Reduction of Type A noise in the NIST magnetic suspension mass comparator

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Abstract. The magnetic suspension mass comparator at NIST will be used to facilitate the dissemination of the kilogram, realized in the NIST-4 Kibble balance, from vacuum to air. The type A uncertainty, that is, the variation of the mass reading over time, is influenced by several factors. Our goal has been to understand all sources of noise and to minimize them to reduce the type A noise uncertainty below 20 µg. Here, we discuss the MSMC in general terms and focus on several sources of noise that we have been able to greatly reduce.

1. Introduction
In the coming year the unit of mass, the kilogram, will be redefined. The new realization will be through experiments that rely on a fixed value of Planck’s constant [1]. A major consequence of this change is that 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 perform this task. Through the use of magnetic suspension, the MSMC provides a direct mechanism to allow mass comparisons to occur between artifacts housed in a chamber held at low pressure (< 1 mPa) and those held in a secondary chamber at atmospheric pressure.

The use of magnetic suspension to facilitate the measurement of forces in environments in which the force sensor cannot reliably function predates the NIST MSMC. The most common application 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 application unique. For example, the average mass suspended in the MSMC is 20 times larger than that of typical densitometers. Furthermore, the required relative uncertainty for the MSMC is much lower than for the fluid density instruments. In this paper, we highlight our recent success in reducing the Type A uncertainty in the measurement.

2. Overview of the MSMC
As detailed in [4, 5] and shown in Fig. 1, the MSMC 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 assembly (consisting of a permanent magnet and coil) to the mass comparator. The lower (air) chamber houses a second permanent magnet that is attached to a custom 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
Figure 1. Generic image of the MSMC. Important components are labeled.

magnetically suspended through an active feedback control system [6]. Otherwise, the mass comparisons are carried out in the usual manner.

3. Improvement in Precision

As reported at CPEM 2016 [7], our first results using the apparatus had a standard deviation of over 200 µg on the steady-state reading of a suspended mass; for reference our desired Type A contribution is < 20 µg. The display resolution of the commercial mass comparator is 10 µg, more than 20 time smaller than the reported measured Type A noise. As reported [8], 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. By fixing the leak in the chamber, the pressure variation has been reduced to the order of 1 Pa per hour. For context, a 10 Pa change is expected to lead to a 10 µg shift in mass because of differences in the buoyant force [9]. Because we can measure pressure at the Pascal level, larger variations can easily be detected. The large temperature fluctuations presented a more interesting challenge. Due to the temperature dependence of the buoyant force, a temperature change of 1 mK will produce about a 10 µg change in mass reading. Instead, we observed mass changes 10 times as large, and occurring at different time scales. Once the temperature variations were isolated to the motor, unplugging produced a drastic improvement in the variation in the mass reading. Fig. 2 shows the strong correlation between temperature
fluctuations and mass readings. The motor was unplugged at the 2 hour mark. The y-axis is a running standard deviation of the data over a 1 minute moving window. We believe the source of the uncertainty results from unstable convection currents that apply a time-varying force to the suspended load [10]. Of course, simply unplugging our motors is not a viable solution; instead we disassembled the motor housings and moved the controllers outside of the chamber. Furthermore, we reduced the holding currents to zero and the driving currents were reduced by more than 50 %. Additional gains can be accomplished by optimizing the speed of the motor, the trade-off being high speeds require less power (less heating) but can create a dangerous environment for the precious artifacts.

Correcting these two effects was important but did not eliminate the noise during suspension of the weighing pan. 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 that uses a heterodyne interferometer. Fig. 3, shows data for the vibrational amplitude spectrum of the weighing pan. The lowest plot (green) shows the spectrum when the weighing pan is not suspended. The other two lines are for suspension utilizing either the hall sensor or optics signal as feedback. The low noise displacement sensor coupled with a new control scheme based on state feedback [11] dramatically lowered the noise, almost to the unsuspended level.

4. A Note on Type B Uncertainty
The type B systematic error that was also reported in Ref. [7] and discussed in Ref. [8] has also been lowered by more than two orders of magnitude. The source of the error was from the flange separating the vacuum and air chambers, and situated between the two magnets [12]. While the flange was made from the seemingly non-magnetic material aluminum, the large local magnetic field gradient at the flange was enough to present a small magnetic interaction that resulted in a systematic error in the mass measurement. A simple experiment consisting of moving the flange a couple of millimeters closer to the upper magnetic assembly decreased the interaction by a factor of two. A solution to this technical problem will be presented at IMEKO 2018.
Figure 3. Vibrational amplitude, $\alpha_{\text{int}}$, of the suspended weighing pan as measured by an interferometer. The green line is the noise floor when not suspended. The limiting noise floor of the magnetic hall sensor during magnetic suspension can clearly be seen when contrasted to that of the suspension while feeding back on the optical signal. The peak in the red line at 5 Hz corresponds to the frequency of the restoring force created by the active feedback controller.

5. 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. Initial results for the system were presented 2016 [7]. Here, we present the improvements made to allow the system to realize mass comparisons with an uncertainty that exceeds the needs of the international mass community at the highest level, i.e. OIML class E1 for a one kilogram mass [13].

References

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