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THE NIST MAGNETIC SUSPENSION MASS COMPARATOR: A LOOK AT TYPE B UNCERTAINTY.

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Abstract: The magnetic suspension mass comparator is a unique system for calibrating kilogram artifacts between vacuum and air. While the magnetic suspension mass comparator allows for direct vacuum-to-air mass measurements, there are several corrections that need to be taken into account. Here, we discuss in greater detail our work to understand the systematic error that results from magnetic interactions with the outside world.

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1. INTRODUCTION

The redefinition of the kilogram in 2018 will alter long established methods for mass dissemination [1]. While the current definition and its subsequent dissemination occurs in air, the new realization will happen in vacuum (< 10^{-3} Pa). This shift is necessary so experiments like the Kibble (Watt) balance [2] and the XRCD project [3] can realize mass at the required levels of precision. For example, the Watt balance relies on interferometry to make precision velocity measurements of the motion of the weighing pan. The variations of the index of refraction in air will affect the measurements and lead to larger uncertainties. However, as one moves down the mass dissemination chain, most end-users will still work at standard atmospheric conditions. The issue lies here, when moving a mass artifact from vacuum to air or air to vacuum the mass value is known to change [4]. The change can be attributed to the adsorption and desorption of molecules in the air from the surface of the artifact. As a result, dissemination methods need to be established for transferring the realized kilogram from vacuum to air to account for these changes. One way of doing this is an established, though indirect method, referred to here as the sorption method. Another way utilizes magnetic suspension, and is aimed towards providing a direct and alternative approach. This paper is focused on the second method, which will allow direct mass comparison between an artifact in vacuum and one in air, and also provide a cross-check on the sorption approach.

The sorption method relies on the repeated measurement of two artifacts of the same material having similar volume but different surface area [5]. The two artifacts are transferred from vacuum to air and back several times. During this period the relative mass change between the two artifacts is measured and an empirical value for the adsorption coefficient can be determined. This value can then be used to account for the mass change per unit surface area when moving an artifact of the same material properties from vacuum to air. Unfortunately, the measured coefficient is known to vary between material types, environment conditions, and the surface quality of the mass artifacts themselves. Thus, repeated measurements and checks for all mass artifacts should be carried out.

The second method, which will be referred to as the magnetic suspension mass comparator or MSMC method provides an alternative by allowing for direct comparisons where material type, quality, etc. are not a factor [6, 7]. The MSMC, see schematic in Fig. 1, is comprised of two, vertically juxtaposed, aluminum chambers. The upper one is typically held under vacuum and will be referred to as the vacuum chamber, while the lower one is held at standard atmospheric conditions and will be referred to as the air chamber. The vacuum chamber houses a 10 kg load commercial mass comparator which has a resolution of 10 μg and a 10 g weighing range. The chamber also houses an apparatus for loading and unloading of masses, both into and out of the chamber and on to and off of the weighing pan of the mass comparator. A special adaptor is connected to the dial weight stack to support the magnetic suspension components. This adaptor holds a pair of downrods that connect to a bridge that is positioned beneath the mass comparator. Hanging from the bridge is a samarium-cobalt (SmCo) magnet surrounded by a tightly wound coil. The coil acts as an electromagnet and provides the variable magnetic force needed for stable suspension of the weighing pan located in the air chamber. Surrounding the coil are a set of magnetic shields used to attenuate the spatial field profile of the SmCo magnet. Directly below the SmCo, but in the air chamber, is an identical magnet with similar magnetic shielding; this is connected to the weighing pan for holding the mass artifacts in air. The air chamber also houses a mass exchange system and holder for positioning the lower magnet assembly and weighing pan in the proper position to achieve suspension. The suspension is covered in more detail by Stambaugh [8].

Briefly, a hall sensor is placed on the flange that separates the vacuum and air chamber and is located directly between the two SmCo magnets. By monitoring the field between the two magnets and feeding back on the electromagnetic coil, suspension of the assembly in the air chamber can be achieved. While magnetically suspended, the entire mass of the sustained suspended assembly is read by the mass comparator in the vacuum chamber. Because the magnetic assembly and weighing pan are suspended during measurements of the mass in vacuum and mass in air, they are ultimately subtracted out of the mass comparison. Thus, one is left with a direct comparison between the masses. Of course, there are corrections that must be accounted for and they are discussed below.

Before delving deeper into the MSMC setup and its associated corrections, it is necessary to point out that a similar measurement device exists that is geared toward the measurement of thermodynamic equations of states [9]. Densitometers utilize known weights submerged in a wide range of fluids to measure $p-\rho-T$. That is the density of the fluid, ρ, at different pressures and temperatures. Here, the magnetic suspension is needed because fluids under test can often be at extremely high pressures (>20 MPa) and temperatures (> 400 K), such environments are incompatible with precision mass comparators. The suspension allows for the measurement of the buoyant force acting on the sinker. From this, the density of the fluid under test can be derived. While the magnetic suspension is utilized in a similar manner, that is to measure mass using a mass comparator located in a different chamber, there are several technical differences between the two techniques, which present unique challenges to each. The first of these is the mass comparator range. The densitometer experiments often use a balance with full measurement range and a capacity of 111 g. This allows for more flexibility in the use of calibration weights. Second, the level of precision sought by the density community is at least a factor of 10 less than our desired levels. Finally, the comparison being made there is ultimately between the added fluid in the lower container to a reference fluid. In other words, the comparison is between measurements in the same chamber; we are comparing between two separate chambers.

In order to make an accurate measurement of the mass difference between the mass in vacuum and that in air, three corrections need to be taken into account. The first is the buoyancy correction, as the mass located in air will have an upward buoyant force acting on it that the vacuum mass does not. Second is gravity, as the two masses being compared are located at different heights. The acceleration of gravity varies enough over the distance as to have a measurable effect on the gravitational force acting on the two masses. Finally, there is the force transmission error correction, which relates to how efficiently the gravitational force acting on the suspended assembly is coupled to the balance in the vacuum chamber [9, 10]. Ideally it would be 100 % efficient, but magnetic interactions with the suspended assembly and the outside world are unavoidable. Such interactions must be either minimized or measured so that they can be accounted for. In this paper, we will briefly review the first two corrections and then discuss the origin of the interactions that make the third type of correction necessary, how it impacts us and what we are going to do about it.

2. CORRECTIONS

1. Gravity

The acceleration due to gravity at a point on earth is dependent on the distance from the center of the earth and the density of materials located near the point of interest. To properly account for the change between the two measurement points, we employed a gravimeter to determine the local gravitational gradient. At the location of our experiment, a gradient of $(-2.74\times10^{-6} \pm 0.03)\ s^{-2}$ was measured [11]. This will lead to a mass difference of 0.296 mg between the vacuum mass and air mass. The uncertainty of the mass difference is 0.003 mg.

2. Buoyancy

Typically, mass comparisons are made between artifacts under the same environment conditions and corrections are needed to account for differences in volume. In this experiment we are comparing artifacts in two different environments, therefore the buoyancy correction must be taken into account by measuring the volume of the artifact and the air density. At the time of this writing, we have not carried out experiments to verify the expected uncertainty, however we have (a) carried out experiments on mass comparisons between masses of several different volumes and (b) determined the expected uncertainty for our measurement of the density of air. The density of air is determined by measuring pressure, humidity, and temperature while mass comparison measurements are taken. The values are then inserted into standard equations for extracting the air density. We estimate [11, 12] the impact will be 0.013 mg; though improvement is possible.

3. Magnetic Force

Background: The basis for the force transmission error is the magnetic interaction with the outside world; consider a magnet hanging from a balance. The mass of the magnet leads to a gravitational force, F_{g_n}, acting on the balance. The read-out force F_W is

$$F_W = F_{g_n} + F_m(z). \tag{1}$$

The magnet may interact with the outside world and the paramagnetic or diamagnetic interaction force, $F_m(z)$, will respectively add to or subtract from the gravitational force [13], leading to a biased reading. In the example just provided, the systematic error will not affect typical mass calibrations because the difference between the readings of two masses are used. The systematic error gets subtracted out because it does not change; the distance between magnetic and outside world is fixed.

For the case of using magnetic suspension to mediate the connection between the vacuum and air chambers, the interaction problem is slightly more involved, see Fig 1. For this simple derivation, forces resulting from buoyancy and changes in gravity are ignored. The overall force acting on the balance when a mass is placed on the weighing pan directly connected to the balance is

$$F_W = F_{g_n,U} + F_m(z_U) + F_{g_n,L} - F_m\left(z_{L,m_U}\right) + F_{g_n,m_U} \tag{2}$$

and for the mass on the suspended pan

$$F_W = F_{g_n,U} + F_m(z_U) + F_{g_n,L} - F_m\left(z_{L.m_L}\right) + F_{g_n,m_L}. \tag{3}$$

Here $F_{g_n,x}$ is the gravitational force acting on x, where $x = U$ for the assembly located in the vacuum (upper) chamber or x= L for the assembly located in the air (lower) chamber, and m_i is the mass of the artifact in either the upper ($i = U$) or lower ($i = L$) chambers. $F_m(z_{L,m_i})$ is the magnetic force between the suspended lower assembly and outside world, with ($i = L$) and without ($i = U$) the mass loaded in the lower chamber. Since we are interested in mass differences, we subtract Eq. (2) from Eq. (3):

$$\Delta F_W = \left(F_{g_n,m_U} - F_{g_n,m_L}\right) - F_m\left(z_{L,m_U}\right) + F_m\left(z_{L.m_L}\right) \quad (4)$$

or

$$\frac{\Delta F}{g} = \Delta m = \Delta m_W + \frac{F_m\left(z_{L,m_U}\right) - F_m\left(z_{L.m_L}\right)}{g}. \quad (5)$$

In this simple model the desired mass value will be shifted by $\delta m = \left(F_m\left(z_{L,m_U}\right) - F_m(z_{L.m_L})\right)/g$. It is this value that must be minimized. The term δm can be related to the magnetic coupling factor ϕ used in McLinden [10] by the relation, $\phi = 1 + \delta m/m_{m_L}$; m_{m_L} is the mass of the artifact in the lower chamber.

The challenge of accounting for the force transmission error has been covered in depth [9, 10, 14]. However, while instructive, developed methods are not directly applicable to the MSMC and the dissemination of mass. The approach taken for densimeters is to either (a) keep the vertical position of the suspended magnet fixed or (b) measure the effect in situ. To keep the vertical position, $z_{L,m_U} = z_{L,m_L}$, fixed for different mass values, the current can be adjusted to compensate for the change in mass. This poses several problems for the MSMC, as the current, I, needed to compensate for the kilogram change is approximately 1 A: (1) the coil is located in the vacuum so heating is an issue; and (2) the electrical connection to the coil involves high gauge wires that cannot sustain such large current loads. It may be possible to operate at $+I/2$ for one mass value and $-I/2$ for the other. In the steady-state, the average current and thus heating would at least be constant. However, removing the generated heat load from vacuum would still present a challenge. Operating the coil in air, and the suspended pan in vacuum is plausible, but in the current design not straightforward. Then there is still the issue of pushing such a large, constant current through the high gauge wires connecting the coil to the outside word.

Alternatively, in McLinden [10], a prescription is laid out for measuring the effect *in situ*. This approach is not feasible in the MSMC. In short, to correct for the systematic error *in situ* one would need to know the absolute mass values in vacuum and air, which is the very point of the current experiment. If we could start with such knowledge, the system would cease to have utility.

Another approach would be to minimize dF_m/dz. First, this can be achieved by positioning the flange that separates the two magnets closer to the upper magnet. Of course, this has its limits. The separation between the two magnets is fixed, so the distance by which the flange can be moved away from the suspended magnet is finite. Furthermore, if the flange is too close to the coil, variations in the average coil current can also cause interactions. Yet another approach is to minimize the strength of the interaction by decreasing the magnetic permeability of the material between the two magnets.

Finally, we note that another possible source of magnetic interaction comes from the surrounding fluid [10, 14]. The suspended magnetic assembly is kept in a sealed chamber at atmospheric conditions. Approximately 20 % of the air is composed of oxygen. Several groups in the density community have reported force transmission errors resulting from interactions of the suspended magnet with the paramagnetic oxygen in the air.

Results: While corrections for buoyancy and gravity are expected and unavoidable, systematic errors resulting from magnetic interactions are more difficult to predict and correct, and are thus best avoided. Choices such as constructing the chambers using aluminium were done to minimize such effects. When the system was deployed for the very first vacuum to air mass comparison, a systematic error of 92 mg was measured when comparing a mass in the vacuum chamber to one in the air chamber (vacuum-air). When both chambers were held at air (air-air) the effect was 100 mg. After further investigation, it was determined that the difference between the air-air and vacuum-air resulted from the flexing of the aluminium flange separating the two chambers after evacuating the upper chamber. Running suspension without the flange was impractical, so an auxiliary setup was built, where measurements could be made with no flange between the two magnets. In this case, the error dropped to ≈1 mg, which was the resolution of the balance used for the testing. Inserting a thinner aluminium plate between the magnets showed a return of the systematic error, though with a smaller magnitude. Furthermore, the relative position of the flange between the magnets was found to affect the systematic error; the systematic error decreased as the flange was positioned closer to the upper magnet (further from the bottom). All these results are consistent with the expected result indicated by Eq. 5.

In order to solve this problem, there are three options: (1) keep the separation distance between magnets constant, (2) minimize the overall effect, or (3) reduce the magnitude of the change in the systematic error when going from air-air to vacuum-air to a relatively constant value that can be measured accurately and precisely and then corrected for. While the first option is possible, it presents several technical problems. For now, we have decided to explore the latter two options. At the time of this writing, we are testing options and investigating different materials to minimize the magnetic permeability and interaction. By reducing the overall effect, we expect the change from flexing in the flange to decrease significantly, allowing us to follow-up with option (3) above. Air-air measurements can be done to quantify any remaining effect, which could be corrected if sufficiently small. Since the air-air measurements are only concerned with mass differences, the weights used would not require calibration as only their mass values relative to one another would be needed.

Finally, in the measurements we have carried out thus far, we have focused on difference measurements, i.e., we were not configured to accurately measure shifts in mass values, only the differences. To test for any influence from the oxygen in the environment, we carried out mass comparisons using both room air in the lower chamber and a nitrogen enriched atmosphere in which there was of < 1 % O_2 in the chamber. The upper chamber contained room air at atmospheric pressure. After accounting for the buoyancy difference between humid air and nitrogen, we were unable to measure a difference above the 1 mg level. A further, more detailed measurement and analysis is planned to look for smaller effects.

4. CONCLUSION

The MSMC, through magnetic suspension, allows for a direct comparison between two masses, one in air and the other in vacuum. Like the magnetic suspension systems used for measuring thermodynamic properties of fluids, the magnetic suspension allows the balance to reside in a distinct environment from the measured mass. However, because we are interested in calibrating the mass in air using the mass in vacuum, many of the measurement approaches used by the density community are not applicable; especially when dealing with magnetic interactions between the interface and lower magnet. We have identified the aluminium flange currently separating our two magnets and vacuum from air, as the source of the measured systematic error. Different approaches for dealing with such source of systematic error are currently being investigated, and progress toward this goal will be presented in the talk.

5. REFERENCES

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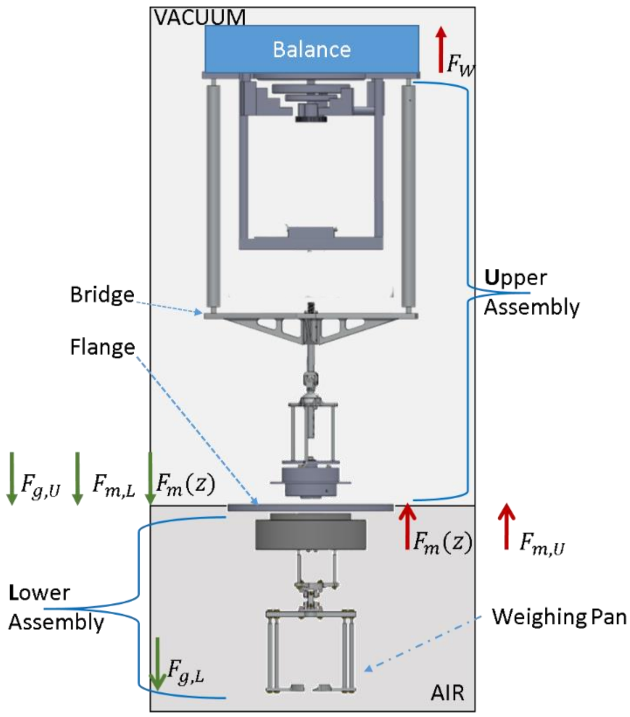

Figure 1: Force diagram for MSMC.