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**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

# SINGLE PHASE MEASUREMENT IN UME KIBBLE BALANCE – 3*

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**ABSTRACT**

*Kibble Balance developed in National Metrology Institute of Turkey allows the new definition of kilogram to be realized in single phase where the Faraday's Law of Induction and Lorentz Law of Force are tested simultaneously thanks to its design with moving magnet. Although there are numerous advantages of this design, like being less sensitive to environmental and experimental conditions, there appear the problem of distinguishing the voltage induced across the ends of the coil as a result of Faraday's Law of Induction and the voltage due to the current delivered to coil to generate the Lorentz Force, with a relative uncertainty of some parts of a billion. In order to get the best possible performance of the digital multimeter measuring the voltage of the coil, a waveform generator is connected in series to the multimeter as a compensating voltage source so that the voltage due to the supplied current is almost eliminated in the input of the multimeter. However, temporal voltage fluctuations in the waveform generator may induce additional voltage at the coil. In this paper, we show that these random effects are eliminated with an uncertaınty of 15 ppb in case the experiment lasts for at least 48 hours.*

**Keywords:** *Kilogram, Planck Constant, Kibble Balance, Single Phase Measurement.*

## UME KİBBLE BALANS – 3 İLE TEK FAZDA ÖLÇÜM

### ÖZ

*Türkiye Ulusal Metroloji Enstitüsü'nde geliştirilen Kibble Balance, hareketli mıknatıslı tasarımı sayesinde, yeni kilogram tanımında Faraday İndüksiyon Yasası ve Lorentz Kuvvet Yasasının aynı anda test edildiği tek fazda ölçüme olanak tanıyor. Bu tasarımda, çevresel ve deneysel koşullara daha az duyarlı olması gibi sayısız avantaj olmasına rağmen, Faraday İndüksiyon Yasasının bir sonucu olarak bobinin uçlarında indüklenen voltaj ile akımdan kaynaklanan voltajı milyarda birkaç bağıl belirsizlikle ayırt etme sorunu ortaya çıkmaktadır. Bobin voltajını ölçen dijital multimetreden mümkün olan en iyi performansı elde etmek için, kompanzasyon voltaj kaynağı olarak multimetreye seri olarak bir dalga formu üreteci bağlanır, böylece akımdan kaynaklanan voltaj, multimetrenin girişinde neredeyse ortadan kalkar. Fakat, dalga formu üretecinde zamana bağlı voltaj dalgalanmaları, bobinde ek voltajı indükleyebilir. Bu yazıda, deneyin en az 48 saat sürmesi durumunda bu rastgele etkilerin 15 ppb belirsizlikle elimine edildiğini gösteriyoruz.*

**Anahtar Kelimeler:** *Kilogram, Planck Sabiti, Kibble Balans, Tek Fazda Ölçüm.*

## 1. INTRODUCTION

The advances in science and technology and the measurement accuracy are closely interconnected with each other such that a major progress in one eventually culminates with a breakthrough in the other. The measurement accuracy of a physical quantity is restricted by the agreed definitions of the relevant units. In order to minimize these restrictions, after decades of pioneering scientific work, the International System of Units (SI) underwent a substantial modification in the definitions of four of the seven base units: the kilogram, the Kelvin, the ampere and the mole (Stock, Davis, de Mirandés, & Milton, 2019). The most substantial revision was in the definition of SI mass unit, the kilogram (Richard, Fang, & Davis, 2016). Prior to the revision, kilogram was the last SI base unit to be defined in terms of a material artefact, the International Prototype of Kilogram (IPK). It has been kept in the International Bureau of Weights and Measures (BIPM) since the agreement of the IPK to be the basis for the unit of mass in 1889. The accuracy of mass or mass related measurements in this artefact-based definition was constrained by the irreversible contamination or mechanical wear on the IPK. As the mass of IPK was assumed exactly to be equal to one kilogram with zero error and zero uncertainty, the validation of such possible alterations in the IPK mass was unfeasible. In addition, the traceability to the kilogram was ultimately only available from the BIPM since IPK, since it was under the authority of the BIPM. The long-awaited ambition for there to be a uniform, long term stable and worldwide accessible unit of mass, lead to the redefinition of kilogram in terms of the fixed value of Planck constant, a fundamental constant of nature. It took nearly 130 years for this dream to come true as future technologies were needed to realize it with sufficient accuracy. The new definition of the kilogram, adopted since 20 May 2019, does not recommend a technique for the practical realization of the unit in terms of Planck constant, thus allowing to take advantage of future developments without the need to redefine it once again. Currently, there are two methods with the capability of realizing the new kilogram at the required total relative uncertainty of $2 \times 10^{-8}$: The Kibble Balance (KB) experiment (Robinson, & Kibble, 2007; Kibble, & Robinson, 2014; Wood et al., 2017; Fang et al., 2020; Kim et al., 2020; Baumann et al., 2013; Haddad et al., 2017; Thomas et al., 2017;

Li et al., 2020; Sutton, 2009; Ahmedov et al. 2018; Marangoni et al., 2019) and the X-Ray Crystal Density (XRCD) experiment (Fujii et al., 2016; Kuramoto et al., 2017; Bartl et al., 2017). Moreover, within the revised SI, as opposed to the previous situation, the traceability of the kilogram can be provided by any National Metrology Institute (NMI) operating a primary realization method.

Kibble Balance experiments have been constructed in the NMIs from different parts of the world in different geometries and with different experimental protocols. This is a favorable situation for better understanding of the possible systematic errors. The link between the kilogram and Planck constant in KBs is achieved by the comparison of the mechanical power with the electrical one. The main components of the KB experiments are a magnet and a coil. The power comparison is achieved in two concurrent or simultaneous phases depending on the operation protocol of the system. National Metrology Institute of Turkey (UME), operating under the umbrella of the Scientific and Technological Research Council of Turkey (TÜBİTAK), contributes to the ongoing worldwide research with a Moving-Magnet Kibble Balance Experiment as opposed to the traditional approach with a moving coil. Single phase measurement scheme is one of the most important outcomes of this configuration where the Faraday's Law of Induction and Lorentz Law of Force are tested simultaneously. Apart from many distinctive advantages, there is one difficulty to be tacked in simultaneous scheme such that the total voltage across the ends of the coil pair should be decomposed with relative uncertainties of about some part of a billion as the induced Faraday's voltage across the ends of the coil due to the motion of the magnet with respect to the coil (Faraday's Law of Induction) and the voltage due to the supplied current to the coil (Lorentz Law of Force). As the performance of the digital multimeter used in voltage measurements gets better at 1 V range, a compensating voltage is generated by a waveform generator connected in series to multimeter so that the input voltage of the multimeter is almost solely the Faraday's voltage. However, due to the temporal voltage fluctuations in the waveform generator, an additional voltage is induced on the coil. In this paper, we show that it is possible to distinguish the induced voltage due to the motion of the magnet assembly and the voltage due to the electric current across the ends of the coil with uncertainties of parts per billion despite the noise generated by the waveform generator in case the duration of the experiment lasts at least 48 hours.

In the following section, the KB principle is explained. The UME KB-3 is introduced in Section 3. In Section 4, the electrical measurement procedure in UME KB-3 is explained in details and supported with experimental results. The last section is reserved for conclusion.

## 2. KIBBLE BALANCE PRINCIPLE

The Kibble Balance principle links the macroscopic mass $m$ of an artefact with the Planck constant $h$ of the quantum world by comparing the mechanical power with the electrical one. Initially, it was called as Watt Balance. It is replaced with Kibble Balance after the inventor of the idea, Dr. Brian Kibble passed away in 2016. The comparison is achieved in two concurrent or simultaneous phases (the moving and the weighing phases) depending on the operation protocol of the system. In the moving phase, the underlying principle is the Faraday's Law of Induction where the relative motion with a velocity $v$ between a coil of length $L$ and a surrounding magnet having a radial magnetic flux density of $B$ induces a voltage $V$ across the ends of the coil such that $V = BLv$. In the weighing phase, the gravitational force acting on the mass artefact is counter balanced by the Lorentz Force generated on the coil carrying a current $I$ in the magnetic field yielding $mg = BLI$ where $g$ is the gravitational acceleration. The common factor $BL$ appearing in both phases of the experiment cannot be measured with high accuracy. In the ideal case of the velocity and Lorentz Force being in the direction of the gravitational acceleration, the combined equations give rise to the Kibble Balance principle

$$mgv = VI, \quad \textbf{(1)}$$

where left-hand side is the mechanical power while the right-hand side is the electrical one. The common factor disappears under the assumption of its steadiness in two phases. Although the Planck constant does not appear explicitly in Eq. (1), it comes into play as the electrical quantities are measured by using Josephson Voltage Standard and Quantum Hall Standard.

The time integral for of the Kibble Balance equation is known as the Joule balance principle.

$$mgZ = \Phi I, \tag{2}$$

where $\Phi$ is the magnetic flux in the coil induced due to motion of the magnet assembly with respect to the coil and $Z$ is the displacement of the coil. In UME KB-3 the Joule Balance principle is used.

## 3. THE UME KB-3

The originally devised KB experiment at the National Physical Laboratory (NPL) by Brian Kibble relates the mechanical and the electrical powers by means of a stationary magnet assembly and moving coil within the air gap of that magnet assembly. The majority of the KBs developed in the NMIs for realizing the new definition of kilogram followed in the footsteps of this initial design. UME, on the other hand, has shifted this ground by a design with a moving magnet assembly and stationary coil residing in the air gap. On account of this construction, the simultaneous operation of moving and weighing phases becomes possible. The notable outcome of single phase measurement is that it relaxes the need for monitoring the environmental and experimental conditions with a relative uncertainty at the order of parts per billion. The moving magnet design leads to additional significant advantages like using a local vacuum for displacement measurements rather than a global one and performing mass measurements in ambient air conditions instead of under vacuum. The displacement measurements, carried by laser interferometers, oblige the refractive index to be stable along the paths of the laser beams in order to reach the required uncertainties by the kilogram realization experiments. In moving coil experiments, as the coil cannot be decoupled from the rest of the set-up, a global vacuum covering the entire system is the only option to ensure this requirement. The moving magnet design, on the other hand, allows the use of a local vacuum in the vicinity of the magnet assembly (Ahmedov et al., 2020). As a result, the set-up become more economical since the rest of the system does not have to be vacuum compatible. The ambient air mass measurement is favorable for further disseminating the kilogram which takes place entirely in air. Consequently, a vacuum/air transfer mechanism for the mass artifact is not necessary and the possible sorption effects due to such transfer are avoided (Davidson, 2010).

The design of the UME KB-3 apparatus is given in Figure 1.

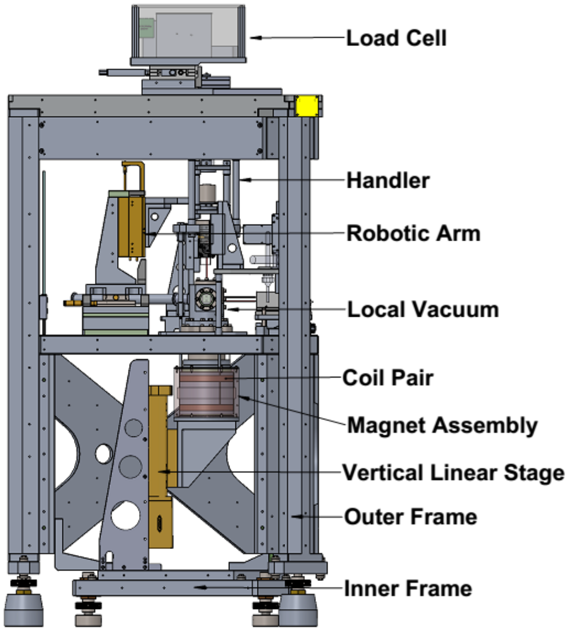


**Figure 1.** The solid drawing of UME KB-3 apparatus.

It is constructed on two mechanically decoupled rigid support frames. The moving magnet assembly is placed on the inner support frame while the stationary coil pair is hanging from the outer support frame. In this way, the mechanical vibrations due to the magnet motion on the inner frame are not reflected on outer frame where the force and displacement measuring systems are mounted. The vertical motion of the magnet assembly is delivered by the vertical linear stage fixed on the inner support frame. The reversely winded coil pair is used instead of a single coil in order to minimize the effect of Earth magnetic field on the system (Ahmedov et al., 2020). The robotic arm places the mass artifact on the handler and takes it off from the handler. The load cell measures the difference between the gravitational force on the mass artifact and balancing Lorentz Force generated on the coil pair.

## 4. ELECTRICAL MEASUREMENTS

The magnet assembly undergoes a triangular like motion with respect to the coil pair along the direction of gravitational acceleration at a period of 1 s. The vertical displacement of the magnet for 10 s is illustrated in Figure 2.

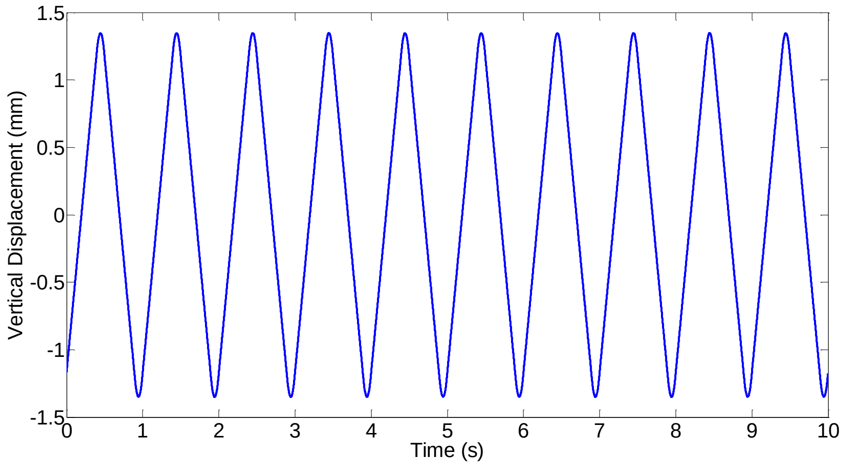


**Figure 2.** The vertical motion of the magnet for 10 s.

As a result of the magnet motion, a triangular shaped flux is generated through the coil pair. In other words, the square shaped Faraday's voltage, proportional to the time derivative of the flux with a minus sign, is induced across the ends of the coil pair. As the moving and weighing phases of the experiment are performed at once, in addition to the Faraday's voltage, there is also the voltage due to the electric current delivered to the coil pair by the current source. Therefore, the output voltage of the coil pair is the sum of Faraday's voltage and the voltage due to the supplied electrical current and it needs to be decomposed as its clear from Eq. (2). The resistance of the coil pair is 166 Ω and the supplied current is 38.4 mA yielding an electrical voltage on the coil pair of around 6.4 V. The voltage data across the ends of the coil pair is collected with Keysight 3458A Digital Multimeter with a sampling frequency of 2 Hz. The high voltage due to the supplied current to the coil pair forces the measuring device to work at 10 V range with a resolution of 100 nV. It provides a resolution 10 nV at 1 V range. In order to switch to 1 V range, a Keysight 33512B waveform generator is connected in series to the multimeter across the coil pair as a compensating voltage source. In Figure 3, the circuit diagram of the electrical measurements is given. WG stands for the waveform generator. A standard resistor $R$ is connected in series to the coil pair for the determination of the electrical current supplied to the coil pair with better uncertainty. The Guildline 7330 standard resistor of $25\ \Omega$ is kept in the 7108-256 Fluke Resistor Bath with temperature stability 10 mK. The temperature coefficient of the standard resistor is low enough $(-3.22 \times 10^{-8} \pm 2.1 \times 10^{-9})/\mathrm{K}$ to satisfy the desired total relative uncertainty by the realization experiment.

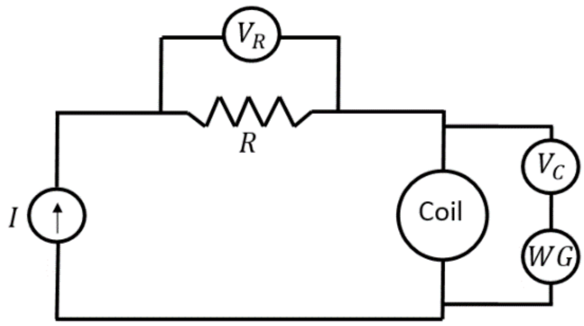


**Figure 3.** The output voltage of the coil pair.

In Figure 4, the output voltage of the coil pair is given for 10 s for illustration purposes where the electrical voltage is compensated by the waveform generator. As the amplitude is lover than 1 V, the multimeter operates at 1 V range. However, due to the temporal variations of the compensating voltage by the waveform generator, an additional voltage may be induced on the coil pair. Therefore, it is critical to check whether the current induced voltage could be decoupled from the Faraday's voltage and the random contribution due to the waveform generator is eliminated in long-term measurements or not. In order to do so, the magnet assembly is kept at rest (Faraday's voltage is not induced on the coil pair) while the electrical current is delivered to the coil pair by the current source. The compensating voltage is generated by the waveform generator connected in series to the multimeter.

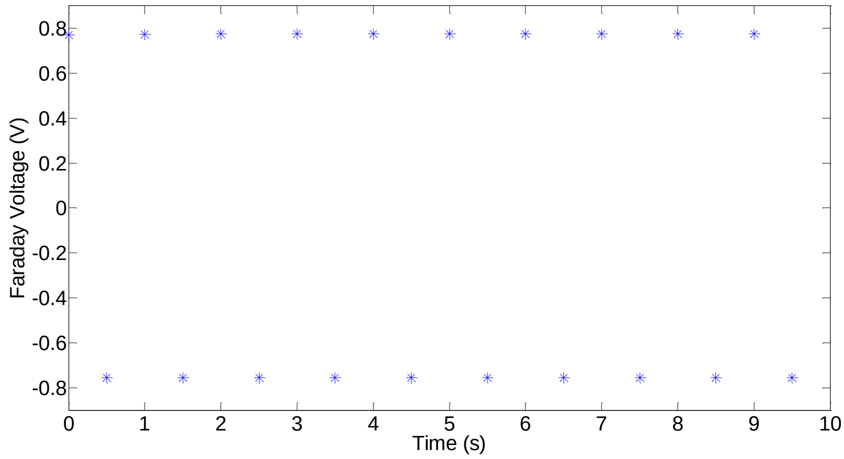


**Figure 4.** The output voltage of the coil pair. The sampling frequency of the multimeter is set to 2 Hz. The integration time of the device is set to 450 ms.

In Figure 5 the average value of the normalized electrical current effect as a function of time is given in blue stars. The normalization is done with respect to the total flux. The red dashed line indicates the expected zero contribution. In Figure 6, the standard uncertainty of the normalized electrical current with respect to time is given in blue stars. The red dashed line at 20 ppb stands for the highest total relative uncertainty anticipated by the realization experiments. It is clear that the mean value converges to zero within the uncertainty of 15 ppb for 48 hours or more. It has been observed that the major contribution in this measurement comes from the fluctuation in the current source rather than the induced voltage by the temporal variations of the waveform generator. This test is performed by applying solely the compensating voltage on the coil pair by the waveform generator when the output current by the current source is set to zero. The effect due to the waveform generator converges to zero within 5 ppb relative uncertainty about 10 hours. In conclusion, using a waveform generator is a practical solution in the realization experiment with a KB for having a better performance with the digital multimeter.

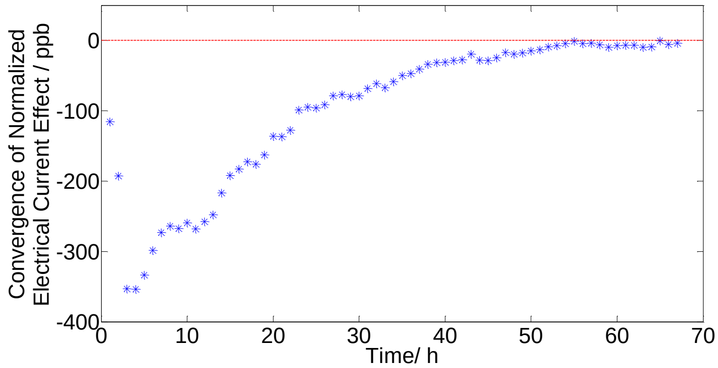


**Figure 5.** The average value of the normalized electrical current effect with respect to is given in blue stars. The normalization is done with respect to the total flux of the coil. The red dashed line indicates the expected zero contribution.

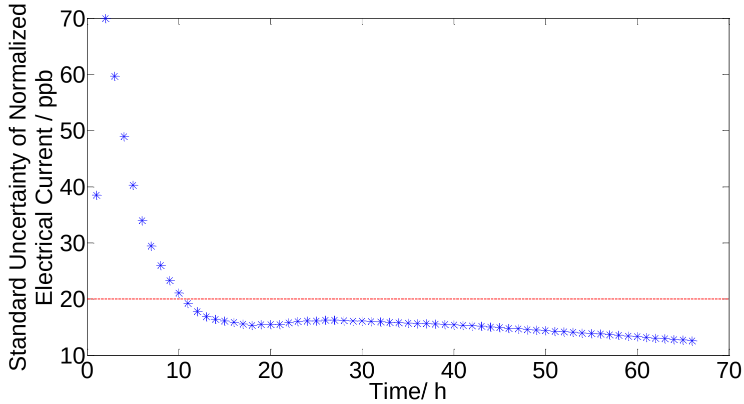


**Figure 6.** The standard uncertainty of the normalized electrical current effect with respect to time is given in blue stars. The normalization is done with respect to the total flux of the coil. The red dashed line at 20 ppb stands for the highest total relative uncertainty anticipated by the realization experiments.

## 5. CONCLUSION

Kibble Balance experiments allows the realization of mass unit in terms of Planck constant by the comparison of the mechanical power with the electrical one in accordance with the new definition of the kilogram. TÜBİTAK UME followed a different path in providing this link such that the UME KB-3 is constructed with a moving magnet as opposed to the traditional ones with a moving coil with the motivation to perform the measurement in one single phase. Despite many distinctive advantages of the simultaneous testing of Faraday's Law of Induction and Lorentz Force Law, there is one difficulty to be handled. The total voltage across the ends of the coil pair should be decomposed with relative uncertainties of about some part of a billion. The current induced voltage has an amplitude of 6.4 V. The digital multimeter measuring the voltage of the coil has a better performance at lower ranges. This is why; a waveform generator is connected in series to the multimeter as a compensating voltage source. However, one has to be careful since the temporal variations of the waveform generator may induce additional voltage on the coil pair. We have observed that this effect converges to zero for 10 hours within 5 ppb relative uncertainty. Therefore, the waveform generator is a practical solution for having better performance with the multimeter. However, fluctuations due to the current source require at least 48 hours measurement time for 15 ppb uncertainty. This uncertainty could be further reduced by decreasing the resistance of the coil pair or replacing the current source with a more stable one.

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## CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

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