

# Magnetic Levitation System for the Dissemination of a Non-Artifact Based kilogram

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## Abstract

We describe a new approach to directly link air and vacuum mass measurements. This approach uses magnetic levitation along with vacuum and balance technology to realize vacuum mass measurements. It provides direct traceability to the International Prototype kilogram through the U.S. national prototypes without the intermediary use of vacuum artifacts. This approach will provide a direct link between the national standard of mass currently defined in air and the vacuum-based realizations founded on fundamental constants. We describe the proof-of-concept experiment, basic operation principles and challenges, initial modeling calculations, preliminary results, and the expectations of the next generation system\*.

## Introduction

The unit of mass, the kilogram, is the last remaining fundamental SI unit defined by an artifact. There are three main shortcomings to this artifact definition: First, there is a constant danger that the artifact will be damaged or destroyed through mishandling or a catastrophic event at the Bureau International des Poids et Mesures (BIPM) in Sevres, France. Second, since there is only one defining artifact for the entire world, comparisons involving the International Prototype kilogram (IPK) must be done at the BIPM, clearly an inconvenience for distant laboratories. Third and most importantly, the kilogram suffers from long-term instability, which has been attributed to surface effects<sup>1</sup>. Numerous efforts worldwide are aimed at redefining the kilogram with an

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\* Certain commercial equipment, instruments, or materials are identified in this document. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

invariant of nature.<sup>2</sup> These efforts are centered on three main experiments: the watt balance or electronic realization of the kilogram<sup>3</sup>, the Avogadro or silicon approach<sup>4</sup>, and the atom-based kilogram or ion accumulation<sup>5</sup>. However, all of the above approaches suffer from many limitations including the conflicting needs of performing the experiment in vacuum and the reality of the current definition of mass in air at atmospheric pressure.

For an alternative definition of the kilogram to rival the current artifact definition, a relative uncertainty of  $2 \times 10^{-8}$  or better<sup>6</sup> is required. This level of precision can only be achieved, in the watt balance for example, if major sources of uncertainty, such as those associated with index of refraction of air and air buoyancy correction, are either eliminated or minimized. For this reason, the watt balance is currently running under vacuum conditions, which is incompatible with the current realization of the mass unit (and all associated methods of dissemination of the unit) in air at ambient atmospheric pressure. Transfer of the unit to vacuum requires an unbroken traceability chain to the International Prototype kilogram, as well as characterization of the stability of the artifacts and their surfaces during transfers from air to vacuum and vice versa. This requirement remains a major challenge for further advances in redefining the unit of mass. Therefore, there is a critical need for redefining how artifact mass metrology is maintained and disseminated; furthermore, it requires the ability to measure artifacts in vacuum, and directly tie the vacuum measurements to both the IPK and the alternative definition with a measurement uncertainty as good as or better than the uncertainty of the alternative definition of the kilogram.

Many of the world's metrology labs make an indirect link between air and vacuum mass measurements by measuring mass in vacuum and then characterizing the absorption layers of contaminants<sup>7</sup> during vacuum to air exchanges and vice-versa. We describe a system based on a specially designed high precision mass balance for the *simultaneous* comparison of a mass in air to a mass in vacuum. This system relies on a magnetic levitation technique (described below) to couple a mass pan in air, through a non-magnetic interface, to a separate vacuum chamber containing the second mass pan and the high precision mass balance. This system will enable the direct linkage of the NIST watt realization in vacuum to the current SI definition of the kilogram in air.

### **Motivation and Proof of Concept Apparatus**

Around 1950, the experiments of Clark<sup>8</sup> and Beams<sup>9</sup> suggested that magnetic suspension could be used as a sensitive analytical balance under conditions where standard balances are difficult to use, such as for weighing materials inside vacuum chambers, in liquid, vapors, or gases. Since that time, many useful instruments involving magnetic levitation have been developed, including commercial balances,<sup>10</sup> densitometers,<sup>11</sup> and the spinning rotor gauge for measuring gas pressure<sup>12</sup>. For a mass balance application, the method of magnetic levitation used is very critical to the overall performance of the balance, as well as to the construction of the system. If the position of the levitated mass is not stable about a point of equilibrium, the precision of the mass comparison

will be limited by the fluctuation of the balance's reading. In addition, the presence of any stray magnetic field gradients due to the presence of ferromagnetic materials near the balance will influence its reading<sup>13</sup>. Therefore, the magnetic field configuration used for levitating the mass in air must be properly shielded from the balance, and all materials used in the construction of the system must be non-magnetic.

As a result of Earnshaw's theorem,<sup>14</sup> stable levitation of a ferromagnetic object cannot be achieved through the exclusive use of permanent magnets. Instead, it is necessary to regulate the magnetic field using an active feedback control system, e.g., a solenoid whose magnetic field can be varied. The role of the variable magnet (solenoid) is to quickly adjust the overall magnetic field in response to a change in the levitated object's position. Positional feedback can be provided in many ways using a variety of different sensor technologies. Servo control of the magnetic field is used to realize stable levitation using the positional feedback signal as an input.

For the proof-of-concept apparatus, the magnetic levitation system must generate enough force to levitate a 1 kg mass standard and its pan suspension assembly. There are competing interests to be addressed when choosing a levitation scheme. First, the gap distance between the magnet poles needs to be large enough to accommodate the thickness of the interface between the vacuum and air chambers. Second, the change in force per unit vertical distance

between the poles should be as small as possible in order to improve stability and reduce the resolution requirements on the positioning feedback system. Finally, the configuration must produce stable levitation that is not easily made unstable by a torque or force in any direction. Therefore, a restoring force is needed for any deviation in position that is perpendicular to the levitating magnetic field.

In order to evaluate the magnetic fields produced by a given levitation design, we used commercially available finite element analysis-based (FEA) simulation software to solve Maxwell's equations. The software is very versatile, allowing the use of both static and dynamic fields as well as magnetic and non-magnetic materials. Construction materials are chosen from a built-in library and configured into an array that can be solved both two and three dimensionally. From the FEA solution of the array, one can create flux plots and determine the forces acting on the levitated body. The force on a magnetized object placed in a magnetic field may be calculated from the following vector equation:

$$\vec{F} = \vec{\nabla}(\vec{M} \cdot \vec{H}) \quad (1)$$

Here, F is the force, M is the magnetic moment of the object, and H is the magnetic field. Equation 1 states that the force goes as the *gradient* of the magnetic field; in other words, a non-uniform magnetic field is necessary for a force to be exerted on the object. Fortunately, the same FEA-based software used to simulate the magnetic field of the levitation models can also calculate the force on the object to be levitated. The following sections describe the simulation

of three different levitation designs under consideration for use in the proof of concept apparatus.

### **Attractive Magnetic Levitation Model**

Figure 1A shows an attractive magnetic levitation system. The force for levitation is produced by two permanent magnets whose magnetic moments are oriented in a parallel direction so that the magnetic pole faces attract each other, as depicted in the block diagram of Figure 1B. The upper magnetic pole is fixed while the magnetic pole in the lower chamber (attached to the mass to be levitated—not shown) is free to move vertically. Permanent magnets are colored orange and the pole faces are colored blue. The upper magnet has a solenoid attached to it for active control of the levitating force as discussed above. Figure 1C shows that the distribution of flux lines between the poles is very dense, indicating a strong attractive force.

Figure 2A presents a graph of the force on the object to be levitated as a function of its distance from the upper magnet (referred to as “the gap”) using the attractive configuration. Permanent magnets are specified by their ability to resist demagnetization, called the coercivity, which is expressed in units of A/m. In the attractive model, the force on the levitated object will depend on the coercivity of the permanent magnet materials used, and the three plots in Figure 2A correspond to different coercivity permanent magnet materials. Referring to

Figure 2A and Table 1, a 2.4 kg mass pan can be levitated at a gap distance of 19.7 mm if the strongest coercivity magnetic material is used in the construction of the levitation system. Placing a 1 kg mass on the pan to raise the total levitated mass to 3.4 kg changes the gap distance to 14.6 mm. While this gap will allow a thick glass vacuum window to be used, the positional sensitivity is also the largest for any of the three types of magnets, -0.43 mg/nm. The other two types of magnets yield a smaller positional sensitivity, but the gap size is also reduced, especially for the weakest of the three magnet materials (-813 242 A/m).

Figure 2B shows the sensitivity of the vertical and horizontal forces to a small change in horizontal position for two different initial vertical positions. Note that while the vertical force  $F_z$  remains nearly the same, the horizontal force changes in a nearly linear fashion. Furthermore, the horizontal force is negative, meaning that it is in opposition to the direction of movement, similar to the restoring force of a stretched spring. This is a very desirable characteristic of the attractive model, as it eliminates the need for active horizontal control.

### **Attractive/Repulsive Magnetic Levitation Model**

Figure 3A shows a different type of model, one that uses both attractive and repulsive magnetic forces. In this model the end of the connecting rod to the air chamber mass pan has a ring-shaped permanent magnet with the polarity as shown. This ring magnet is situated in the magnetic field produced by two other

ring magnets, one above and one below the connecting rod ring magnet. From the relative polarities of the three magnets involved, it is easily seen that the lower ring magnet repels the connecting rod magnet while the upper ring magnet attracts it. The orientation of magnets and a simulation of the magnetic field for this configuration are shown in Figures 3B and 3C respectively; a Force vs. Vertical Position plot is shown in Figure 4A. Figure 4B shows that the horizontal force increases for a small horizontal deviation in position; this means that a change in horizontal position will induce a force that will tend to knock the levitated object out of equilibrium. Table 2 summarizes the information presented in Figure 4.

### **Repulsive Magnetic Force Levitation Model**

Figure 5A shows a model that uses a purely repulsive magnetic force to achieve levitation. It is evident from the magnet polarities shown that the lower ring magnet must balance the weight of the connecting rod, suspension pan, and mass under test through a purely repulsive magnetic force. A variable field solenoid is attached to the fixed magnet in order to maintain stable levitation. Plots of vertical and horizontal force as a function of position are presented in Figures 6A and 6B. Figure 6B shows that the horizontal force increases for a small horizontal deviation in position, leading to instability. Generally speaking, stable magnetic levitation using a repulsive force configuration is difficult to achieve. Active control of the horizontal and rotational degrees of freedom is needed, which makes the system much more difficult to implement. However,



the purely repulsive configuration has the advantage of being less sensitive regarding force as a function of vertical position than the attractive force model, which relaxes the requirements on the vertical positional feedback system.

### **Proof-of-Concept Apparatus Design and Performance**

The characteristics of each of the three levitation models are summarized in Table 3. Based on the inherent horizontal stability and the relative simplicity of construction, we decided to build a proof-of-concept levitation system using an attractive magnetic force model. Although simulations indicated that the sensitivity of the vertical force vs. gap distance may be a factor of 10 larger than for the models using a repulsive force, we used this design because of its relative simplicity and the presence of a horizontal restoring force.

A schematic drawing of an attractive magnetic levitation design is shown in Figure 7. For simplicity, the proof-of-concept apparatus was constructed with both masses in air at atmospheric pressure. In Figure 7, the vertical position signal is provided by a “shadow sensor” photodiode that detects a laser beam that just skims the top of the magnetic pole that is attached to the levitated assembly. The solenoid field is servo controlled about a position corresponding to a certain output level of the photodiode detector. Any change in the detected light level will cause the solenoid field to be appropriately increased or decreased to maintain stable levitation. Servo control is implemented with a simple PID (Proportional, Integral, and Derivative position loop) controller computer board.

The mass of the levitation parts including the pan suspension is 0.60 kg. Figure 8 is a plot of Magnetic Force vs. Pole Separation calculated from the FEA simulation software using the construction parameters of the system. This plot shows that the stable separation position between the fixed and levitated parts (mass pan without 1 kg mass) is 22 mm. When a 1 kg mass is placed on the pan, the total mass of the levitation parts is 1.60 kg and it can be balanced at a separation distance of 8.5 mm. Note that at this position, the attracting force gradient is 0.14 mg/nm.

A 10-kg balance was used in the Proof-of-Concept apparatus. The manufacturer's specified readability and repeatability of this balance are both 1 mg, but the precision of actual measurements will depend on environmental and experimental conditions. When measuring a 1 kg mass under magnetic suspension, the measured standard deviation was 11 mg, a factor of 10 higher than the balance's specification. Much of this noise may come from inadequate temperature control, turbulent airflow from the laboratory, and instability of the position of levitation. The accuracy of mass measurements is also influenced by experimental conditions. For instance, a parasitic magnetic force was found between the levitation device and the test table; this was not unexpected, as the table has significant permanent magnetism. This extra force adds to the force provided by the magnetic poles, so that when the test mass was placed on and off the levitated mass pan, the distance between the table and the levitated parts changed by 12 mm instead of the expected 13.5 mm (see Figure 8). This effect causes the balance reading to be inaccurate, and we found that the extra

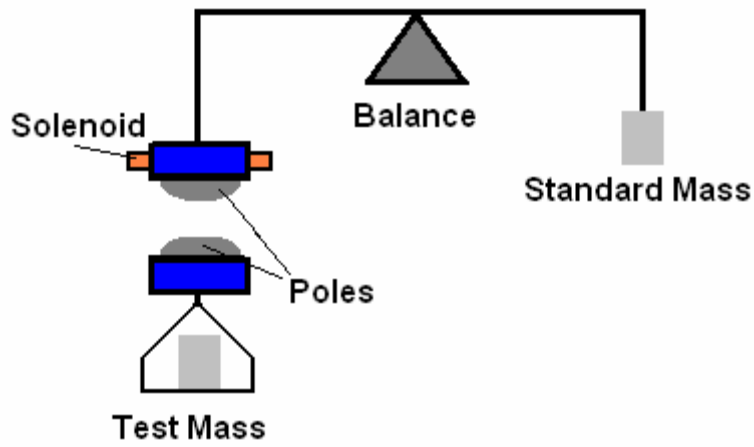
magnetic force was the cause of a 1.2 g change in the 1 kg artifact's apparent mass. After replacing the ferromagnetic table with a non-magnetic optical table, the difference between the 1 kg mass measurements on the balance pan and on the levitated pan was reduced to 33 mg, and the effect of the force due to the magnetic field leakage on the 10 kg balance was measured to be 21 mg.

### **Next Generation Design**

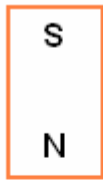
To achieve the goals stated in the introduction of this paper, an improved magnetic levitation system addressing the problems identified in the proof-of-concept apparatus must be designed and implemented. Creating a non-magnetic environment, replacing the shadow detector with a laser interferometer, using a balance with higher readability and stability, and using magnetic shielding around the magnet poles will significantly improve the precision and accuracy of the weighing results.

In addition to the improvements mentioned above, the second generation system must demonstrate the ability to simultaneously compare masses in air and vacuum. A special non-magnetic vessel is being constructed which will contain air and vacuum chambers separated by a glass interface (to allow the interferometer's laser beam to pass through). A custom designed, vacuum-compatible, high precision mass balance is also under construction. We will report on the performance of the special chamber and balance in a future publication.

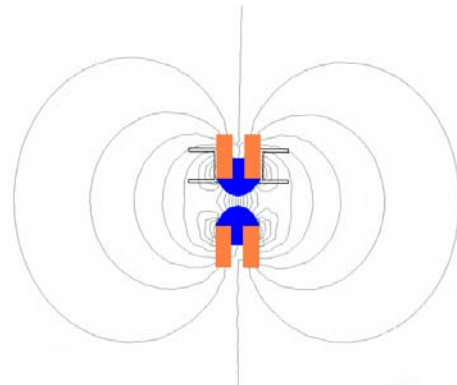




A

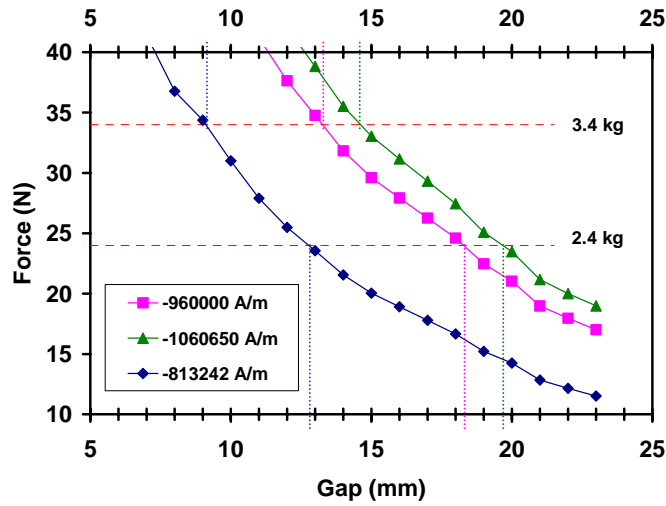


B

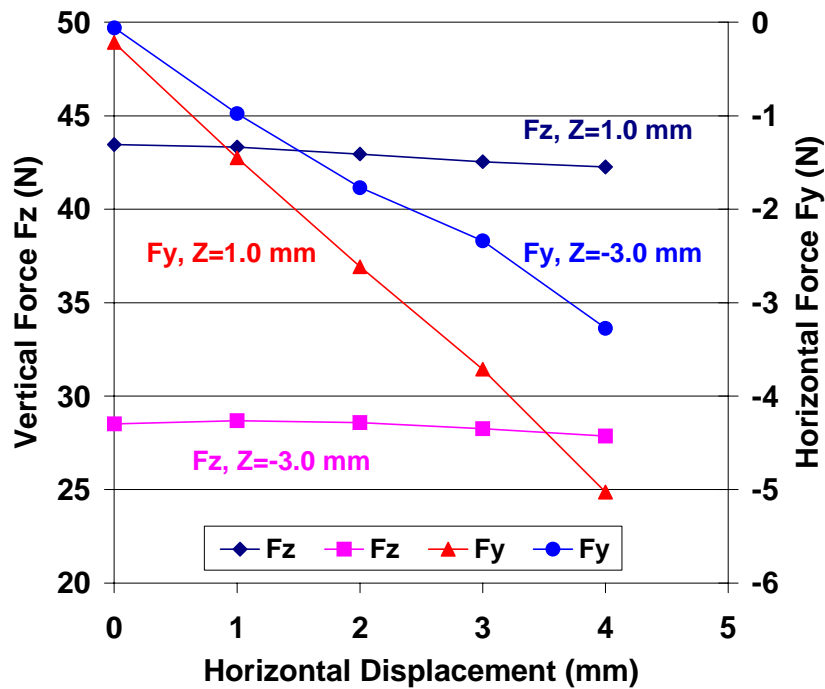


C

**Figure 1.** **A.** Levitation model using an attractive magnetic force. The test mass is the levitated object, and both the standard and test masses are in air at atmospheric pressure. The laser and detector are used for vertical position feedback. **B.** Magnetic pole orientation for attractive model. **C.** Magnetic field simulation showing flux lines



A.



B.

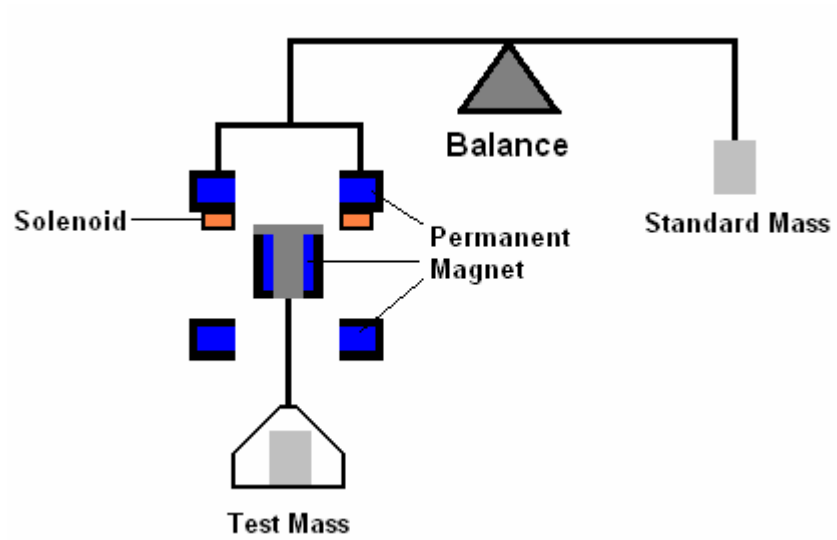
**Figure 2.** Calculated plots showing the force on the lower (levitated) object for the attractive model.

**A.** Force vs. Pole separation distance (Gap) for different permanent magnet coercivities

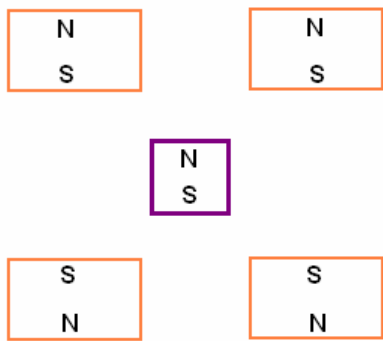
**B.** Effect of horizontal displacement on the vertical and horizontal forces. The negative values for  $F_y$  indicate a restoring force opposite the direction of a small horizontal displacement.

	Magnet material 1	Magnet material 2	Magnet material 3
Coercivity	-813 242 A/m	-960 000 A/m	-1 060 650/A/m
2.4 kg	12.8 mm	18.3 mm	19.7 mm
3.4 kg	9.2 mm	13.3 mm	14.6 mm
Difference	-3.6 mm	-5.0 mm	-5.1 mm
Sensitivity	-0.27 mg/nm	-0.39 mg/nm	-0.43 mg/nm

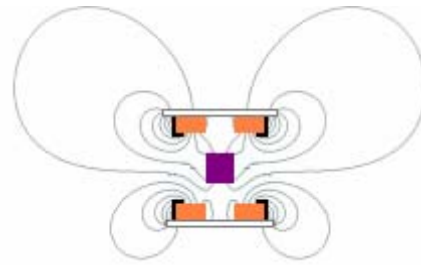
**Table 1.** Levitation distances and position sensitivities for two levitated objects whose difference is 1 kg. The force vs. position plots in Figure 2 were used



A.



B.

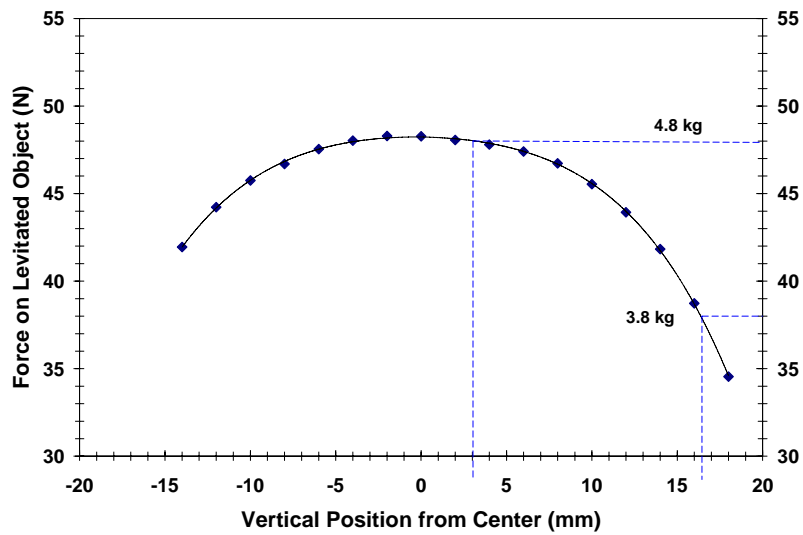


C.

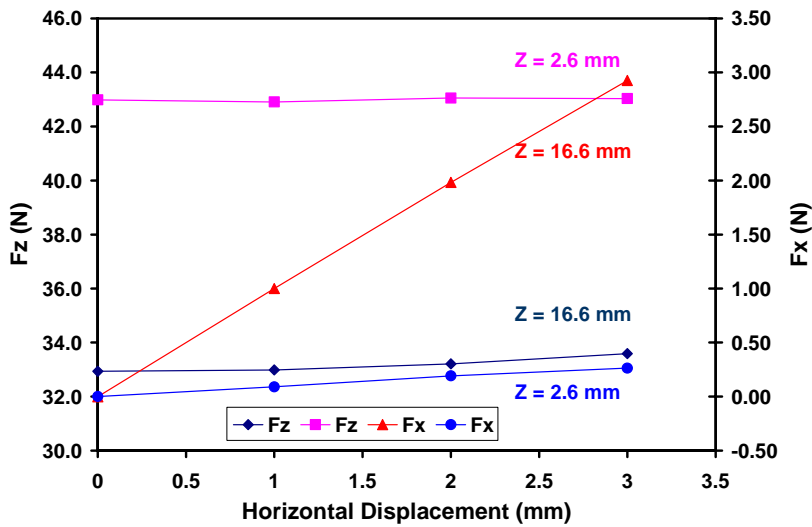
**Figure 3.** **A.** Levitation model using a combination of attractive and repulsive magnetic forces. The test mass is attached to the levitated object. **B.** Magnetic pole orientation for combination model. **C.** Magnetic field simulation showing flux lines

B





A

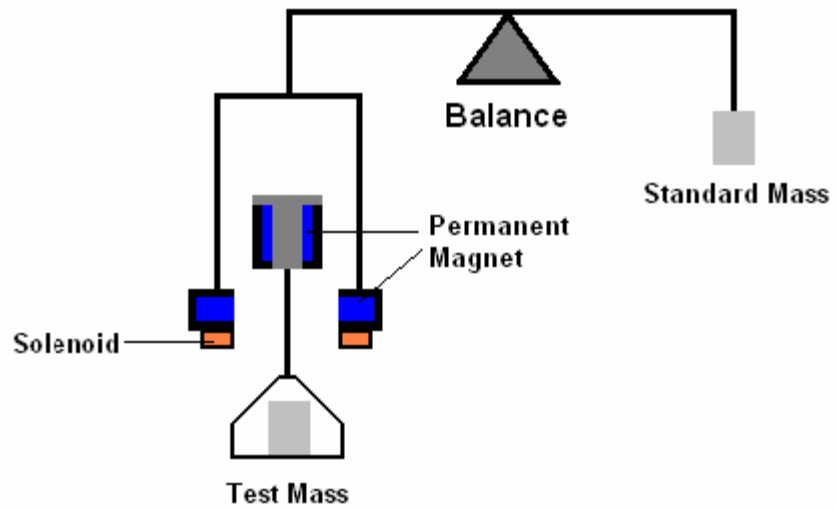


B

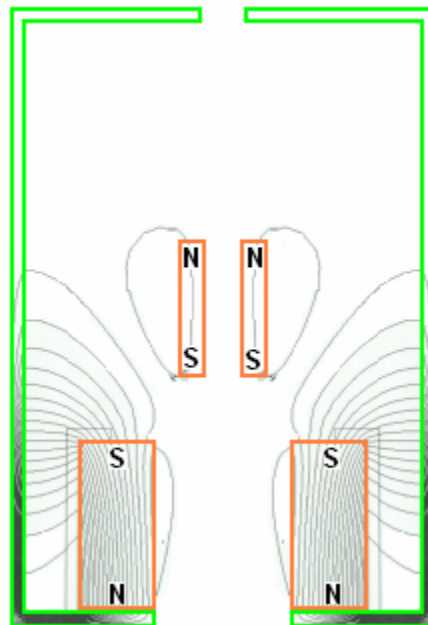
**Figure 4.** Calculated plots for the Combination Attractive/Repulsive model showing the force on the lower (levitated) object. **A.** Vertical force vs. vertical position from center (mm). **B.** Effect of horizontal displacement on the vertical and horizontal forces. The horizontal force increases positively, causing positional instability.

<b>Magnet material coercivity</b>	-960 000 A/m
<b>3.8 kg</b>	16.5 mm
<b>4.8 kg</b>	3.0 mm
<b>Difference</b>	13.5 mm
<b>Sensitivity</b>	-0.09 mg/nm

**Table 2.** Levitation distance and position sensitivity for two levitated objects whose difference is 1 kg. The Force vs. Position plot in Figure 4A was used

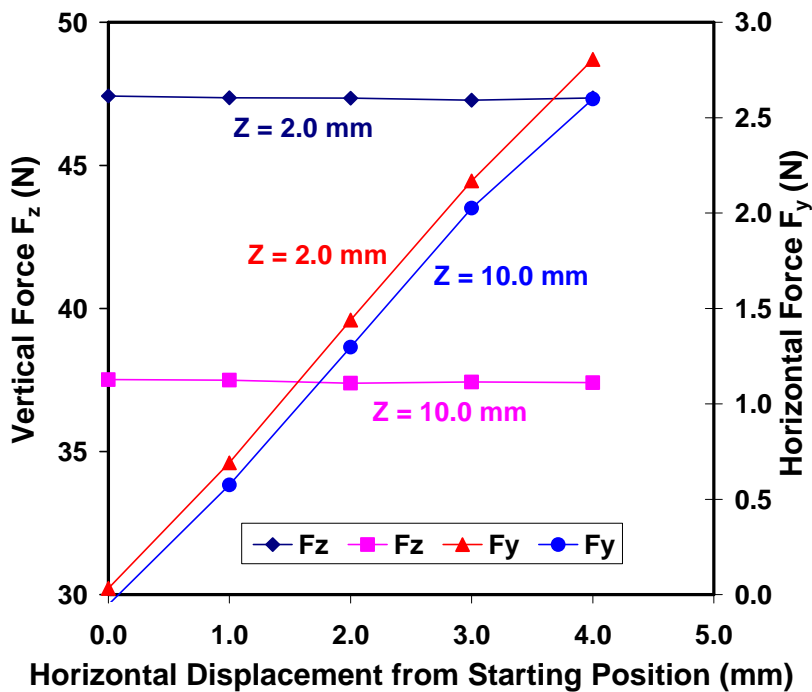
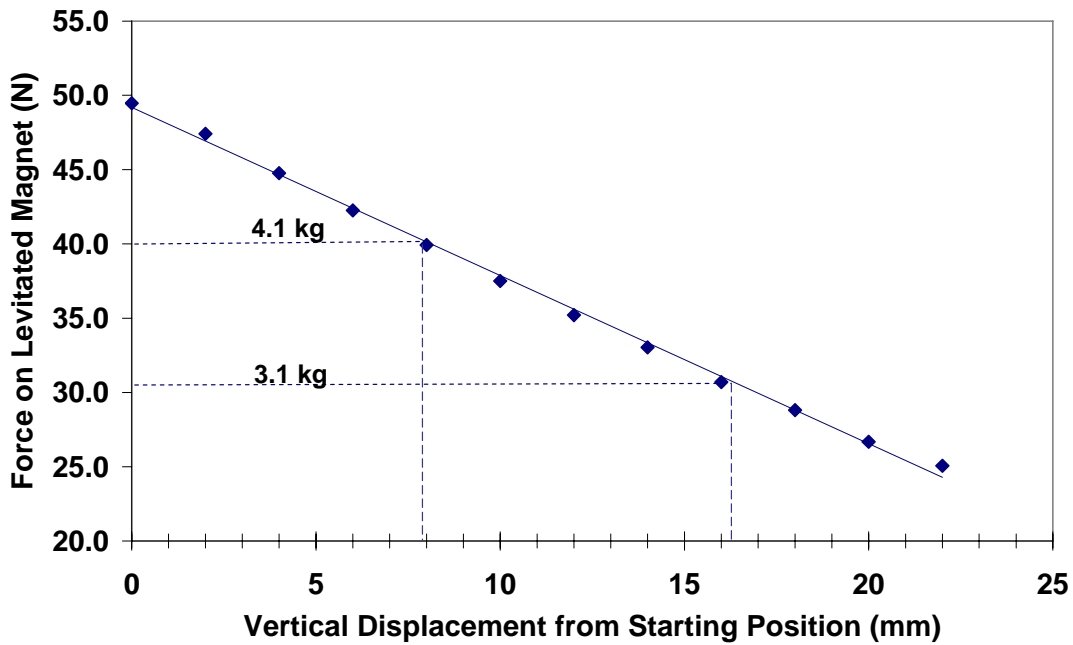


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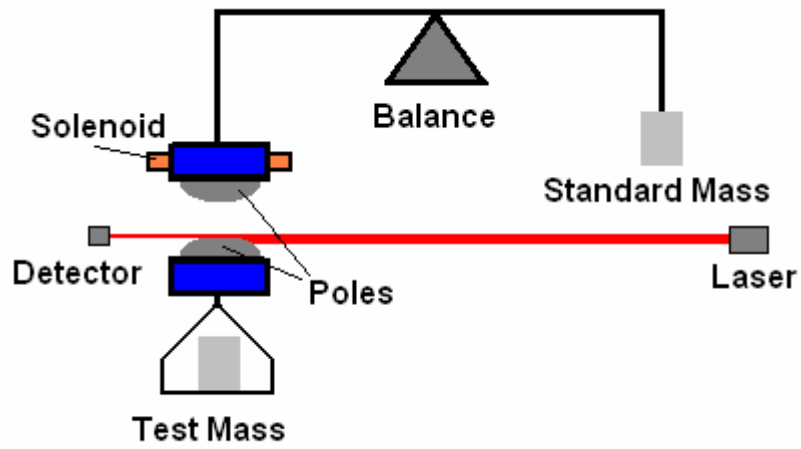
**Figure 5 A.** Levitation model based on repulsive magnetic force. **B.** Magnetic field simulation showing flux lines. The green material is magnetic shielding, which “short circuits” flux lines.



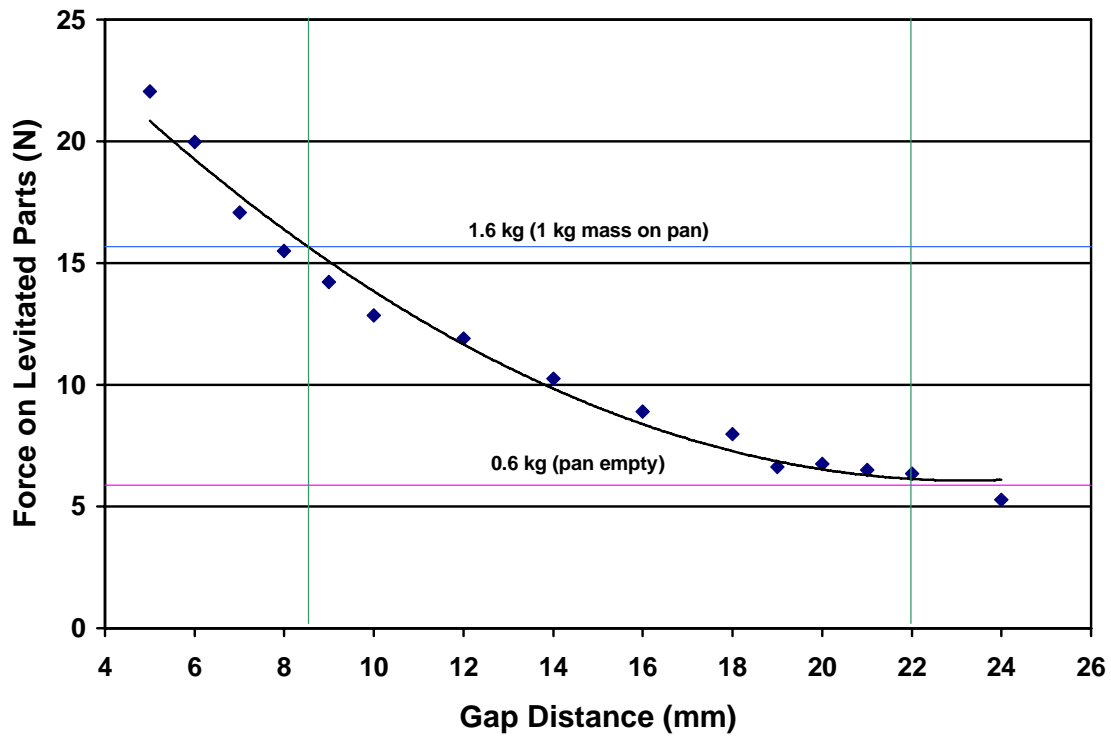
**Figure 6.** Calculated plots for the Repulsive model showing the force on the lower (levitated) object. **A.** Vertical force vs. vertical position from center (mm). **B.** Effect of horizontal displacement on the vertical and horizontal forces. The horizontal force  $F_y$  increases positively, causing positional instability.

	<b>Attractive Model</b>	<b>Repulsive Model</b>	<b>Combination Model</b>
<b>Ease of Construction</b>	<b>Easiest</b>	Hard	<b>Hardest</b>
<b>Vertical Force Sensitivity</b>	<b>Greatest</b>	In Between	<b>Least</b>
<b>Response to Horizontal Displacement</b>	<b>Restoring Force</b>	<b>Repulsive Force</b>	<b>Repulsive Force</b>

**Table 3.** Comparison of the characteristics of the levitation models considered for use in the proof-of-concept apparatus. Green indicates a desirable feature, red indicates an undesirable feature.



**Figure 7.** Schematic of Proof-of-Concept levitation design using attractive magnetic force. The vertical position of the levitated mass pan is provided by the “shadow detector” arrangement shown and discussed in the text.



**Figure 8.** Magnetic Force generated by the attractive model used in the proof of concept apparatus. The black line is a least-squares fit to the data. The empty mass pan will levitate at around 22 mm (intersection of pink and green lines with graph) and the 1 kg mass on the pan will levitate at 8mm (intersection of blue and green lines with graph).

## References

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  - <sup>10</sup> For example, the Mag-Lev Balance by Abbess Instruments and Systems, Inc., Ashland, MA USA website: <http://www.abbess.com/phycis/maglev.html>
  - <sup>11</sup> Dale V. Ulrich, D.W. Kupke, and J.W. Beams, *Proceedings of the National Academy of Science*, **52**, 349-355 (1964).
  - <sup>12</sup> J.K. Fremerey, *J. Vac. Sci. Technol.* **A3**, 1715 (1985).
  - <sup>13</sup> R. Davis and M. Gläser, *Metrologia* **40**, 339-355 (2003).
  - <sup>14</sup> S. Earnshaw, *Trans. Cambridge Phil. Soc.*, **7**, 97-112 (1839).