Acoustic Balance: Weighing in Ultrasonic Non-Contact Manipulators

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***Abstract*—Acoustic traps and levitation systems can lift, translate and manipulate a wide range of objects and materials without contact. This enables new manipulation capabilities for robots that may not be possible otherwise. This paper presents an acoustic balance, a contactless method for weighing acoustically trapped objects in air. The method works by measuring a step response: the system commands a change in the phase of the acoustic emitters, which results in a sudden change in the equilibrium position of the trap. The object held within the acoustic trap undergoes damped oscillation as it settles into the new equilibrium point. The mass of the trapped object can be determined from the frequency of oscillation. Combined with methods for adding and merging materials in the trap, the method presented here can potentially enable a robot to operate a closed-loop process to acquire or maintain a desired quantity of material. Using weight as an error signal, material could be added by the acoustic system until the required quantity is in the trap.**

***Index Terms*—Weighing, Acoustic Levitation, Non-Contact Manipulation.**

I. Introduction

Acoustic levitators (or traps) can manipulate a variety of objects in air, ranging from millimeter scale objects [1], liquid droplets [2], powder-like granular matter [3], and small living organisms [4]. This paper presents a contact-less method for weighing the contents of an acoustic trap, a sensing mode which can enable new capabilities for material handling robots. One advantage of acoustic levitation over other methods is that it does not rely on specific electrical or magnetic properties of the object. It can therefore be applied to a wide variety of materials, enabling a large set of applications ranging from biomedical research [5] to robotics [6].

An attractive feature of acoustic traps and levitators is the non-contact manipulation capabilities which does not need intermediate surfaces and containers like vials, measuring scoops, or weighing pans. Transferring small quantities of powders or liquids to intermediate surfaces can lead to sample contamination or measurement inaccuracy as material is lost in each transfer. If acoustically trapped material could be weighed using the trap itself, it could enable new automated approaches to closed-loop material handling that are not possible today. Combined with the acoustic levitator's multi-object control and positioning capabilities [7], a powder, liquid, or set of small objects could be captured in the trap, weighed, and additional material added and merged with the captured object depending on the weighing result. Marco et. al [8] have shown droplets can be transported and merged via multifocal point acoustic levitators.

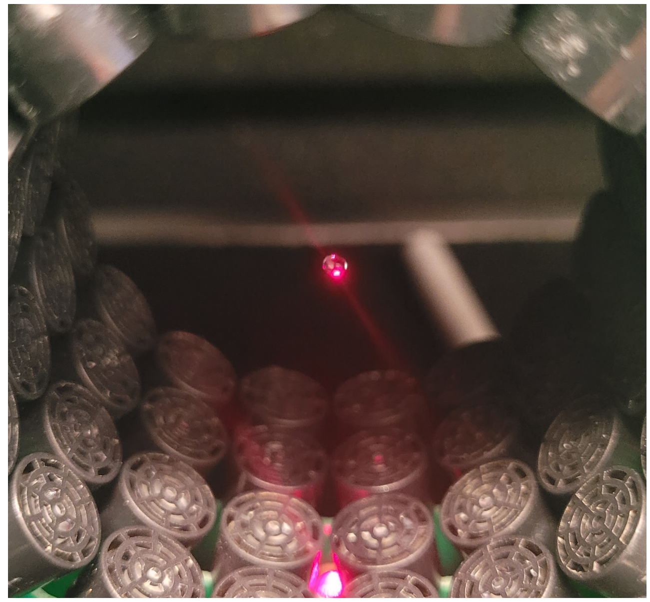

Fig. 1: A levitated droplet of mineral oil suspended in an acoustic field and weighed by the acoustic balance.

Our method works by applying a step function perturbation to the position of the trap's minimum and observing the frequency of the object as it oscillates down to its new equilibrium position. The principle of determining mass from shifts in the resonance frequency of a mechanical structure is well established [9]. Representative mechanical resonators include micro-electromechanical structures [10] and a piezoelectric transducer vibrating in a microfluidic tube channel [11]. Past acoustic levitation work used shifts in the resonance frequency of suspended liquid droplets to determine material characteristics, such as the density of droplets [12]. This requires a known sample volume to covert to droplet mass which may be difficult to obtain when weighing living organisms, or other geometrically complex objects.

Weighing of trapped objects has been demonstrated for optical and magnetic traps. Hillberry [13] describes the use of optical tweezers for weighing trapped objects and Dutta [14] shows similar weighing functionality for a magnetic trap. These levitation methods require the object to have specific optical or electromagnetic properties.

Often times, acoustically levitated samples are on the scale of micro- to milligrams in mass, about the size of a microliter droplet of solution. Ultrasonic handling of samples is already being used in laboratory settings to dispense these droplets

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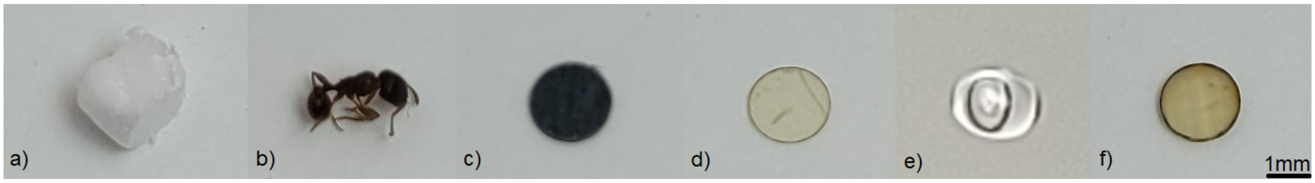


Fig. 2: The variety of objects used as test masses to validate the acoustic balance: **(a)** polystyrene, **(b)** ant, **(c)** hardfiber disk 5 mil thick, **(d)** FR4 disk 5 mil thick, **(e)** mineral oil droplet with air bubble trapped inside, and **(f)** FR4 disk 10 mil thick

[8], [15]. It may also be desirable to measure and monitor objects as they progressively change in mass, such as an evaporating water droplet, or become increasingly difficult to monitor as the number of samples simultaneously under examination increases. Acoustically levitated weighing of samples can allow a robot to collect crucial mass data about an individual sample and automate tasks such as sorting, modifying, or adding additional solution to a liquid droplet. Due to the sensitivity required to detect the small quantity of mass or change in mass, a torque or current sensing method embedded in a robotic arm likely would not meet the necessary resolution to accurately measure the mass of objects at this scale. Acoustic traps can merge the sample manipulation and precision measurement mechanisms, enabling automated lab operation with no contamination or operator error. In the past, we have shown an acoustic trap configured as a robotic end-of-arm tool that picks up millimeter-scale objects from a table top, which the robot uses to sort object by color [16].

This paper presents a method for determining the mass of small objects trapped in a phase controlled multi-acoustic element levitation system, an acoustic balance. Balance describes a device which weighs by comparison of mass and therefore needs an object of known mass to calibrate subsequent measurements. The acoustic balance relies on a reference object of known mass to establish the k value for determining the mass of subsequently measured objects.

The results show that the weighing system can obtain mass estimates for acoustically levitated objects with a minimum mass of at least 0.2 mg with a percent error of 5.56% or better.

II. Principles of Levitated Object Weighing

Acoustic traps manipulate objects through pressure wave gradients. Marzo [1] et al. showed that multi-channel, phase controlled acoustic elements can manipulate and move objects like polystyrene foam peanuts through the air, overcoming gravity. The restoring force acting on the trapped object in this weighing system can be approximated using the acoustic radiation force on a spherically shaped particle in air, expressed as the gradient of the Gor'kov potential [17], $F_{rad} = -\nabla U$, and other methods such as finite element analysis can better represent the acoustic force field for specific objects or known geometries [18].

An object suspended in the acoustic trap is subjected to a restoring force that confines the object similar to a mass spring system. Omitting damping forces, the confining force on the object can be linearly approximated by the equation $m\frac{d^2x}{dt^2} + kx = 0$, where k is the restoring force constant, and x is the horizontal displacement. The relationship between the object's mass, m, and resonance frequency, f can be described by the expression for the natural frequency of a harmonic oscillator, eq. 1.

$$m = \frac{k}{(2\pi f)^2} \tag{1}$$

The object oscillates due to a sudden change in the acoustic field, shifting the stable, equilibrium point of the field horizontally along the x axis.

III. Acoustic Weighing Methods

Fig. 2 shows the types of objects tested. These include polystyrene cubes, ants, hardfiber disks, fr4 disks and mineral oil droplets. The actual mass of each object tested was also recorded using a Mettler Toledo XPR2U balance with a minimum sample weight of 0.03 mg, precision of 0.001 mg and smallest readable digit (readability) of 0.0001 mg [19].

Fig. 3 shows a cross section of the acoustic levitation system, with the laser beam positioned on the x = 20mm plane and the object positioned at x = 21mm, referred to as position 1. The acoustic trap displaces the object, moving the object to x = 20mm, position 2, from its location at position 1. This 1 mm step allows for enough trapping discontinuity to cause the object to oscillate while remaining trapped within

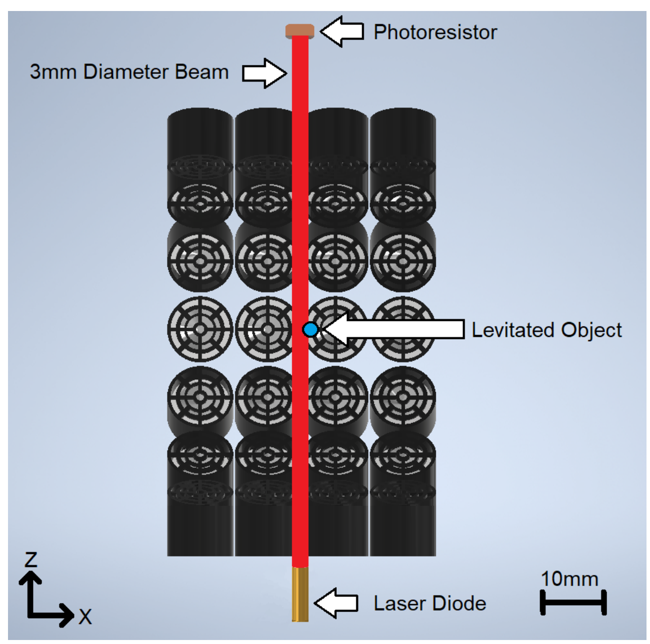
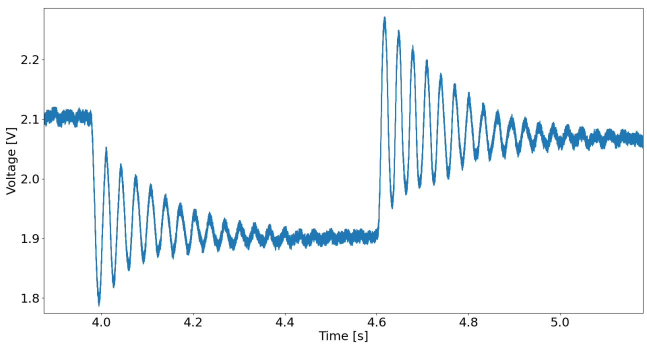
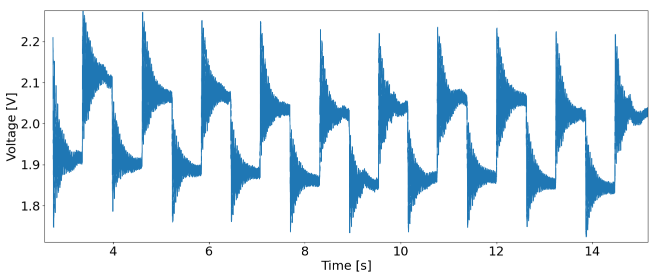


Fig. 3: Cross section view of the acoustic trap. The laser diode travels through the gaps between the transducers along the x = 20mm plane and is aligned such that an object positioned in the middle of the acoustic trap will occlude the laser from the photoresistor.



(a)



(b)

Fig. 4: **(a)** The voltage signal from the photoresistor corresponding to the displacement and oscillation of the particle in the acoustic trap. The trapped object matches an underdamped oscillating system in both the primary displacement, t=4.0s to t=4.6s and the secondary displacement of the object within the trap, t=4.6s to t=5.2s. **(b)** The full waveform recording for a single test object. The object is displaced 20 times total shown by the 20 damped oscillations. The total time to measure a single object is about 12 seconds.

the targeted acoustic position. A sudden displacement allows the system to quickly record the damped natural frequency to approximate the resonance frequency and calculate the object's mass using the force constant for the acoustic trap. The movement phase from position 1 to position 2 is called the primary displacement. After the object has stopped oscillating, a secondary displacement can be performed, moving the object from position 2 back to position 1. Fig. 4a shows both the photoresistor voltages during the primary and secondary displacement steps. The primary and secondary displacements are performed 10 times each to obtain a better frequency measurement, 20 frequency samples in total. Fig. 4b shows the raw photoresistor voltage over the span of all 20 displacements. The Fast Fourier transform is computed for each primary and secondary displacement wave and the mean frequencies and frequency standard deviation of the primary and secondary displacements are computed to obtain 2 mean damped natural frequencies and 2 standard deviations. The frequency standard deviations for the primary and secondary displacement data sets are represented as a percentage of the mean set frequency. The mean frequencies are then converted to mass values using 2 force constants, one calibrated for primary displacement and another for secondary, avoiding the assumption that both frequencies can be converted to masses using the same force

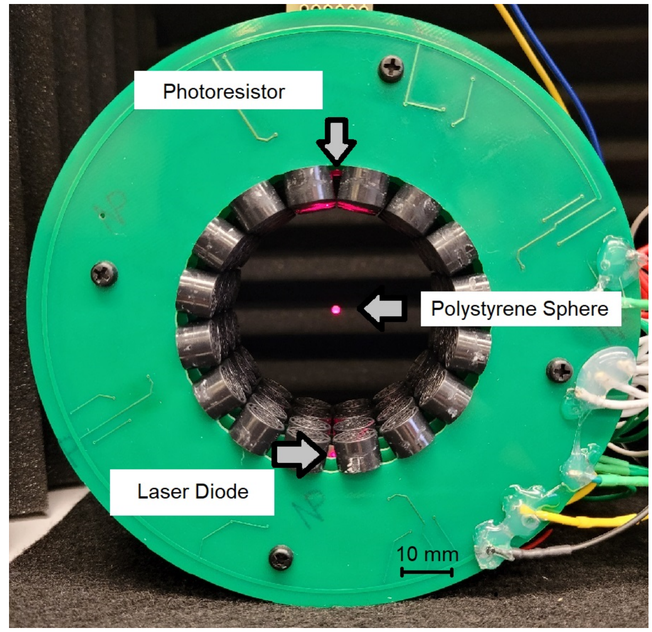


Fig. 5: Acoustic trap levitating a polystyrene sphere. The sphere is illuminated in red by the laser diode as the sphere partially occludes the laser from the photoresistor (positioned between the top transducers).

constant. This method compares the test object mass to the calibration object's mass like a balance.

The acoustic force experienced by the test mass within the acoustic field is dependent on the object's shape and material density, the ambient air temperature and the acoustic pressure field. Therefore, a suitable calibration mass is one that is similar in shape and material composition as subsequently weighed objects. This reduces potential calibration related weighing error attributed to object shape and material properties. At the time of weighing, a sensor measures the ambient air temperature in the acoustic balance and the model used to calculate the phase angles controlling the acoustic emitters is adjusted. This helps to ensure acoustic pressure field consistency between weighing attempts since the speed of sound in air is proportional to the square root of temperature in Kelvin [20]. Factors that influence the acoustic pressure field, such as acoustic emitter driving voltage or the number of transducers used to form the acoustic pressure field, should be kept consistent after calibration.

Another factor that may indirectly influence the effectiveness of acoustic weighing is the settling time of the object after being displaced. Fig. 4a shows how the oscillations of the first response are damped out before the secondary displacement occurs at t=4.6s. The settling time is the time the object takes to reach steady state after it has been perturbed. This also determines the rate in which subsequent measurements can be made. For objects with greater air resistance, the settling time can be even less as the oscillations are damped out quicker.

A. Balance Calibration

To calibrate the balance, the reference object is acoustically weighed 10 times to obtain a mean natural frequency, a total of 200 frequency samples. The mean damped natural frequency from the laser-based displacement sensor and the directly measured mass from the XPR2U were then used to compute the linear force coefficient, k, for each calibration mass. Table I shows the directly measured mass values obtained during the calibration procedure by the XPR2U.

TABLE I: Calibration Masses

Calibration Object	Mass (mg)
Polystyrene	0.255
Ant	0.173
Hardfiber Disk	0.437
FR4 5mil Disk	0.582
Mineral Oil	0.863
FR4 10mil Disk	1.527

B. Acoustic Levitation and Sensing Hardware

The oscillation frequency of the levitated object is measured using a 3mm beam diameter 650nm laser diode (LD-5MW-650NM) and a 10kΩ to 200kΩ photoresistor (1528-2141-ND) with a detection window of 4mm x 3mm, shown in fig. 3 with the levitated object positioned partially occluding the beam. The variable resistance of the photoresistor is converted to a variable voltage by a voltage divider circuit. The voltage signal shown in fig. 4a is recorded by a Saleae Logic 8 digitizer configured to sample at 2.5 mega-samples per second (MSps), a much higher sampling rate than a camera.

The acoustic trap uses a 64 transducer (Murata MA40S4S), cylinder shaped geometry with 4 stacked rings of 16 transducers and a diameter of approximately 47.6 mm. Each transducer is independently phase controlled. The Cyclone V FPGA (Field Programmable Gate Array) sends time multiplexed output channel waveforms to shift registers which demultiplex each signal into 8 output channels. These output channels are then voltage level shifted from the 3.3V, 40 kHz, square waves to a 32V peak-to-peak square wave by a HEF4104BT level shifting integrated circuit. Phase values for each transducer are calculated by a computer and sent to the FPGA via a USB-to-UART serial connection. The acoustic trap is a standing wave levitator with opposing emitters. This restricts the maximum size of a trapped object to about 2.5mm. By controlling the acoustic trap and performing the displacement maneuver with phase modulation rather than an acoustic emitter on-off method, multiple objects can potentially be levitated and controlled simultaneously with the acoustic weighing procedure.

IV. Weighing Results

A. Acoustic Balance Minimum Mass and Percent Error

Table II shows the percent error of the acoustic balance measurements compared to the Mettler Toledo balance measurement. The percent error for all the various test mass objects are either 5.56% or better except for the polystyrene and ant

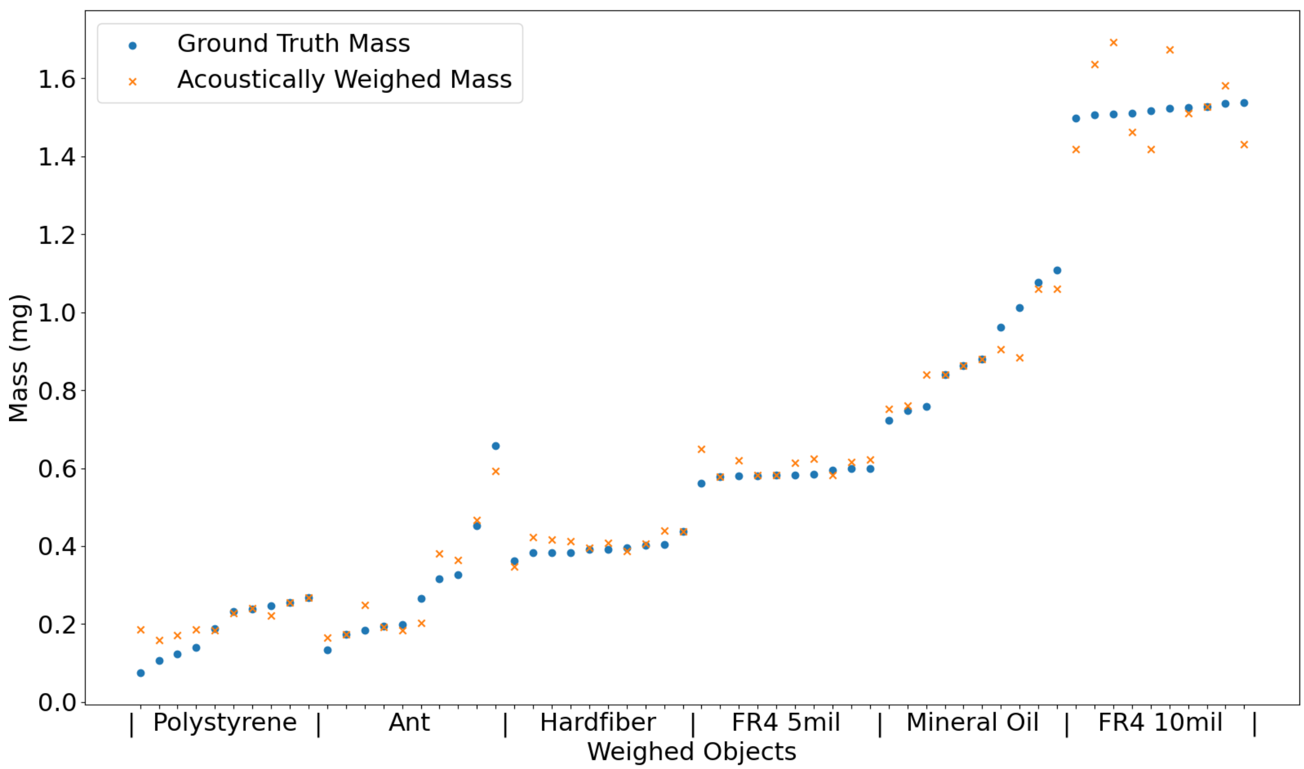


Fig. 6: The test masses measured using the acoustic balance compared with ground truth mass data collected using the Mettler Toledo XPR2U balance. As the test object mass drops below 0.2mg, the measurement error increases indicating 0.2mg is the minimum mass. The FR4 10 mil disk has a greater absolute difference from ground truth when compared to the other test objects. However, the FR4 10 mil disk also has the lowest frequency standard deviation percentage. Together, the absolute error and standard deviation percentage indicates that the approximately 1.5mg mass is the maximum measurable mass for this levitation system.

TABLE II: Acoustic Balance Results

Test Object	Polystyrene	Ant	Hardfiber Disk	FR4 5mil Disk	Mineral Oil	FR4 10 mil Disk
Mean Percent Error (%)	20.17	13.17	4.70	4.39	4.18	5.56
Mean Frequency Standard Deviation (%)	7.97	12.27	4.44	2.94	15.76	2.91

test masses. Additionally, fig. 6 shows the acoustic balance did not accurately weigh the polystyrene and ant objects less than 0.2mg. This would indicate that the minimum mass the acoustic balance can measure is about 0.2mg and that the balance was not sensitive enough to accurately weigh the least massive objects. Considering the test object group with the greatest mass, the FR4 10 mil data has the largest absolute mass variance relative to the other samples, even of similar shape and percent error. Combined with the low frequency standard deviation at 2.91%, the FR4 10 mil thickness test object likely has the lowest linear force coefficient compared to the other test masses. This indicates that the FR4 10 mil disk is near the upper limit of mass this levitation system is capable of sufficiently trapping and weighing. The range of accurate measurement for this specific acoustic levitation device is then between 1.5mg and 0.2mg.

B. *Frequency Measurement and Standard Deviation*

Even though the acoustic levitator was capable of levitating the various objects, some objects were more difficult to measure than others. The frequency standard deviation percentage indicates the fluctuation of the frequency measurement relative to the test object mass. Mineral oil, for example, has a mean frequency standard deviation percentage of 15.76% indicating the frequency samples obtained when measuring the mineral oil samples varied by about 15.76% of the sample mass. The ant samples also had high deviation percentages as well. A contributing factor to the higher deviation is the additional noise due to mineral oil droplets refracting the laser and the ant shape causing spinning in the acoustic trap. However, the acoustic balance measured samples above the minimum mass amount with a percent error of less than 5.56%, and only 4.18% for oil. While some materials and object shapes can cause increased noise, these challenges can be compensated for by increasing the number of frequency samples and applying acoustic field shaping techniques to minimize object spinning within the trap.

C. *Object Settling Time and Measurement Rate*

By increasing the number of samples required to obtain a confident measurement, the time to measure increases. The time to perform a mass measurement is also determined by the settling time, or the waiting time required between perturbations to allow the test object to stabilize in the acoustic trap. In general, the settling time is determined by the damping force, air resistance, and therefore makes objects with greater drag forces easier to measure as frequency measurements can be performed in quicker succession. This also means that for certain objects, perturbation direction also matters since some objects have a greater air resistance when move horizontally versus vertically.

D. *Acoustic Balance Performance Range*

The measurement results indicate that the acoustic balance can measure objects with a percent error of 5.56% or better in the range of 1.5mg to 0.2mg. The acoustic system was also tested with object sizes ranging from a 2.5mm long ant to a 0.5mm sized cube. A variety of types of objects were also tested including liquid mineral oil, ants, and FR4.

E. *Robotic Manipulators with Acoustic Weighing*

Acquiring the weight of an object while being manipulated can enable interesting and new techniques for acoustic manipulators. By using the acoustically obtained weight as a closed-loop feedback mechanism, material can be incrementally added to and combined with droplets, powder, or other objects in the acoustic manipulator. This sensing method is especially useful in mass-based sorting and dispensing of precise quantities of material in applications like automated laboratory processes and additive manufacturing. These techniques can be applied to the development of robot manipulated tools or end effectors which can enable a general purpose robot to perform precise chemical or biological sample mixing tasks.

F. *Discussion of System Improvement*

While acoustic balances can add a new sensing method to acoustic levitation systems and robotics, some future directions of work can potentially increase the repeatability and accuracy of this weighing method or remove the need for a calibration object. Future changes to the hardware could also improve the minimum and maximum size and mass limitations.

The acoustic balance leverages two trapping positions 1mm apart that the object is displaced between. The two positions are treated as having different force coefficients and thus the calibration object needs to calibrate for two acoustic positions. This means that the object is measured using two potentially different force coefficients which could have different levels of sensitivity. Equation 1 shows that for higher k values, or higher acoustic trapping forces, the same object will have a higher squared resonance frequency, f^2. This also means that for higher k values, 0.1mg in mass is represented by a wider frequency range, relative to lower k values.

Rather than performing the displacement of the object horizontally along the axis of the cylindrical shape of the levitator, the system can take advantage of the symmetry of the levitator geometry and displace the object along a series of nodes formed around the cylinders axis. Since the radial symmetry of the acoustic field means each node about the center is of similar trapping force, the calibration object would only need to calibrate for one trapping node and the force coefficient can be potentially reused for each node about the ring equidistant to the central axis.

Another area for improvement is by characterizing the dynamics of specific shape and material combinations within the trap and using this information to improve the acoustic model, the model itself could generate an estimated force coefficient, skipping the calibration step. Further improvement in this area could include development of finite element model which can predict the acoustic force dynamics given certain assumptions about the object shape.

Hardware changes can further improve weighing performance. By increasing the number of acoustic emitters or changing the type of emitter to a more powerful transducer, the new hardware system could manipulate objects of larger mass, also increasing the force coefficient. As mentioned previously, by increasing the force coefficient, the acoustic balance gains additional mass resolution as the same mass step is represented by a larger frequency step. Changes to the acoustic emitter geometry or phase profile could also increase the range of object sizes.

V. Conclusion

This method for weighing acoustically levitated objects by step response resonance frequency can measure the mass of objects levitated and manipulated by the acoustic trap. The system uses a reference object to establish a baseline for restoration force and extrapolate a restoration force constant used to calculate subsequently weighed object mass. The acoustic balance has a percent error 5.56% or better and a minimum object mass of 0.2mg. The system adds a contactless mass sensing method applicable to fields such as robotics and automated laboratory processes. Relative changes in mass of the same sample can also be monitored using this method, allowing for the observation of samples as their mass changes over time through continuous sampling. This technique for weighing acoustically trapped objects can enable development of closed-loop manipulation tools or end effectors to automatically add material to samples under observation or dispensing a desired quantity of material, a function useful in a variety of fields including automated laboratory operation and additive manufacturing.

Acknowledgements

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