source of noise, and it could be solved to a great extent by using a vibration-damping material between the coil and the platform. Further refinement has been accomplished by software signal processing on the measured data by the automation program as explained in the previous section. In fact, the software-based operation provided a cost-effective solution for improving the performance of the balance to a satisfactory level under the given circumstances.

As has been found, the signal processing by software has been effective in retrieving the desired coil voltage signal to an accuracy of better than 1 %. As explained in the weighing operation, correctly fixing the value of ***BL*** is very critical for the static mode, which depends on the accurate measurement of the coil voltage in the dynamic mode. To obtain a weighing accuracy of better than 1 % demands a coil voltage measurement accuracy of better than 0.1 %. Therefore, modifications in the hardware design by incorporating more effective shielding and filtering in the hardware to eliminate the noise is highly essential to further improve the performance of the balance. By keeping the same basic configuration, hardware modifications are being worked out to build a more accurate balance that can make the mass measurement with an accuracy of much better than 1 %. For the weighing operations, the mechanical integrity of the hardware is very crucial. The consistency and repeatability of the measurements have been found to be critically dependent on the stability of the knife-edge. Still further improvement is required in magnet design, optical systems for all displacement measurements and the like. The authors are working in this direction, and specific details regarding the modifications and measurement results will be presented in a future publication.

6 Conclusions

This paper's primary purpose has been to describe the software developed for the functional test of the Kibble balance's demonstrational model. Measurements carried out with the balance demonstrate that the developed software conforms to the requirements very well. The measurement results obtained are good enough to judge the software's satisfactory performance in both static and dynamic modes. Using the developed software considerable experimentation is possible, contributing immensely in improving the balance's performance with the flexibility to modify the software as per the requirement. Additional modules, for instance, calculation of measurement uncertainties, can be easily incorporated into the developed software.

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References

1 Schlamminger S & Haddad D, *Comp Rendus Phys*, 20 (2019) 55.
2 Stock M, Davidson S & Fang H, *Metrologia*, 54 (2017) S99.
3 Ehtesham B, John T, Yadav S, Singh H K, Mandal G & Singh N, *MAPAN*, 35 (2020) 585.
4 Ehtesham B, John T & Singh N, *MAPAN*, 36 (2021) 333.
5 Wood B M, Sanchez C A, Green R G & Liard J O, *Metrologia*, 54 (2017) 399.
6 Haddad D, Seifert F & Chao L S, *Metrologia*, 54 (2017) 633.
7 Thomas M, Ziane D & Pinot P, *Metrologia*, 54 (2017) 468.
8 Richard P, Fang H & Davis R, *Metrologia*, 53 (2016) A6.
9 Kim M, Kim D & Woo B C, *Int J Precis Eng*, 18 (2017) 945.
10 Sutton C M, Clarkson M T & Kissling W M, The feasibility of a watt balance based on twin pressure balances, paper presented to the 2016 Conference on Precision Electromagnetic Measurements (CPEM 2016), 10-15 July 2016.
11 Chao L, Seifert F, Haddad D, Stirling J, Newell D & Schlamminger S, *IEEE Trans Instrum Meas*, 68 (2019) 2176.
12 Beer W, Eichenberger A L & Jeanneret B, The METAS watt balance: a summary of progress, paper presented to Conference Digest Conference on Precision Electromagnetic Measurements, 16-21 June 2002.
13 Eichenberger A, Baumann H, Jeanneret B, Jeckelmann B, Richard P & Beer W, *Metrologia*, 48 (2011) 133.
14 Sonntag C, Mametja T & Karsten A, A Low-Cost Kibble Balance for Africa, paper presented to 2020 Conference on Precision Electromagnetic Measurements (CPEM), 2020.
15 Kumar A, Kumar H & Ojha V N, *Curr Sci*, 113 (2017) 381.

16 Corporation NI, LabVIEW, User Manual (USA) 2003.

17 Mametja H P, Karsten A E & Buffler A , NMISA's precursor Kibble watt balance presented to Test and Measurement 2018 Conference and Workshop, South Africa, 2018.

18 Xu J, You Q, Zhang Z, Li Z & Li S, *IEEE Trans Instrum Meas*, 66 (2017) 1309.

19 Xu J, Zhang Z & Li Z, *Metrologia*, 53 (2016) 86.

20 Fang H, Bielsa F, Li S, Kiss A & Stock M, *Metrologia*, 57 (2020) 045009.

21 BIPM, Mise en pratique for the definition of the kilogram in the SI, 2020 https://www.bipm.org/utils/en/pdf/si-mep/SI-App2-kilogram.pdf

22 Kibble B P & Hunt G J, *Metrologia*, 15(1979) 5.

23 Kibble B P, Robinson I A & Belliss J H, *Metrologia*, 27 (1990) 173.

24 Schlamminger S, Steiner R L & Haddad D, *Metrologia*, 52 (2015) L5.

25 Ehtesham B, Ushakiran, John T, *Indian J Pure Appl Phys*, 58 (2020) 99.