Piezo Dust Detector

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Abstract—There is a large amount of man-made debris that is in orbit around the Earth. These debris particles are travelling at very high velocities—greater than 1 km/s—and pose a threat to satellites that are put into orbit. Much of it cannot be tracked by the telescopes on Earth, however, because they are not sensitive enough to observe particles smaller than about 10 cm in diameter. In order to protect sensitive equipment such as externally facing cameras, there must be a device on board the satellite that can detect such debris. If impacts begin occurring at a higher rate, the camera lens can then be shielded, protecting it from further harm. A piezo detector has been designed to perform this task on board the ARMADILLO nanosatellite, which is being constructed by students at the University of Texas at Austin.

Index Terms—PDD, PZT, piezo dust detector, LEO, space debris

✦

1 INTRODUCTION

In an ideal case, a satellite that is set into orbit around the Earth would experience neither drag nor impacts with space debris. Its orbit would be unchanging over time, and, assuming it could tolerate a vacuum environment, its equipment would never be damaged. In reality, however, the space environment of an orbiting satellite is far from ideal. While drag can be overcome by periodically applying a thrust to the satellite, space debris is not so easily compensated for.

Space debris comes in a variety of different sizes and materials. Many laboratories across the world attempt to monitor this debris optically using large, highly sensitive telescopes. The NASA Orbital Debris Observatory tracks space debris using a three-meter liquid mirror telescope. Due to sensitivity limitations, however, objects smaller than about 10 cm in diameter cannot be measured. Objects that are in Low Earth Orbit may then have velocities on the order of 10 km/s.[1] At such speeds, inpact with a particle even 1 cm or smaller in diameter could seriously damage a satellite. Smaller objects may not threaten the structural integrity of the satellite, but could easily damage valuable equipment, such as camera lenses, that are on board. Thus, a mechanism is needed for the satellite to detect this debris and protect its sensitive equipment when the flux of these particles becomes too large.

2 DETECTING SPACE DEBRIS

2.1 Piezoelectricity and PZTs

In certain materials, an externally applied stress can cause an electric charge to accumulate on the surface of the material. This phenomenon is known as the piezoelectric effect, and is commonly seen in such natural materials as quartz and topaz. One of the many applications of piezoelectric materials is their use as a converter between mechanical and electrical energies. If an object collides with the piezoelectric material, a stress will be applied to the material. The electrical charge that is created can then be collected and used in an electronic circuit.

The design of the piezoelectric dust detector (PDD) has taken advantage of this property, using lead-zirconate-titanate (PZT) as the piezoelectric element. The PDD is being designed for the ARMADILLO nano-satellite for the University of Texas as Austin. ARMADILLO will be placed in Low-Earth Orbit (LEO) at an altitude of about 400 km, which is comparable to that of the International Space Station. At this altitude, there is a large amount of man-made space debris due to past satellites that either were destroyed or that deposited equipment that was no longer needed into the space environment. All of this debris has the potential to collide with ARMADILLO and possibly damage its equipment, such as the camera that will be on board. The PDD should have the capability to detect a collision with a piece of space debris and return an estimate of its impact energy.

2.2 Main Detector Unit

PZT is the basic element of the detector. A three-by-three array of nine PZT plates compose the Main Detector Unit (MDU), as shown in Figure 1.

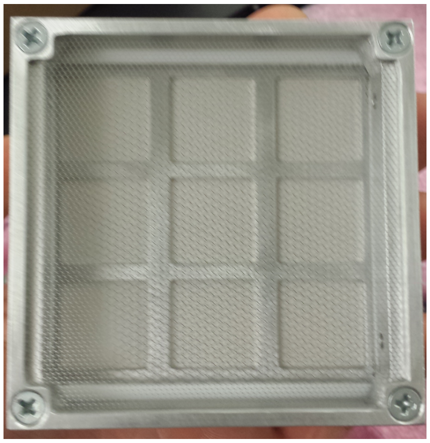


Fig. 1. MDU

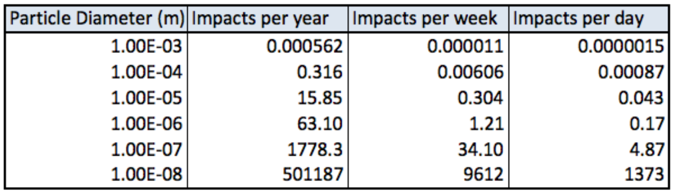
Upon impact, the plate will start to oscillate and create a signal that will be sent to the PDD electronics. An analog-to-digital converter (ADC) then processes that signal and relays its digital output to the FPGAa microcontroller that is used to program the ADC as well as communicate with the on-board computer (OBC). The digital information is temporarily stored in the RAM of the FPGA until it is called upon by the OBC, which is able to communicate with the ground via radio. This is a simplified overview of the communications that occur within the PDD electronics, but it covers all of the details that are necessary for the purpose of these experiments.

3 LOW EARTH ORBIT ENVIRONMENT

Testingof the PDD can easily be focused by first understanding the conditions that the detector will be exposed to in LEO. Conveniently, ARMADILLO is scheduled to be set into orbit at approximately the same altitude as the International Space Station. For that reason, information about the space environment of PDD should be readily available. The ISS has an orbital velocity that ranges between 7 km/s and 8 km/s, depending on its current position in orbit. Thus, the assumption has been made that ARMADILLO will have approximately the same velocity when it is in orbit. This provides an estimate for the maximum impact velocity that the PDD could experience. If the two objects have orbital velocities of 8 km/s and are travelling in opposite directions, the collision would have a relative impact velocity of 16 km/s. NASA also states that the average impact velocity of debris with the ISS is 10 km/s.

The total kinetic energy of the debris particles, though, can not be calculated unless their masses are known. At the altitude of LEO, nearly all of the objects in orbit are man made. They were left behind by past satellites that either deposited unneeded equipment or simply exploded. The average density of objects in LEO is 2.8 g/cm^3. Since satellites are designed to be lightweight, the most dense material that could likely be found in LEO is steel (approximately 8 g/cm^3), which could be used to bind parts of the satellite together.

NASA's DAS 2.0.2 software, which is available to the public for free download, provides information about space debris and meteoroids based at various orbital altitudes. Using the parameters of an orbit in LEO as well as the physical dimensions of ARMADILLO, a simulation was performed to calculate the particle sizes and rate of collisions that the PDD will likely experience. The general results of that simulation are summarized in Figure 2.



Particle Diameter (m)	Impacts per year	Impacts per week	Impacts per day
1.00E-03	0.000562	0.000011	0.0000015
1.00E-04	0.316	0.00606	0.00087
1.00E-05	15.85	0.304	0.043
1.00E-06	63.10	1.21	0.17
1.00E-07	1778.3	34.10	4.87
1.00E-08	501187	9612	1373

Fig. 2. Results of DAS 2.0.2 Simulation

According to the data sheet provided for the PZT plates (STEMiNC piezo material SM410), the plates have a limited sensitivity that only allows them to detect impacts with an energy of at least 100 nJ. Particles smaller than 1 μm in diameter would have an impact energy below 100 nJ, assuming an impact velocity of 10 km/s. So, most particles smaller than 1 μm in diameter will not be able to be detected by the PDD. On the other hand, it is unlikely that there would be any impacts with particles larger than 100 μm. If a collision with such a particle did occur, it would have a very large impact energy

—possibly large enough to break one of the PZT elements. This is of great concern for testing the PDD, and it should be known how to identify a broken PZT using only the signal data.

4 DROP TOWER SETUP

Baylor University's Drop Tower, shown in Figure 3, was used to simulate space debris impacts on the MDU. Metal BBs are loaded into the dropping mechanism, which can be raised or lowered to any height up to 3 feet. The laser that is mounted above the dropping mechanism locates where the BBs will impact the target. This setup provides accurate drops, ensuring that the correct PZT is always being impacted, and allows precise calculation of the impact energy based on the initial potential energy of the BB.

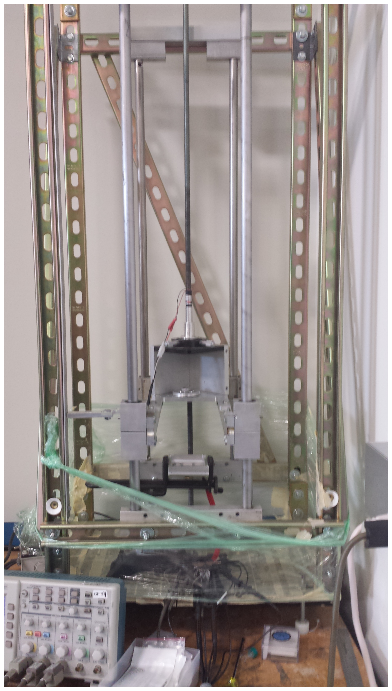


Fig. 3. Drop Tower

Each of the nine PZT elements is connected to a different channel on one of the three oscilloscopes shown in Figure 4. The oscilloscopes used were Tektronix 3000 series scopes. Before each drop, each of the oscilloscopes is set to collect a single sequence of data, triggered by a single channel. In this case, it is not crucial that all three scopes should be triggered at the same instant, and so it is acceptable to trigger each of them separately.

A computer is then able to communicate with the oscilloscopes via GPIB connection. The three scopes are connected by a daisy chain, and each has its own GPIB address, ranging from 1 to 3. Using a LabView program that was created for this project, any data that is displayed on the oscilloscopes can then be collected and stored in a text file. This text file includes such information as the time per division, volts per division, and channel number for each column of signal data from the MDU.

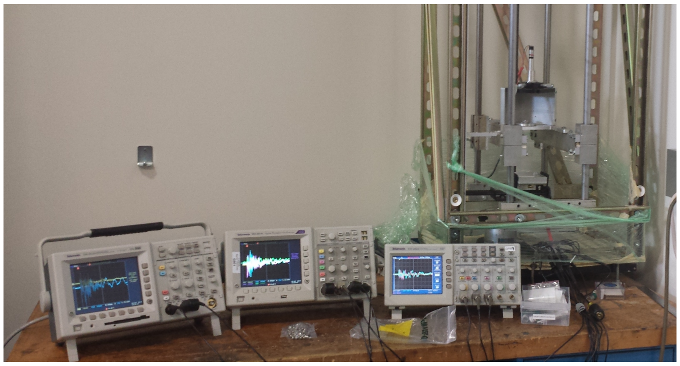


Fig. 4. Drop Tower and Oscilloscopes

5 PZT SIGNAL

5.1 Voltage

As the impact energy increases, more energy is transferred from the particle to the plate. That transferred energy then deforms the plate, producing an electrical charge by the piezoelectric effect. So, as impact energy increases, there will be a greater deformation of the plate, resulting in a larger charge created by the plate. It is expected that a linear relationship should exist between the impact energy of a piece of space debris and the voltage of the produced signal.

Stainless steel and aluminum BBs of various masses were dropped onto individual plates of the MDU from a series of different heights. This provided a range of impact energies over which to test the signal response of the PZT plates. The peak-to-peak voltages were then plotted as a function of the impact energy, and a linear model was fitted to the data (Figure 5).

The line of best fit is shown to be:

$$V = 22,772\,E + 1.452$$

Where V is the peak-to-peak voltage of the signal, and E is the impact energy of the BB. There is also a standard deviation of $\sigma = 1.096\,V$ from the linear model.

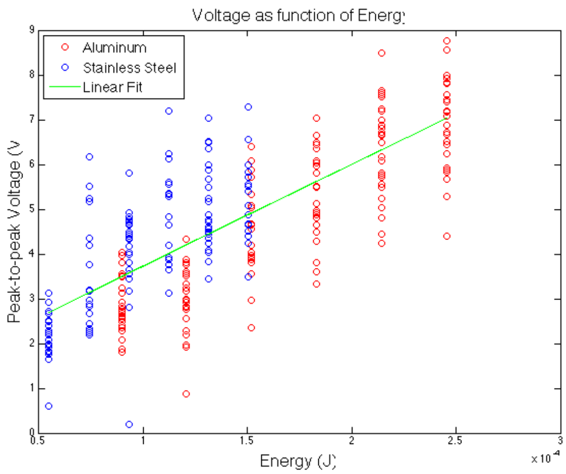


Fig. 5. Voltage vs. Impact Energy

Using this linear model, it is possible to retroactively predict the impact energy of space debris based on the peak-to-peak voltage. Problems arise, however, from the fact that the standard deviation from the model is so large. This makes it difficult to retroactively predict impact energy to within even 1×10^{-4} Joules. Further, it will be shown later that the PDD will primarily come into contact with space debris with energy on the order of 1×10^{-4} J or less. So, from the linear model shown in Figure 5, it appears that the linear model does not yield a precise estimate for the impact energy.

The model as shown, however, only covers a small portion of the possible impact energies. The possibility exists that the MDU will come into contact with much higher energy impacts. Specifically, if a debris particle was much more massive—possibly steel, or another dense material—and travelling at the 16 km/s, the impact energy could be several orders of magnitude greater. At such energies, assuming that the standard deviation remains constant at all energies, the linear model shown in Figure 5 could easily distinguish this impact from a lower energy impact. The linear model will then be able to provide valuable estimates for the impact energy of space debris over the complete spectrum of possible energies.

5.2 9-Channel Response

The PZT that is impacted is not the only one that will return a signal, though. In fact, all nine channels of the MDU should register a signal. The PZT plates are highly damped by the frame of the MDU, and some of the vibrational energy from the plate that is impacted is passed onto all of the other plates. The peak-to-peak voltage of the other plates is small compared to that of the impacted plate, but these carry all of the same vibrational frequencies and decay exponentially as the impacted plate does. The peak-to-peak voltage of all nine channels was plotted over a range of impact energies, shown below in Figure 6.

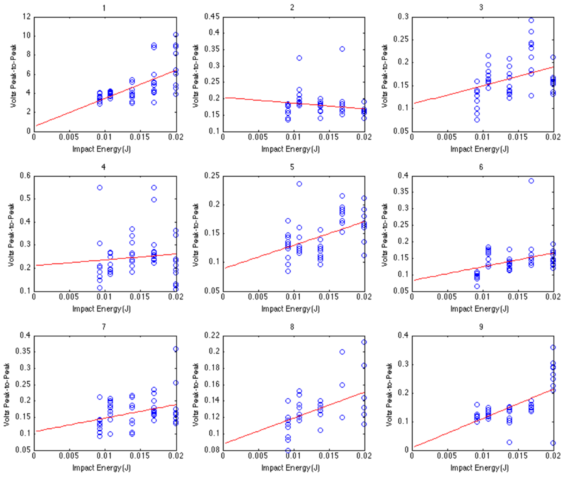


Fig. 6. Voltage vs. Impact Energy, plotted for all channels when dropping on PZT number 1

Note that the axes scales vary dramatically from one plot to another. The voltage on the non-impacted channels shows a slight upward trend as the energy increases, but this is a very small increase compared to that of the impacted channel.

5.3 Frequency

As mentioned earlier, when a debris particle impacts one of the PZT plates, the plate will begin to oscillate. This oscillation can generally be understood as behaving like a damped harmonic oscillator—the resulting signal appears like the superposition of sinusoids and decays exponentially over time. The complete waveform, however, contains many different frequencies. Like any other thin plate, the PZT has a fundamental mechanical frequency at which it oscillates. This is the frequency at which the length (and width) of the square plate is equal to one half of the wavelength of oscillation. For a PZT plate of our dimensions (21 mm x 21 mm x 0.55 mm) that is clamped on all sides, the fundamental frequency has been calculated to be 210 Hz.

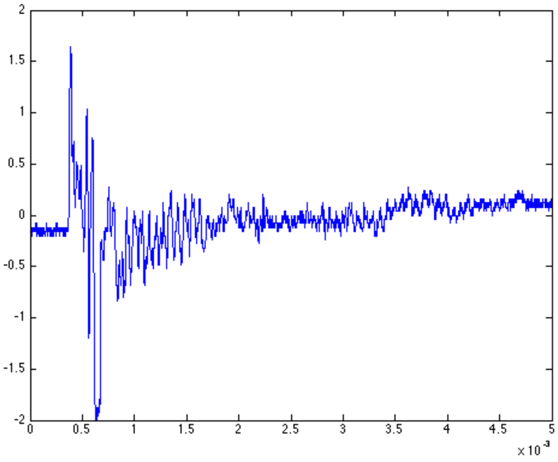


Fig. 7. PZT Raw Signal

Other harmonic frequencies are also present in the complete signal, which are integer multiples of the fundamental frequency. By the superposition principle, a complete waveform is made up of many different frequencies, each of its own magnitude, superimposed upon one another. The harmonic frequencies may be less prevalent than the fundamental frequency (smaller in magnitude), but several of them can still be identified within the complete signal. The first and second harmonic frequencies, when clamped on all sides, have been calculated to be 430 Hz and 650 Hz, respectively. Fourier analysis consistently identifies the fundamental frequency, and occasionally the 430 Hz frequency can be identified from the fourier transform.

Because of the piezoelectric effect, there are also electrical effects on the PZT oscillation. This results in a fundamental electrical frequency of oscillation, in addition to the mechanical frequencies that have already been mentioned. The manufacturer of the PZT plates, STEMiNC, specifies that the resonant electrical frequency is 78 kHz when the plate is free to oscillate on all sides. Since the plate is clamped by the frame of the MDU, there should be an upward shift in that resonant frequency. Fourier analysis shows that there is a 98 kHz signal that dominates the raw PZT signal. Other higher-order harmonic frequencies to this 98 kHz may be present, but they are too weak to be easily identified by fourier analysis.

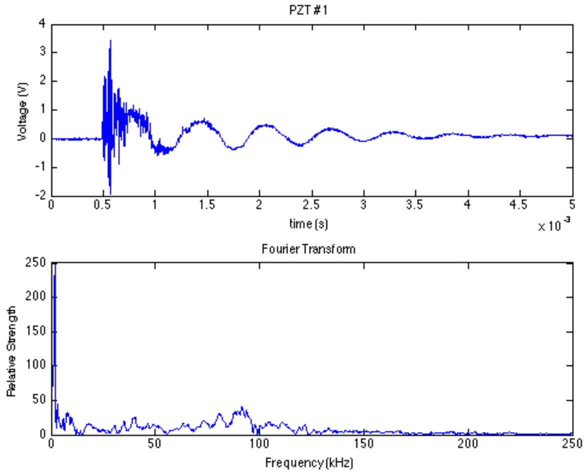


Fig. 8. Fourier Transform

There is also a small peak in the fourier transform that appears just after the mechanical frequencies, at about 1.5 kHz. This portion of the complete waveform has a significant effect on the signal, but it does not seem to be either a mechanical or electrical resonant frequency. It is not one of the harmonic mechanical frequencies that was calculated earlier. It would be extremely unusual to see a mechanical vibration at such a high frequency, as that would place a great amount of stress on the PZT plate. Also, it is much too low of a frequency to be in the regime of electrical vibrations. While there has not been enough time to carry out some complicated calculations before the REU program ends, it is has been hypothesized that this 1.5 kHz signal results from the spring-loaded pogo pins that create an electrical connection with the PZT plates.

5.4 Signal Decay

In order to more fully understand these waveforms, it is also helpful to fit a model to the data using MATLAB. For this model, it is assumed that the PZT plate behaves like an underdamped harmonic oscillator, decaying exponentially over time:

$$V(t) = A\,e^{-\beta t}\sin[\omega t + \phi]$$

where β is the decay constant of the signal. An example model is shown in Figures 9 and 10.

The complete signal, however, contains too many vibrational frequencies to be adequately modelled by a single harmonic oscillator equation. For that reason, the raw signal data was put through a low-pass band filter to isolate the low-frequency, mechanical vibration. Then, the raw data was also put through a high-pass filter, isolating the electrical vibrations, which are at or above 98kHz. Each of these new sets of data can then be more closely modelled by the damped harmonic oscillator equation.

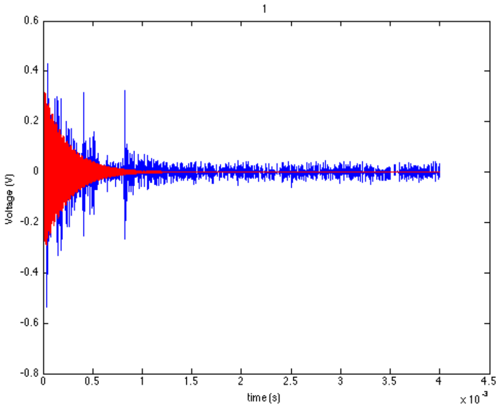


Fig. 9. High Pass Filtered with Fitted Model

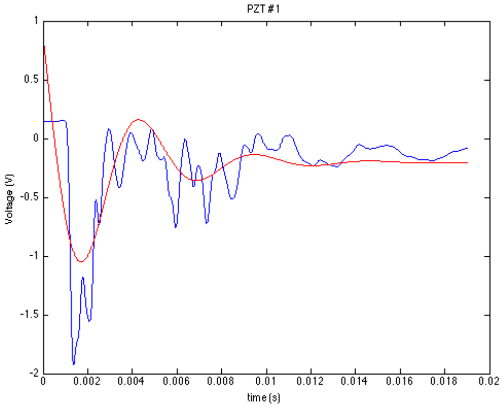


Fig. 10. Low Pass Filtered with Fitted Model

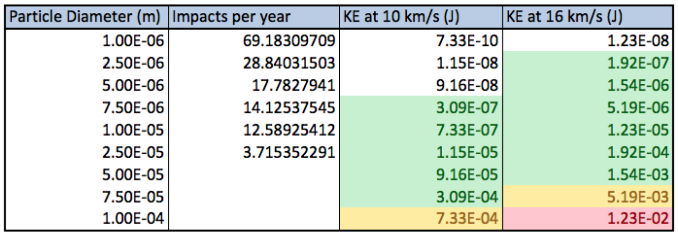
The decay constant for each set of data can then be extracted and used to compare how well the signal is damped by the frame of the MDU. The electrical vibration is damped out more quickly, with a decay constant of around 5000. After about a millisecond, the mechanical vibration begins to dominate the PZT signal, having a decay constant with a value near 300. Since nearly all of the signal damping is due to the MDU frame, a large change in these values would signify a that the boundary conditions for the given PZT have changed—either the plate has been broken or it has shifted and no longer sits flush against the frame.

6 BROKEN EQUIPMENT

A challenge of working with satellite components is that none of the equipment can be inspected or modified once the satellite is set into orbit. Each component must be tested to ensure that it will withstand the space conditions during orbit. The PDD will be coming into contact with hypervelocity debris particles, a vacuum environment, and temperatures much higher than those at atmospheric conditions. If one of the satellite components fails, there should also be a method for identifying from signal data that it is broken, which is then sent back to the ground.

6.1 Risk of Broken PZT

While using the Drop Tower, a single drop with an impact energy of 3.277 mJ managed to crack one of the PZT plates. Since this impact energy could easily be seen in space debris collisions, a second look was taken at the DAS 2.0.2 simulation from earlier. The manufacturer of the PZT plates specifies that the minimum detectable impact energy is about 100 nJ. This simulation aimed to focus on particles that would have an energy above that threshold. The results, shown below in Figure 11, assume that the incident particle has a density of 2.8 g/cm^3, which is the average density of debris in LEO.



Particle Diameter (m)	Impacts per year	KE at 10 km/s (J)	KE at 16 km/s (J)
1.00E-06	69.18309709	7.33E-10	1.23E-08
2.50E-06	28.84031503	1.15E-08	1.92E-07
5.00E-06	17.7827941	9.16E-08	1.54E-06
7.50E-06	14.12537545	3.09E-07	5.19E-06
1.00E-05	12.58925412	7.33E-07	1.23E-05
2.50E-05	3.715352291	1.15E-05	1.92E-04
5.00E-05		9.16E-05	1.54E-03
7.50E-05		3.09E-04	5.19E-03
1.00E-04		7.33E-04	1.23E-02

Fig. 11. Second DAS 2.0.2 Simulation

The green highlighted energies represent impact energies less than or equal to those that the plates have already experienced without breaking in the lab. Those highlighted in red are greater than 3.277 mJ, which broke the PZT. Those highlighted in yellow are below 3.277 mJ, but the plates have not been successfully tested at or above that energy.

Finally, those that are not highlighted are below 100 nJ, the minimum threshold for the PZT plates, and likely could not be detected if a collision occurred. This simulation is encouraging, because it shows that a large majority of the impacts in LEO should not crack the PZT plates. Those that do have the potential to break a plate should be relatively rare, leaving plenty of time between such collisions to identify a broken PZT.

6.2 Frequency Shift

There are several methods that can be used to identify a broken PZT plate. The most apparent method is to examine the fourier transform, noting that there the vibrational frequencies shift once the plate has been cracked. A crack or large chip in the plate effectively changes the boundary conditions of the PZT. For example, a PZT was broken as shown below in Figure 12.

Fig. 12. Broken PZT

Because of the complete crack along the left side of the plate, the left edge is now unclamped, leaving it free to oscillate. This lowered the vibrational frequencies in both the mechanical and electrical regimes, giving new frequencies of about 200 Hz and 90 kHz for the respective fundamental frequencies. There is no other reason that the plate's vibration would change so dramatically except that it had been cracked. So, observing a shift in frequency can be a relatively easy way to identify a broken PZT.

6.3 Decay Constant

As mentioned earlier, the signal from each PZT is primarily damped by the frame of the MDU. If the plate is broken, it will not be as tightly bound to the frame—since one side of the plate is no longer clamped to the frame. So, it is expected that the decay constant of the signal should decrease. For the PZT shown in Figure 12, the calculated high- and low-frequency decay constants decreased to about 3000 and 200, respectively. At its most basic, this means that the signal lasts for a much longer period of time with a broken PZT.

This measurement may be less obvious than the frequency shift that was mentioned in the last section, though. The FPGA and OBC have limited memory, and only a short portion of the waveform will be saved. Only 200 data points are saved of the complete waveform, all at one microsecond time steps from each other. A calculation of the decay constant would likely be only a rough estimate, making it more difficult to determine a change once the plate is broken. The calculation can be used, however, as additional confirmation along with a noticed frequency shift. If both measurements suggest that a plate has or has not been damaged, then it will be easier to cofidently state whether one or the other is true.

6.4 Fourier Peak Broadening

There is yet another method for identifying a broken PZT which utilizes fourier transforms. When a PZT is cracked, it almost certainly will not crack in such a way that the plate would still have symmetric boundary conditions. The crack will be crooked, like the one in Figure 12, or may be set at an unusual angle on the plate. Because the boundary conditions are no longer symmetric, there will be a larger range of frequencies that can be seen in the PZT. This should result in a broadening of the peaks in the fourier transform. It is possible to measure that broadening in frequency-space by calculating the full width at half maximum (FWHM) of the peak, shown in Figure 13.

This is done by first smoothing the fourier transform data so that there are not so many local maxima and minima in the data. This will lead to a more consistent measurement. The data smoothing was done using As expected, the FWHM was significantly larger in the cracked PZT, with a mean value of 190. In the unbroken PZT, the average FWHM was only 120.

Again, as with the decay constant measurement, the FWHM may be much harder to calculate when

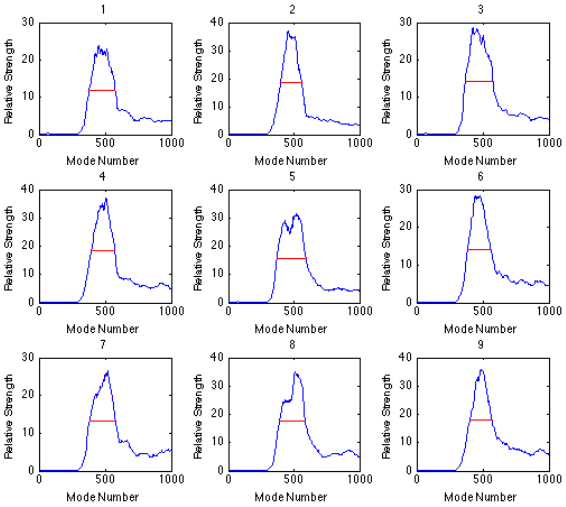


Fig. 13. FWHM calculation

using data collected from the FPGA rather than the oscilloscopes in the lab. The FPGA returns 200 data points from each impact event, which are collected at a rate of 1×10^6 samples per second. When performing a fourier transform from this data, there is only resolution of 5000 Hz between channels of the transform data. It appears to be relatively easy to identify a broken plate by the FWHM when using oscilloscope data, because there is much more clarity—a resolution of 200 Hz per channel in the fourier transform. It is unlikely, given the current sampling rate and the number of data collected by the FPGA, that the FWHM measurement will be able to identify a broken piezo plate. Like the decay constant, however, this measurement may help to confirm a broken plate if there is also evidence of a decreasing decay constant and a shift in frequency. It is expected that a noticed frequency shift will be the most powerful tool, but the decay constant and FWHM may also be able to offer additional support.

6.5 Voltage from Broken PZT

At what point is the PZT too damaged to give meaningful data? The frequencies, decay constants, and FWHM measurements may all change as the plate is damaged, but the purpose of the PZT is to predict the impact energy of space debris. As it turns out, the response from the PZT shown in Figure 12 is nearly unchanged from that in the unbroken plate. Ten identical BB drops were performed on the plate both before and after it was broken. The average peak-to-peak voltage for the unbroken-PZT and broken-PZT signals, respectively, were 3.91 V and 4.00 V. Additionally the unbroken and broken signals had standard deviations of $\sigma = 1.09$ V and $\sigma = 1.20$ V, respectively. The differences between the two sets of data are nearly indistinguishable.

The plate was then intentionally broken even further, as shown in Figure 14.

Fig. 14. Repeatedly Broken PZT

At this point, the plate has been broken to the point that it barely retains any electrical connection to the MDU. An impact of energy equal to the previous BB drops now hardly produces 100 mV of peak-to-peak voltage. The plate is no longer yielding any meaningful data. So, there is clearly a point when a PZT is too broken to be useful anymore; however, the plate must be repeatedly broken before it comes to that point. Since there should not be many impacts of high enough energy to break a plate, it is unlikely that any of the plates are broken so severely.

7 INTEGRATION WITH ELECTRONICS

As mentioned before, when there is an impact on one of the PZT plates, the FPGA digitizes the signal from the plate and returns 200 data points, collected at 1×10^6 samples per second. This results in 200 microseconds of signal data for each channel that can be relayed back to ground. An example signal is shown below in Figure 15. When a signal passes through the electronics stack, there is consistently an upward shift in the frequency of the signal. This was confirmed by injecting pure sinusoidal signals of various frequencies into the electronics stack and observing the returned data with a higher frequency. Specifically, the 98 kHz signal, coming from the electronic vibration, that was prevalent in the original signal, is shifted upward to about 110 kHz after passing through the electronics. Also, it should be noted that the signal is amplified by a factor of 1.5 due to the op-amps within the electronics.

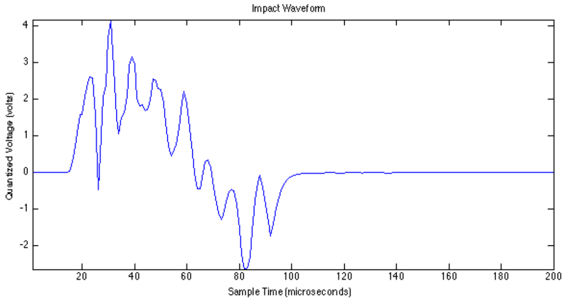


Fig. 15. Complete Signal from FPGA

This signal appears to be very different from the oscilloscope data shown earlier, but it provides all of the necessary information. Fourier analysis, shown in Figure 16, reveals the low-frequency mechanical vibrations at or below 5 kHz as well as the electrical vibrations at 110 kHz. Although the signal suddenly flatlines after about 100 microseconds, the signal can be seen decaying over time. While there has not yet been time to test a wide range of impact energies, the peak-to-peak voltage of this signal also seems to agree with the linear model that was developed earlier.

8 VACUUM TESTING

To this point, the PDD has been tested to ensure that it can withstand impacts with space debris, and that the data collected from those collisions can be used to estimate impact energy. It must also be shown, however, that the device will be able to tolerate a vacuum environment. At extremely low pressures (on the order of 1×10^{-4} Torr or lower), it becomes much more difficult for heat to dissipate away from the system. Electronic components, in particular, produce a significant amount of heat that is ordinarily dissipated into the surrounding air. It could be possible for some components to exceed their maximum operating temperatures. If a chip burns up once the PDD has been set into orbit, there is no way to replace it, and the electronics stack could become completely useless.

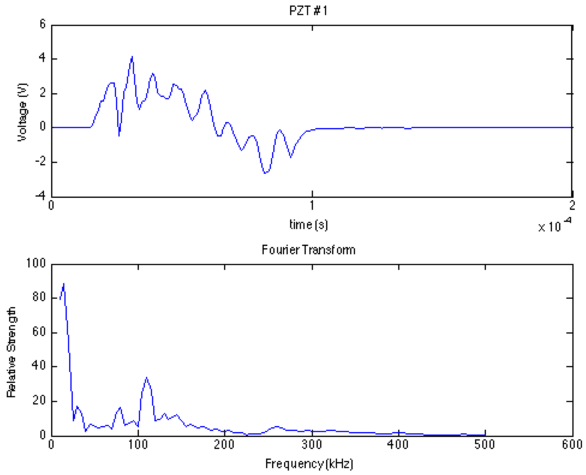


Fig. 16. Fourier Transform of FPGA Signal

8.1 Infrared Camera

At ordinary atmospheric conditions in the lab, the electronics stack was brought up to full power and allowed to run for an extended period of time. Using an infrared camera, it was possible to identify 16 "hot-spots" on the electronics—chips that were especially hot in the lab and that had the potential to get very hot in a vacuum environment. An example image of the electronics stack, taken with the infrared camera, is shown in Figure 17.

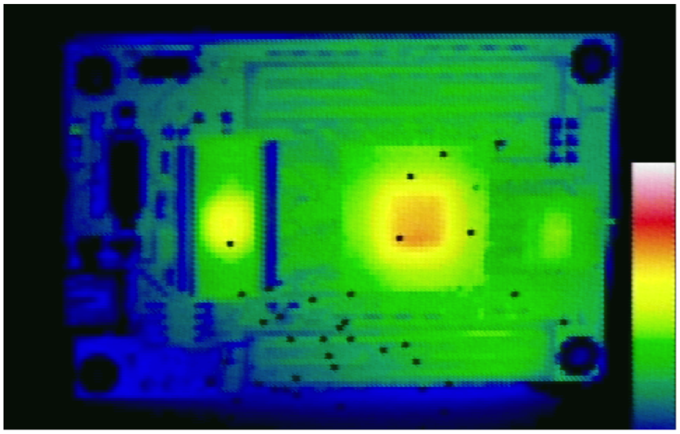


Fig. 17. IR Camera Image of one side of the Electronics Stack, including the Spartan chip

8.2 Data Collection

A thermistor was placed on each of the 16 locations identified with the infrared camera so that all of the temperatures could be monitored in the vacuum. As the thermistors heat, the amount of current that flows through them changes. The current was then monitored by a LabView program, recording the temperature of all 16 channels approximately every 3 seconds. The entire electronics stack was placed inside the vacuum chamber of the Inductively-driven Plasma Generator (IPG). Then, the pressure in the chamber was pumped down to 1×10^{-4} Torr. Once the pressure was stabilized, the electronics stack was brought up to full power and allowed to run continuously for about 9.5 hours. The temperature data for some of the relevant locations was plotted and is shown in Figure 18.

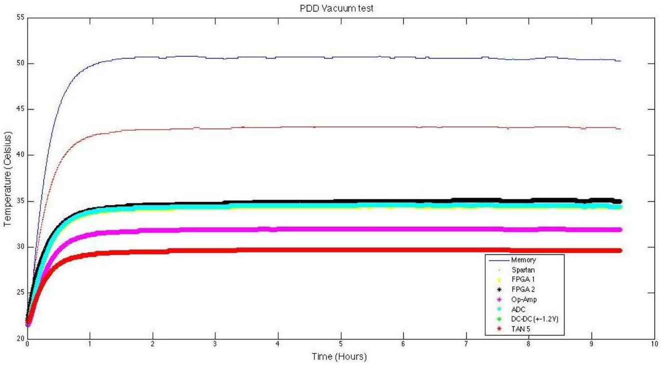


Fig. 18. Vacuum Temperature Data

The hottest channel, by far, corresponds the Memory chip, It stabilized at 51 degrees Celsius, which is well below the maximum operational temperature for the chip. So, the electronics stack should be able to withstand a vacuum environment without burning up any of its components.

9 RESULTS

The PDD appears to be working as planned. The impact energy of space debris can be predicted from the peak-to-peak voltage of the resultant signal using the linear model presented in Section 5.1. The complete signal can also be characterized using fourier analysis and nonlinear modelling to extract the vibrational frequencies and decay constants, respectively. If a PZT is broken, it should be possible to identify that from additional fourier analysis or nonlinear models. Even if the PZT is broken, the peak-to-peak voltage of a signal should still follow the linear model until it has been broken repeatedly and begins lose the electrical connections to the MDU. The FPGA and electronics stack digitize the signal and return a short sample of the signal that can be relayed to ground. The same signal analysis methods can be used to analyze this signal. Finally, it has been shown that the PDD should stand up to vacuum conditions without damage to any of its components.

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