

Compact sensitive piezoelectric mass balance for measurement of unconsolidated materials in space

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ABSTRACT

In many in-situ instruments information about the mass of the sample could aid in the interpretation of the data and portioning instruments might require an accurate sizing of the sample mass before dispensing the sample. In addition, on potential sample return missions a method to directly assess the captured sample size would be required to determine if the sampler could return or needs to continue attempting to acquire sample. In an effort to meet these requirements piezoelectric balances were developed using flexensional actuators which are capable of monitoring the mass using two methods. A piezoelectric balance could be used to measure mass directly by monitoring the voltage developed across the piezoelectric which is linear with force, or it could be used in resonance to produce a frequency change proportional to the mass change. In this case of the latter, the piezoelectric actuator/balance would be swept in frequency through its fundamental resonance. If a mass is added to the balance the resonance frequency would shift down proportionally to the mass. By monitoring the frequency shift the mass could be determined. This design would allow for two independent measurements of the mass. In microgravity environments spacecraft thrusters could be used to provide acceleration in order to produce the required force for the first technique or to bring the mass into contact with the balance in the second approach. In addition, the measuring actuators, if driven at higher voltages, could be used to fluidize the powder to aid sample movement. In this paper, we outline some of our design considerations and present the results of a few prototype balances that we have developed.

KEYWORD: Piezoelectric, mass balance, resonance, flexensional actuators

1. INTRODUCTION

A variety of NASA missions have been proposed for sample return from planetary bodies including moons^{1,2}, comets³, asteroids⁴ and planets⁵. For these proposed missions, a method to directly assess the captured sample size is required to determine if a suitable amount of sample has been acquired and if the sampler could be returned or there is a need to continue to attempt to acquire sample. In addition, many in-situ instruments might require information about the mass of the sample to aid in the interpretation of the data and portioning or sample handling systems might require an accurate sizing of the sample mass before dispensing the sample. The main properties that need to be considered in developing a mass measuring system are the sample size, homogeneity, integrity and the local gravity. A variety of direct and indirect measurement methods have been investigated by studying terrestrial mass/sample measurement systems and a list of the various techniques is shown in Table 1. If the sampled material is known and its density and integrity are fixed one could devise a variety of indirect measurements to determine the sample mass/volume. These include capacitance/resistance level sensors, ultrasonic level sensors and beta gauges for unconsolidated material and contact sensors/pistons or optical sensors for consolidated materials (e.g., cores). The major disadvantage of these approaches are that the material properties, including the porosity and particle size, need to be known or determined to produce confidence in the measurement accuracy. Unfortunately in many cases the exact composition of the sample and the porosity are unknown prior to sampling. In an effort to establish a reliable measurement method, we have investigated sample mass measuring systems for unknown samples that are applicable to space environments. A challenging sampling system for a mass measuring instrument design is a touch and go sampler on an asteroid or comet which produces an unconsolidated sample. In this case due to the miniscule local gravity a direct measurement of mass would require the spacecraft to produce an acceleration a from which we could generate a measurable force $F = m_s a$ where m_s is the sample mass. The most direct solution would be to have the sample canister compress a spring under a gravitation field or acceleration that is measured using a strain gauge as is shown in Figure 1 a). However, in a microgravity environment or using a spacecraft induced acceleration the forces produced by a reasonable sample size ($< 1\text{kg}$) is of the order of a milli-Newton full scale which is the equivalent of $< 0.1\text{ g}$. full scale on Earth. Typical mass scales on Earth that accurately measure sub gram mass values require clean, level, vibration and impact isolation environments which, if

required, would place a lot of constraints on the flight system. In addition, the sample mass would be a fraction of the potential container mass so this reduces the sensitivity.

Table 1: Various methods of measuring mass

Method	Direct/Indirect	Relationship	Contact/ Non-Contact	Advantages/Disadvantages
Force sensor Spring & Strain gauge	Direct	$F=ma=kx$ $m \propto x$	Contact	Depends of a or g. In milli g environment need to have soft springs. Sensor system is strain gage on spring.
Force sensor Spring & Strain sensor	Direct	$F=ma=kx$ $m \propto x$	Non-Contact	Depends of a or g. In milli g environment need to have soft springs. Sensor system could be Capacitive, fiber optic Eddy current, lvdts, interferometer etc.
Capacitance/ level meter	Indirect	$C = \epsilon A(x)/t$ Concentric $m \propto x$	Contact	Depends highly on material property ϵ and porosity and homogeneity
Ultrasonic/ level meter	Indirect	$x = 2v\Delta t$ Concentric $m \propto x$	Contact	Depends highly on material property v and porosity and homogeneity
Radiation/Attenuation Gamma, beta, optical	Scattering – Indirect- Surface Attenuation – direct Volume	$I=I_0 \exp(-kx)$ $m \propto f(k)$	Non-Contact	Sample homogeneity, sensor complexity and mass
Piezoelectric force sensor	Direct	$F=ma=kV$ $m \propto V$ or $\Delta m \propto \Delta f$ for resonator	Contact	Two methods of measurement. (Voltage sensitivity and time constant issues.) Frequency is easy to measure accurately. (low frequency resonator required)

A variety of other approaches that might be used to measure the mass directly or indirectly through another property of the sample (optical scattering, dielectric constant, conductivity, etc) are shown in Table 1 and Figure 1. An alternative approach that measures the mass directly is to suspend the mass with a calibrated soft spring (Figure 1 b) and to monitor the extension using non-contact displacement sensors (fiber optic, capacitance, magnetic lvdts, magnetic eddy current sensors, interferometer). Level sensors (Figure 1 c) require known geometry and sample properties (capacitance, resistance, acoustic velocity) and homogeneity and radiation gauges require homogeneous sample or multiple emitters and sensors and potentially time averaging (Figure 1 e). Another approach that has shown some utility in force sensing and mass measurement is the use of piezoelectric sensor. This device can be configured to produce a voltage that is proportional to the force on a surface or to measure a mass via a frequency shift of the piezoelectric resonator. In this paper, we will discuss the feasibility of using piezoelectric sensors to measure mass in low gravity environments. The basic theory for using a piezoelectric transducer as a force sensor and a resonant mass balance will be presented. The limitations of each of the approaches will be discussed and the sensitivity and time constants for a variety of materials

will be evaluated. The results of prototype piezoelectric scales based on flextensional piezoelectric stack actuators that we have tested will be discussed⁶.

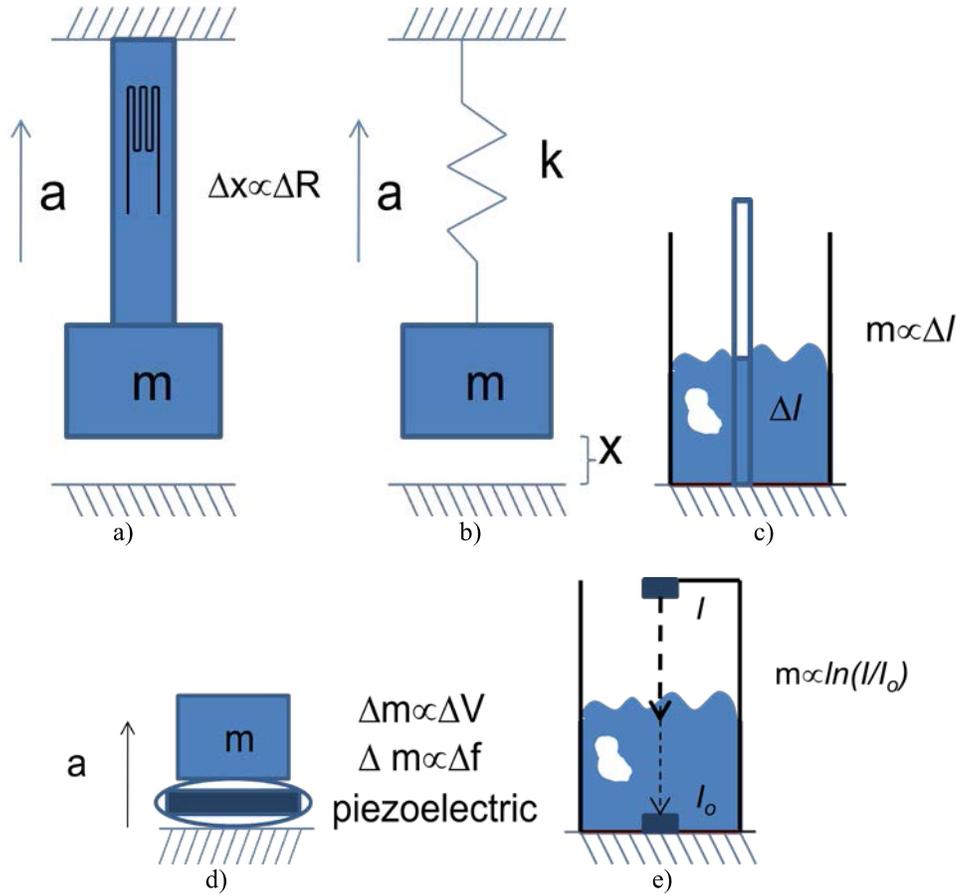


FIGURE 1: Schematic diagrams of a variety of mass measuring systems a) Strain Gauge - contact, b) Strain sensor – non-contact, c) level meter, d) piezoelectric balance, e) radiation attenuation

2. THEORY

a) Force sensor mass balance

For a bulk piezoelectric transducer (as shown in Figure 2), the voltage generated for a given mass supported in a gravitational field or under an acceleration to produce a force F can be determine from the constitutive equations.

$$\begin{aligned} \Delta x &= \frac{1}{k} F + d_{eff} V \\ Q &= CV + d_{eff} F \end{aligned} \quad (1)$$

In the open circuit limit $Q = 0$ and the second equation can be written as

$$V = -\frac{d_{eff}}{C} F \quad (2)$$

Where V is the voltage produced, d_{eff} is the effective piezoelectric constant, C is the capacitance of the piezoelectric transducer and F is the force $F=ma$ or mg . The time constant of the voltage for the voltmeter with an input impedance R is

$$\tau = RC \tag{3}$$

The displacement of the piezoelectric including piezoelectric stiffening is

$$\Delta x = \left[\frac{1}{k} - \frac{d_{\text{eff}}^2}{C} \right] F \tag{4}$$

Where k is the effective short circuit spring constant of the piezoelectric material $k=s^E A/l$.

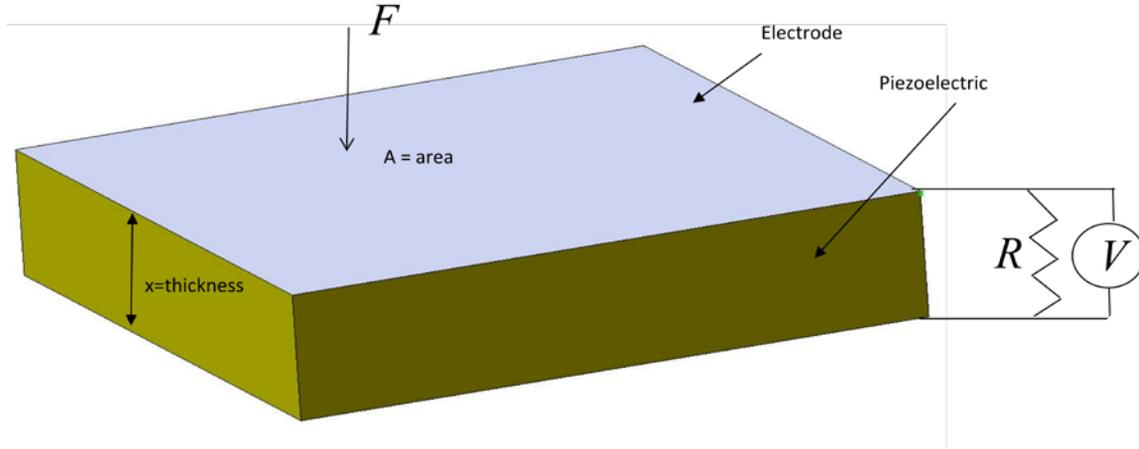


FIGURE 2: Schematic diagrams of a generic piezoelectric mass measuring systems. The top and bottom surfaces of a slab of piezoelectric are electrode and connected to a voltmeter with input impedance R .

Table 2. The nominal volts per kg (1 g gravity) and the time constant for a 1 mm thick and 1 cm² area piezoelectric sample calculated from the effective d_{33} and Capacitance for various piezoelectric materials.

Material	d_{eff} (C/N)	Capacitance (nF)	(V/kg)	τ (s) $R=10^7$ Ohms
PZT CTS 3203 HD	6×10^{-10}	3.0	2.0	0.03
PVDF	3×10^{-11}	0.008	37	0.00008
Single Crystal PMN-PT	2.4×10^{-9}	3.5	6.8	.035

The voltage per kg in an earth g environment and time constant for a 1 mm thick, 1 cm² button of various piezoelectric materials is shown in Table 2. For a bulk sample the voltage per kilogram decreases with increasing capacitance while the time constant increases with increasing capacitance. A piezoelectric stack however has a larger time constant due to the increase in the capacitance of each parallel layer while the voltage produced by the stress is the same for each layer. In addition a transducer design which includes a stack and amplifies the effective piezoelectric coefficient d_{eff} like a flextensional would thereby increase the voltage per kg and the time constant. In the experimental section we present our results on prototype designs of mass balances using piezoelectric flextensionals actuators produce by CEDRAT Technologies(APA 120s, 60s , and 150xx actuators)

b) Low frequency resonator balance

An alternative to the force sensor discussed above is a low frequency macro balance. In this case we have a structure driven by piezoelectric material that has a low frequency resonance. When mass is added to a mechanical face/port of the structure the resonance frequency drops in a similar fashion to the Quartz Crystal Microbalance (QCM) or thin film monitors^{7,8,9,10} however the initial frequency is much lower in order to measure larger masses. In order to

produce a low frequency resonator we again have used a flexensional transducer design and we have used a modified Mason's network model as shown in Figure 3 to model it¹¹. The model treats the flexensional as a bulk piezoelectric however due to the amplification and stress reduction of the flexensional arms one has to multiply the applied mass by the inverse of the strain amplification factor in order to get a reasonable agreement with theory.

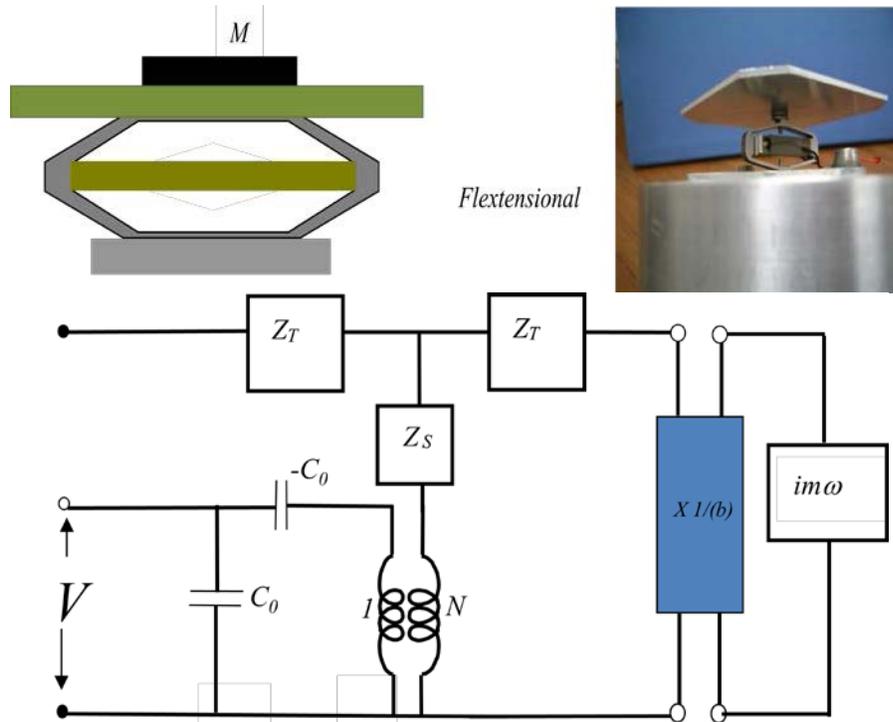


FIGURE 3: Schematic diagram and photograph of a flexensional mass measuring systems along with the electromechanical network model. The base is an aluminum block. (10 cm diameter and 7 cm thick) which can be modeled as an open acoustic port.

The parameters from the free fixed resonator can be used to model the resonance. The flexensional amplification and distributed mass requires a mass factor that can be determined from fitting the data. It can be shown using the circuit that the functional form of the relationship between the resonance frequency and the mass is $f = a/(c+m)^{1/2}$ where a and c are constants of the resonator. At low mass the frequency shift Δf is proportional to the mass change Δm as is found in the Sauerbrey equation⁷.

3. EXPERIMENTAL RESULTS

A schematic diagram of the two mass measuring experiments is shown in Figure 4. In the top diagram the piezoelectric material or transducer is connected to a voltmeter (Kiethley 2700 Digital MultiMeter DMM). The input impedance for voltage levels up to 10 Volts is $> 10 \text{ G}\Omega$ which for the APA 60s and APA 120s actuators produce a time constant > 15000 seconds ignoring the DC resistance of the piezoelectric stack. The APA 150xx had a time constant a factor of 10 less. In this experiment the voltage generated as a function of the applied mass is recorded. The data for the force sensor was determined manually by reading the voltage after the application of the mass. At low voltage levels a measurable drift in the voltage in the voltage was noted and found to produce larger errors in the measurement at low mass levels. The voltage data as a function of the applied mass for the 3 different Cedrat APA actuators (150xx, 120s, and 60s) are shown in Figure 5. The data for the force sensor was determined manually by reading the voltage after the application of the mass.

In the frequency measurement we have swept the impedance as a function of frequency using an impedance meter (Agilent HP 4294a) in place of the oscillator/counter in the bottom figure. The resonance frequency was determined from the maximum of the conductance (f_s series resonance).

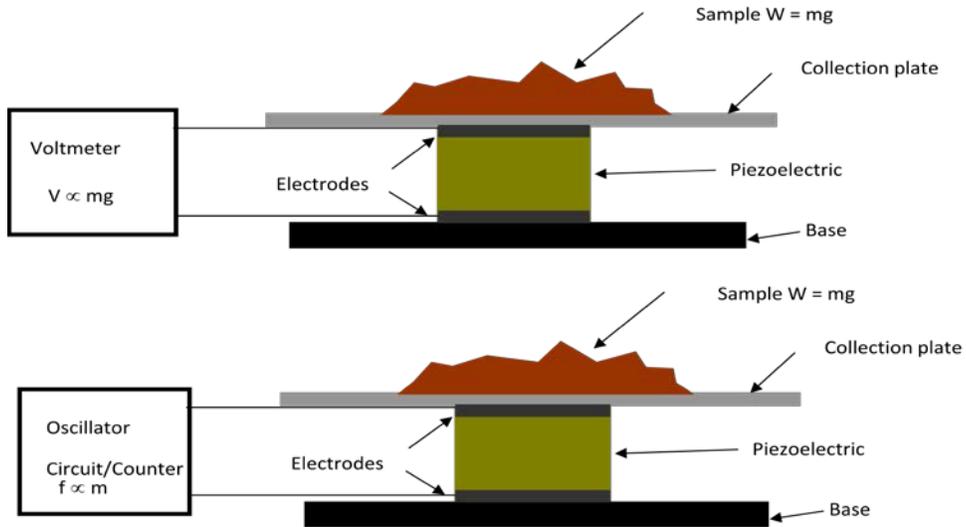


FIGURE 4: Direct method of measuring mass (top): A sample is loaded onto a plate and the weight of the sample compresses the piezoelectric with a stress T and generates a voltage across the piezoelectric proportional to mg . Indirect method of measuring mass (bottom): A sample is loaded onto a plate and the weight of the sample loads the piezoelectric causing the resonance frequency of the piezoelectric and plate to decrease. The decrease in frequency for a small change in mass is proportional to the mass.

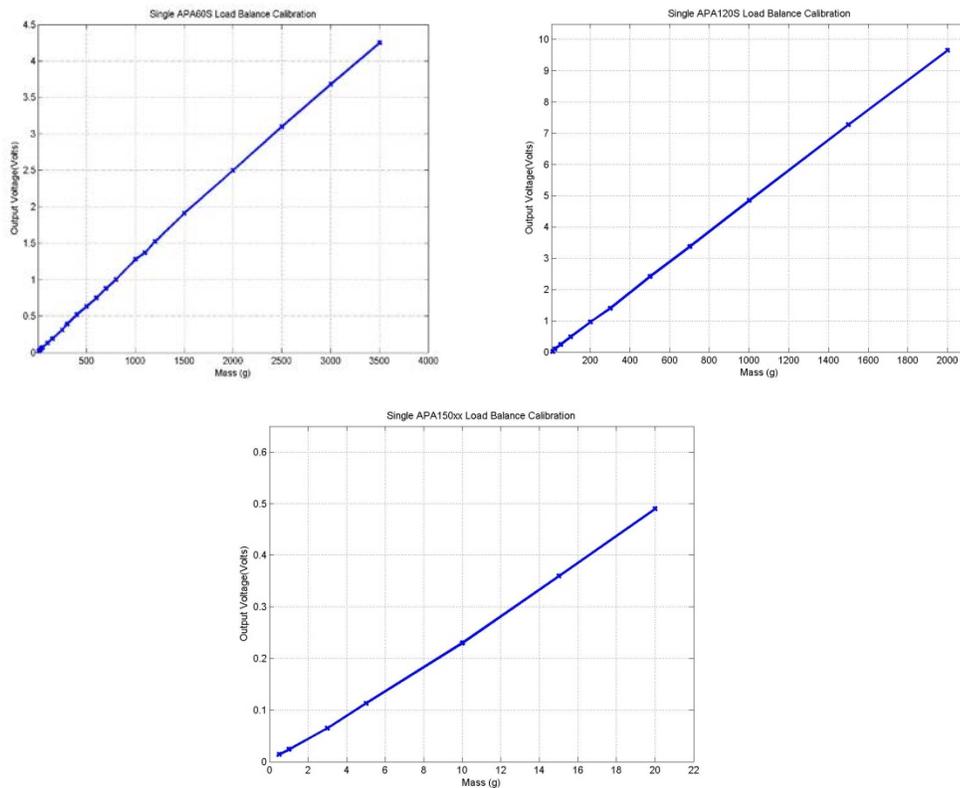


FIGURE 5: Voltage produced for mass steps on scales using the CEDRAT APA 150xx, 120s, and 60s flextensional actuators in a 1 g environment. The average voltage mass sensitivity for the APA 150xx, 120s and 60s actuators are 24.5, 4.75, and 1.21 V/kg

The measured average voltage mass sensitivity for the APA 150xx, 120s and 60s actuators are 24.5, 4.75, and 1.21 V/kg, respectively. The calculated voltage mass sensitivities based on equation (2) are found to be 65.3, 5.90, and 3.20 V/kg where the effective d_{33} value was calculated using the maximum stroke at maximum voltage. The measured value is of the order of 2 less than the theoretical value which may be due to the fact that the maximum displacement at maximum voltage is a large signal measurement since the fields in the stack layers is at or above the coercive field at the maximum voltage of 150 V where the stress on the actuator compared to the blocking force is comparatively a small signal measurement. Indeed a small signal resonance analysis of the fixed free APA 60s actuator with an aluminum plate (15 grams) to measure the mass produced an effective d_{33} of 3.5×10^{-7} C/N a value that was 30% below the d_{33} calculated from the CEDRAT APA specification brochure¹².

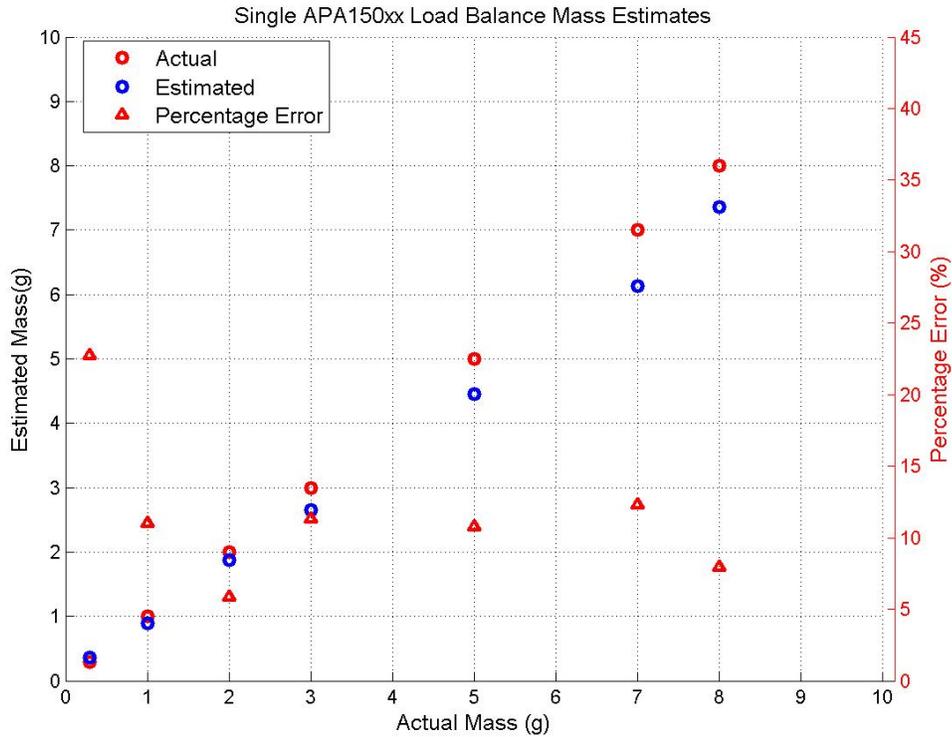


FIGURE 6: The linearity of the APA 150 actuator with up to 20 grams mass added. The blue circles shows the calculated mass from the average slope and the red circles show the actual mass. The error is the absolute value of the percentage difference.

The linearity of the most sensitive APA 150xx load balance is shown in Figure 6. The blue circles shows the calculated mass from the average slope over the 20 gram range and the red circles show the actual mass. The error is the absolute value of the percentage error of the actual and calculated mass from the linear equation $m = kV$ where k is the average slope determined from Figure 5 and V is the measured voltage. From the curve it is apparent that error of the linearity could be improved to few percent if the initial data point was excluded since each estimated mass except for the initial point underestimates the actual mass by about 10% on average. Increasing k by 10 % would therefore decrease the discrepancy between the measured and estimated mass. The data suggests that a balance could be designed to easily measure 1 gram or 9.8 mN with an error of about 10% using a piezoelectric load sensor based on flextensional actuators and off the shelf electronics.

An example of the raw data for a resonance balance is shown in Figure 7, which is a plot of the conductance spectra as a function of frequency at different mass levels for the APA 60s actuator. The fixed-free (with aluminum plate 15 g) data was fit manually using a Mathcad worksheet to determine the effective piezoelectric coefficient of 3.5×10^{-7} C/N for a comparable stack (5x5x18 mm) with a density of 7800 kg/m³. The fixed free effective elastic constant and permittivity is 2.4×10^{-8} m²/N and 7.1×10^{-4} F/m. The resonance frequency as a function of the mass added is shown as the black circles and the open circles show the resultant resonance frequency when a load of $Z = i\omega/b$

added to the free surface of the free-fixed resonator model where $b = 7$ and is related to the flextensional amplification factor. The initial linear decrease in f with increasing m and the saturation are captured by this very simple model.

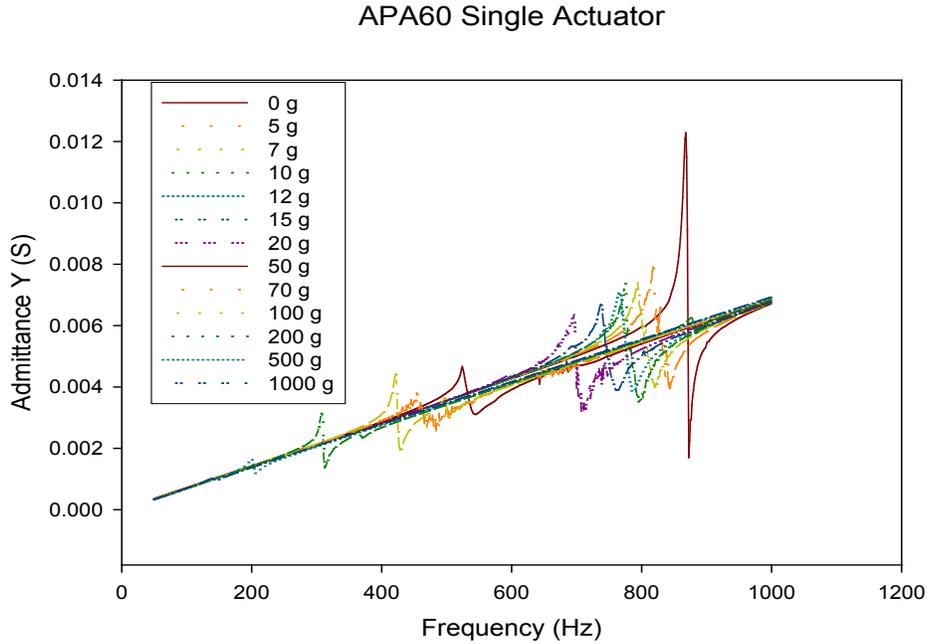


FIGURE 7: The conductance spectra of the APA 60s flextensionals with a fixed end and an aluminum plate. The resonance frequency is determined from the peak in the conductance.

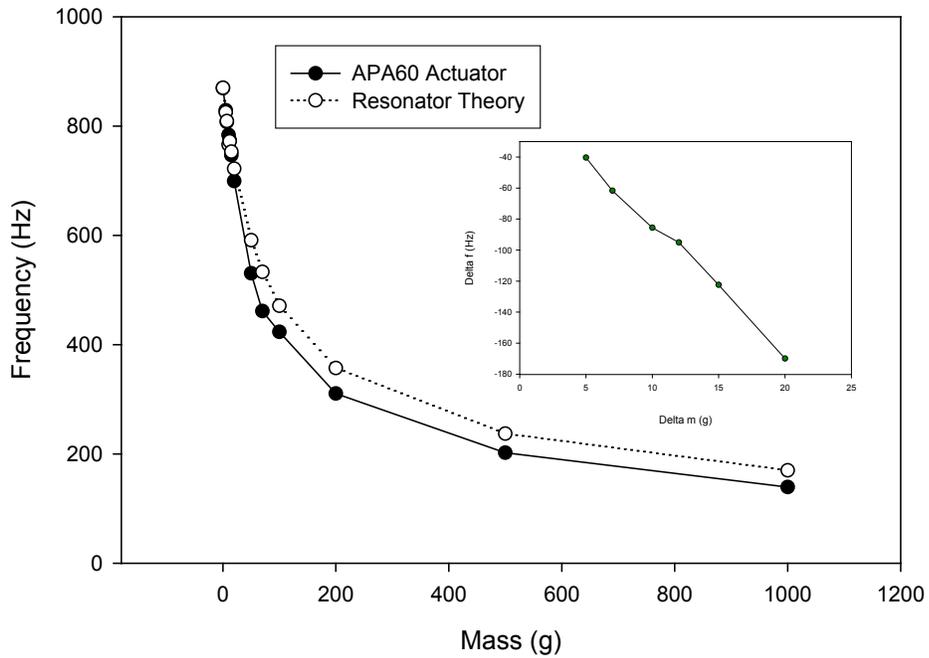


FIGURE 7: The series resonance frequency f_s as a function of the mass on the pan. The curve is linear at small mass level ($\Delta f \propto -\Delta m$) and then saturates at larger mass.

4. DISCUSSION

The data from the prototype load cell and resonance balance suggest that we can design a mass measuring sensor based on a load cell that is sensitive enough to measure 1 gram or 9.8 mN at 10 % accuracy. In addition, from the data in the inset diagram of Figure 7 and the spectra in Figure 6. The resonance balance can be calibrated to this level of accuracy for a 1 gram mass even with the APA 60s actuator. It should be mentioned that the load balance is a differential measurement while the resonance measurement is a direct measurement. The sensitivity of the load balance will depend on the measurement time due to the time constant and electric drift while the resonance balance is independent of the sampling/measurement time. There are other considerations however that need to be considered when choosing the appropriate approach for an instrument that is to be launched. These include the ability of withstand launch random vibrate, pyro-shock testing and thermal cycling. Since the flextensional is a soft spring and a measuring plate needs to be fixed to the actuator a launch lock or displacement limiter would likely be required to insure the actuator is not damaged during environmental testing. In addition the actuator is to be used at low temperatures in the 100K range. Piezoelectric ceramics have temperature dependencies that need to be measured and accounted for. Similar stacks produced by PI Ceramic¹³ showed a reduction in both the piezoelectric constant and capacitance by factors of 0.57 and 0.43 at 100 K which according to equation (2) increases the voltage mass sensitivity by about 33%. At 100K the temperature sensitivity of the effective piezoelectric constant and capacitance is about 2.5×10^{-10} C/NK and 3.9×10^{-9} F/K respectively. The voltage mass sensitivity for the APA 150xx actuator at a temperature at 100 K assuming PI ceramic stacks are used is therefore $V(T) = 35.5$ V/kg.

The resonance balance was tested using consolidated mass elements (brass). The baseline sample for potential sample return missions for a touch and go sampler would be unconsolidated material. In this case one has to consider the acoustic properties of the sample since a resonance balance would shake the material which might or might not pack the material. Ideally we would require that in a full sample canister the dimension of the sample perpendicular to the measuring plate should be a tenth of a wavelength at the drive frequency of the balance. This would insure a linear change of f with mass up to the maximum sample size. If we set the dimension of the sample canister to be 10 cm then the wavelength is 1 meter and the frequency using an acoustic speed of 280 m/s¹⁴ is 280 Hz. This would require a softer flexure than the APA 150xx and again launch locks or displacement limiters. The frequency shift due to temperature is much smaller since the resonance frequency is primarily controlled by the elastic constant which has a minor < 10% change over these temperature ranges. In both these methods the size of the sample canister or measurement plate becomes a critical component of the design. If for example a plate or canister of the order of 100 grams was used the load balance sensitivity would be reduced by a factor of 1 part in 100 at 1 gram sample mass unless the plate or canister can be electrically or mechanically zeroed out.

5. SUMMARY

In this paper we identified a variety of techniques that could in theory be used to measure the mass of a sample. The primary focus of this paper was to investigate the feasibility of piezoelectric mass balances to be developed for autonomous measurements in lunar or microgravity environments to measure mass levels of the order of a tenth of a gram up to about 200 grams. In the higher mass range a variety of solutions exist that could be used to determine the mass to the desired accuracy. These include the piezoelectric load cell, and strain gauge or capacitance sensors connected to a soft spring and the piezoelectric resonance balance. In the lower mass limits increasing the sensitivity requires softening the system which in turn makes the system less robust without the launch locking mechanisms or displacement limiters. In order to meet the 1 mN requirements for a mass measurement of a sample collected from a microgravity sampler off the shelf prototyping would have to be replaced with an integrated mechanical and electrical design.

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