

The NIST Magnetic Suspension Mass Comparator and Precision Mass Metrology

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Abstract—The National Institute of Standards and Technology (NIST) magnetic suspension mass comparator will be used to facilitate the dissemination of the kilogram, realized in the 4th-generation NIST Kibble balance, from vacuum to air. This paper details the current status of the system. The primary focus is on the improvements made since CPEM 2016 concerning both random and systematic sources of error.

Index Terms—Kilogram, Measurement errors, Magnetic levitation, Weight measurement, Electromagnetic forces

I. INTRODUCTION

The International System of Units (SI) is undergoing a major change. In the coming year the unit of mass, the kilogram, will cease to be defined as the mass of the International Prototype Kilogram, and instead be realized through experiments that use a fixed value of Planck's constant [1]. One consequence of the change is that to achieve the highest levels of precision using Kibble balances, the new realization of the kilogram will occur in vacuum and methods of dissemination from vacuum to air are required [2]. The NIST magnetic suspension mass comparator (MSMC) has been designed to do this. The MSMC provides a direct mechanism through the use of magnetic suspension to allow mass comparisons to occur between artifacts housed in a chamber held at low pressure (< 1 mPa) to those held in a secondary chamber kept at atmospheric pressure.

The NIST MSMC falls into a larger class of instruments where magnetic suspension allows the measurement of forces in environments in which the force sensor can not reliably function. The most common of these instruments is used for measuring fluid density [3]. While similar to our approach, there are several differences that make the challenges of each unique. In this paper, we focus on two key experimental difficulties: (1) a random source of noise in the mass reading; and (2) a systematic error in the mass reading. We start by briefly describing the system and noting the size of the errors as of the 2016 CPEM [4], then we introduce the work performed to resolve these errors, and finally we conclude.

II. OVERVIEW OF THE MSMC

As detailed in [5] the MSMC, as shown in Fig. 1, is composed of two pressure-tight chambers connected on top of each other. The upper chamber, held at low pressure, houses a modified commercial mass comparator with custom hardware that provides a mechanism to couple a magnetic

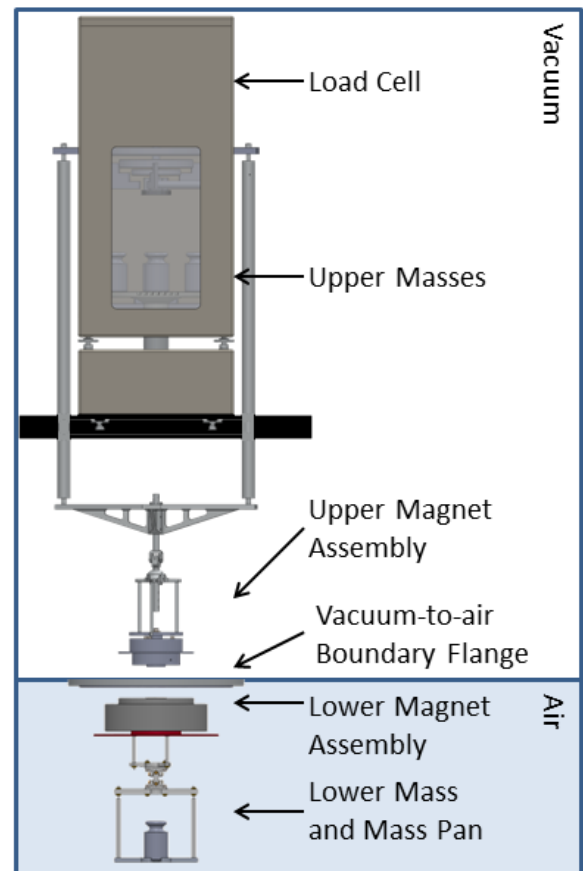


Fig. 1. General image of the MSMC. Important components are labeled.

assembly (consisting of a permanent magnet and coil) to the mass comparator. The lower (air) chamber houses a 2nd permanent magnet and is attached to a weighing pan. A custom built mass-exchange system allows for loading and unloading of masses onto the weighing pan. During weighings, the weighing pan (with or without a mass artifact) is magnetically suspended through an active feedback control system [6]. Otherwise, the mass comparisons are carried out in the usual way.

III. IMPROVEMENT IN ACCURACY AND PRECISION

At CPEM 2016 [4], our first results using the apparatus were presented. Figure 2, is a plot from that presentation. Two important conclusions were drawn from the figure at

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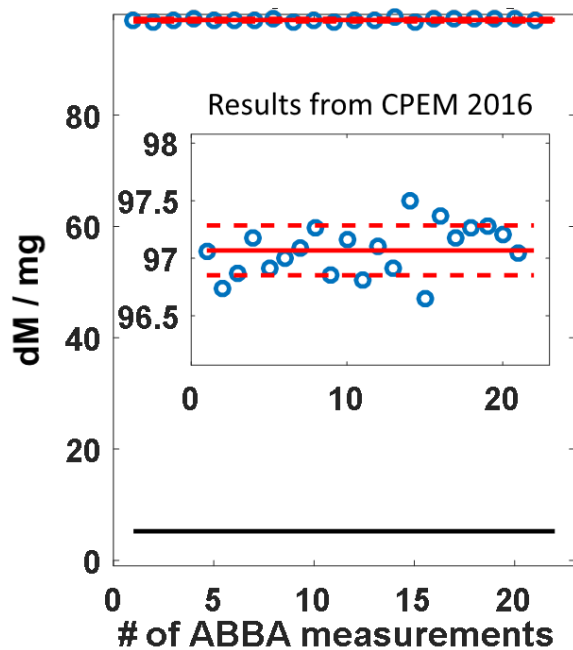


Fig. 2. Results for vacuum to air mass comparisons as of July 2016. At CPEM 2018, new, improved, results will be unveiled.

that time, (1) the precision of an individual measurement was inadequate to meet the goals of primary mass dissemination and (2) the accuracy was clearly unacceptable. The previous two years have been spent correcting these results and making other improvements. At CPEM 2018, we will present our latest results. Here, we outline the work we have done and speculate at where we expect to be at that time.

A. Precision

The display resolution of the commercial mass comparator is $10 \mu\text{g}$, while the results in 2016 show a spread of several hundred micrograms. This is the gap we strove to close over the last two years. To reduce the noise, we identified several potential culprits. The first was the pressure tight lower chamber. We identified the following problems: (1) the pressure varied at an unacceptable level within the measurement window, and (2) unacceptably large temperature fluctuations resulting from one of the motors used in our custom mass exchange system. Correcting these two effects was important but did not eliminate the noise. The third and most critical problem we discovered concerned the noise floor of the hall sensor which turned out to limit the feedback stability. To overcome this, we employed a secondary sensor using a heterodyne interferometer. This low noise displacement sensor coupled with a new feedback scheme based on state feedback dramatically lowered our noise by more than a factor of ten [7].

B. Accuracy

In Fig. 2, the solid black line at $5 \mu\text{g}$ was the expected result after buoyancy corrections, while the solid red line at 90 mg was the measured result. While this large systematic

discrepancy required extraordinary effort to understand, its origin was simple. The flange separating the vacuum and air chambers, and situated between the two magnets, was interacting with the system [8]. While the flange was made from a seemingly non-magnetic material aluminum, the large local magnetic field gradient at the flange was large enough to present a small magnetic interaction, resulting in a systematic, erroneous mass measurement. A simple experiment, moving the flange even a couple of millimeters closer to the upper magnetic assembly, decreased the interaction by a factor of two. Over the past year we have worked on a solution to this technical problem. Because of the exact nature of the measurement, solutions like those discussed by McLinden [9] are not directly applicable. However, we will show that a judicious choice of materials, with lessons from Ref. [9], can reduce this systematic interaction to an acceptable level.

IV. CONCLUSION

The NIST magnetic suspension mass comparator is a unique instrument designed to provide a fast and reliable means to facilitate mass comparison between artifacts located in different environments (namely, vacuum and air). The first results from the system were presented in CPEM 2016. Here we present the improvements made to allow the system to realize mass comparisons with the necessary uncertainty to meet the needs of the international mass community at the highest level, i.e. mass comparison measurements with a relative standard uncertainty at 1 kg of less than 20×10^{-9} .

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