Progress on Vacuum-to-Air Mass Calibration System Using Magnetic Suspension to Disseminate the Planck-Constant Realized Kilogram

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***Abstract* — The kilogram is the unit of mass in the International System of units (SI) and has been defined as the mass of the International Prototype Kilogram (IPK) since 1889. In the future, a new definition of the kilogram will be based on precise measurements of the Planck constant. The new definition will occur in a vacuum environment by necessity, so the National Institute of Standards and Technology (NIST) is developing a mass calibration system in which a kilogram artifact in air can be directly compared with a kilogram realized in a vacuum environment. This apparatus uses magnetic levitation to couple the kilogram in air to a high precision mass balance in vacuum. Technical details of the levitation technique, the vacuum-to-air calibration system, and vehicles for transferring masses into and out of vacuum will be presented.**

***Index Terms* — Magnetic levitation, mass metrology, Planck constant, revised SI, SI units, watt balance.**

I. INTRODUCTION

The kilogram is the only remaining base unit in the International System of Units (SI) that is still defined by an artifact, the International Prototype Kilogram (IPK), which is made of a platinum-iridium alloy and is maintained at the International Bureau of Weights and Measures (BIPM) in Sevres, France. Therefore the quantity of mass can only be realized at the BIPM, and must be disseminated to the rest of the world through a chain of comparison calibrations through the world's National Metrology Institutes (NMIs). The NMIs maintain traceability to K through periodic comparisons of their 1 kg standard(s), which in most cases are also made of the same platinum-iridium alloy, through the working standards of the BIPM. The NMIs then realize a mass scale from approximately 1 mg up to several thousand kilograms through multiple and sub-multiple calibrations involving their 1 kg standard(s) and working standard artifacts.

Redefinition of the kilogram based on Planck's constant will take place perhaps as soon as 2018 [1]. When this happens, an interesting dilemma in the dissemination of the kilogram will result from the fact that both the watt balance and the International Avogadro Coordination (IAC) project will realize the kilogram in a vacuum environment. In order to use the new kilogram realization to calibrate mass artifacts in air, some method of transferring the vacuum realization to atmospheric pressure will have to be employed.

II. NIST METHOD FOR TRANSFERRING VACUUM MASS CALIBRATIONS TO AIR

NIST is currently developing an instrument that is capable of directly comparing the known mass of a kilogram in a vacuum environment to an unknown mass of another kilogram in air using the same high precision mass comparator [2]. In this scheme, an all-aluminum vessel containing two adjacent chambers, one under vacuum and one at atmospheric pressure, is used. A high precision mass comparator (10 kg capacity with 0.010 mg resolution) is contained in the evacuated chamber; this comparator can compare artifacts in the usual way in the evacuated chamber, but can also compare a vacuum artifact to an artifact in the atmospheric pressure chamber by connecting the comparator to the artifact across the vacuum-air boundary via magnetic levitation. This is illustrated in Figure 1.

In the NIST vacuum-to-air mass comparison system, the mass in air is compared directly to the calibrated mass in vacuum using the same high precision mass balance; therefore, it doesn't rely on any empirical modeling, such as that required for calculating the amount of water that is adsorbed onto a mass moved from vacuum conditions to atmospheric pressure air.

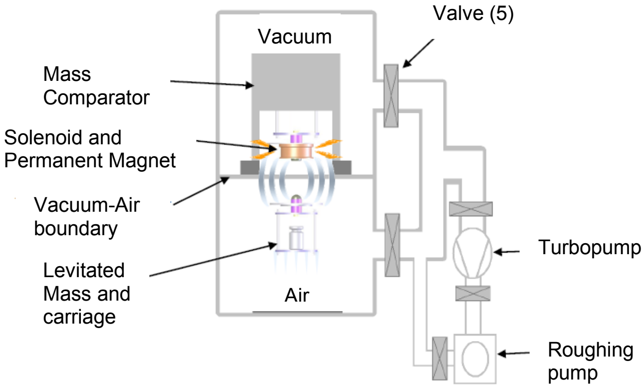

Fig. 1. Schematic of the magnetic levitation principle used in the vacuum-to-air mass comparison system. The all-aluminum vessel has an upper chamber containing a vacuum compatible mass balance and a lower chamber for the artifact to be compared to the mass in vacuum.

The mass comparator's weighing pan is coupled to the mass in air by magnetic suspension. Two Neodymium (NdFeB) permanent disk (3.81 cm diameter) magnets (N52 grade) provide the necessary magnetic field. Since it is not possible to stably levitate objects with only ferromagnets [3], dynamic control is required and provided by a solenoid (75 Ω) wound around the upper magnet. A proportional-integral-derivative (PID) control algorithm, with feedback from a Hall sensor between the two magnets, actively adjusts the coil magnetic field to maintain stable levitation. The Hall sensor is insensitive to the magnetic field from the coil and therefore monitors the vertical position of the lower magnet assembly. A pulse width modulation technique based on the design of Marsden [4] is used to drive the variable current through the solenoid while maintaining constant power dissipation.

III. OPERATION OF THE AIR-TO-VACUUM LEVITATION SYSTEM.

A. Achieving Levitation: Lifters and Extractors

During mass comparisons, the lower mass assembly will have to be repeatedly levitated inside the lower chamber. The magnetic field from the coil is relatively weak compared to the permanent magnets so that lower mass assembly needs to be physically lifted close to the actual levitation position before the PID control algorithm can stabilize the levitation. This is accomplished by three linear actuators (lifters) equally spaced around the magnet assembly. The lifters simultaneously push inward wedges against a ring (see Figure 2) attached to the lower mass assembly which lifts it into position. Three additional linear actuators (extractors) can also push the lower mass assembly down if stuck to the top of the vacuum chamber by the magnetic field.

B. Upper Chamber: Carousel for Loading Masses

The top plate of a commercial mass carousel has been modified so that it can be used to transfer masses under vacuum from a load lock to the mass comparator. In addition to the normal holes in the plate designed to transfer the masses to the mass pan, a series of parallel slots have been cut from the outside of the circular plate. These slots will enable fingers on the end of a linear translator to transport a new mass on or off of the carousel from the load lock.

C. Lower Chamber: Scheme for Loading Masses

Since nothing is physically attached to the lower mass assembly, the lower mass is free to rotate a full 360° when levitated. When it is necessary to transfer a mass to or from the carousel, wire manipulators will be used to rotate the levitated lower mass assembly into the necessary angular position. The levitation is then shut down while the mass is then transferred on or off the carousel. The carousel is located beneath the mass pan. Unused masses are stored on circular pedestals mounted on the top of carousel. The carousel then rotates the masses into position through a slot in the mass pan. The lifters will then lift the entire mass assembly to relevitate.

D. Mass Transfer Vehicles: How Masses Get In and Out of Vacuum

Calibrated masses will be transferred under vacuum from the watt balance to the levitation apparatus in a small portable vacuum chamber on wheels. Similar load locks, with two perpendicular linear translators, on both the watt balance and levitation systems will enable the mass to be transferred in and out of the mass transfer vehicle while under vacuum. Inside the mass transfer vehicle the masses will sit in a circular recess on a slotted holder while wedges on top prevent the mass from tipping during transport. The slotted base will enable fingers from a linear translator in the load lock to insert or remove a mass. In the center of the load lock will be a platform comprised of vertical rectangular posts which will be used to transfer a mass from the linear translator accessing the mass transfer vehicle to the one accessing the upper carousel.

IV. CONCLUSION

Technical details are presented for a magnetic levitation system that is being developed at NIST to simultaneously compare masses in air and vacuum for dissemination of the new kilogram based on precise measurements of the Planck constant. Software automation is used to achieve levitation, set up weighing designs, load and unload masses in the upper and lower chambers, and record mass and environmental measurements.

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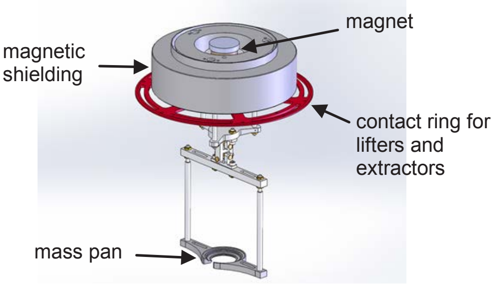

Fig. 2. Schematic of the lower magnetic levitation assembly