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Article

Inexpensive Piezoelectric Elements for Nozzle Contact Detection and Bed Levelling in FFF 3D Printers

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Abstract: Inexpensive piezoelectric diaphragms can be used as sensors to facilitate both nozzle height setting and bed levelling in FFF (Fused Filament Fabrication) 3D printers. A variety of probes have been developed by the authors and others to utilize piezoelectric diaphragms both under the build stage and in the printer head. The reliability, repeatability and sensitivity of these probes has been investigated along with such practical considerations as usability in different environments, the functional life of piezoelectric diaphragms in this use and what improvement to print quality may be obtained. A probe using a piezoelectric diaphragm has been developed and released as an open source product, this probe as well as kits for making probes are available and are proving reliable. The conclusion is that piezoelectric diaphragms are equal to or better than other technologies used for nozzle probing.

Keywords: 3D Printing; Open Source; RepRap; calibration; bed levelling

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1. Introduction

At the core of the RepRap project is the objective that RepRap printers should be able to print many or most of the parts that are used in their own construction while those parts that cannot be printed should be readily available and inexpensive [1]. Piezoelectric diaphragms are readily available and inexpensive as they are used as sounders in many manufactured goods. As piezoelectric discs will also function as sensors they are useful components for making RepRap printers: This paper addresses the suitability of piezoelectric diaphragms as sensors for bed levelling in FFF printers..

FFF 3D printers [2] produce a solid object by printing layers of material one upon another on to a flat build stage. The adhesion of the first layer to the build stage depends on several factors, the thickness of the first layer being a very important one [3] as thick or thin areas can result in a print detaching from the build stage. The nozzle height above the build stage determines the first layer thickness and can be influenced by many things such as: The build stage itself may be less flat than is needed for a good print; initial adjustment may have been effected by thermal expansion of parts of the printer while routine changes of parts such as the printer nozzle or build stage are likely to change the nozzle height and the first layer thickness. Measuring the nozzle height at a number of positions over the area of the build stage before the first layer is printed can allow manual correction or automatic optimization of the first layer or layers.

The early RepRap printers levelled the build stage manually by adjusting three or four sprung adjusting screws. [4] As manual adjustment was laborious and may be required frequently, methods were sought to automatically check the height of the printer nozzle without resorting to tools such as feeler gauges. Once the earliest automatic methods of measuring the relative distance from the nozzle to the build stage it became possible to use software to compensate for distortion of the build stage and ultimately to compensate for geometric errors in the printer itself.

The first methods measured the distance between the print nozzle and the build stage using a switch which could be manually, mechanically or electrically deployed. [5] Proximity sensors are also used including inductive, capacitative, ultrasonic and optical sensors, both industrial and purpose built. Proximity sensors are difficult to place close to the nozzle and will not measure the proximity of a point directly under the nozzle. Other sensors detect the nozzle contact coming into contact with the build stage so measuring the nozzle height as well as its horizontal position.

Nozzle contact sensors include electrical contact types which rely on a clean conductive nozzle contacting a clean conductive build stage; FSR (force sensitive resistor) sensors [6] which detect the pressure of the nozzle on the build stage beneath which several FSRs are mounted; Accelerometers which detect the deceleration of the print head when the nozzle contacts the build stage; Strain Gauge sensors using foil strain gauges, elements etched directly into the PCB or load sensor elements; microphonic sensors which detect the vibration caused by nozzle contact and piezoelectric sensors. The piezoelectric sensors described in this paper are nozzle contact sensors.

Although there had previously been discussion in public forums of the possible use of piezoelectric diaphragms as sensors in RepRap printers, the first reported use of them was by Njål Brekke. [7]

The piezoelectric diaphragms described in this paper are typified by the Murata 7BB series [8] and any functionally similar replacements from unidentified manufacturers. These diaphragms are used in musical novelties, as the voice in toys, to produce the warning sound in alarms, to replace the mechanical click sound in tactile keyboards and in a great many other ways.

Conversion of electrical energy to mechanical energy in piezoelectric diaphragms is by what is correctly termed the "Inverse Piezoelectric Effect" however piezoelectric materials also exhibit the "Direct Piezoelectric Effect" [9] where mechanical energy is converted to electrical energy: It is this effect which is used by the sensors described in this paper. The diaphragm consists of a piezo-active ceramic disc bonded to a metal disk and a conductive layer on the opposite surface which form the electrical connections.

The design intent of these piezoelectric diaphragms is the conversion of electrical energy to mechanical movement when an electrical potential applied to the piezo-active ceramic causes the centre of the diaphragm to bow relative to the periphery. The ceramic used will also operate in the reverse sense, a pressure that causes the diaphragm to bow or to bend will generate an electrical charge between the electrodes. In addition, a pressure applied directly between the face and the substrate without causing it to bend will also generate an electrical charge.

In order to assess the usefulness of inexpensive piezoelectric diaphragms as sensors in FFF printers an experiment has been designed and equipment constructed to simulate nozzle contact events in FFF 3D printers. Various pressures are applied directly to a piezoelectric diaphragm and the voltage generated are recorded.

It is known from early tests [10] that the response of piezoelectric diaphragms can be considerably reduced but these were only records of a single pressure release event and would not be indicative of long term performance, although it was noted that some makes of piezoelectric diaphragms were much better

The limitation of use at higher temperatures is investigated as well as the effect of large numbers of simulated nozzle contact events at room temperature and at temperatures near the limit of sensitivity. Data is compared for diaphragms before and after thermal cycling to assess the ageing of the diaphragms in service.

The development of a Z probe integrated into the printer hotend is described by Simon Khoury in the discussions section of this article.

2. Materials and Methods

A jig to simulate nozzle contacts was constructed and mounted in a Proxxon MF70 light milling machine [11] modified for CNC control which was programmed to provide the required mechanical action. The jig as depicted in **Figure 1** has a small table mounted on an actuator rod which is connected to a 3D printed parallel mechanism, the parallel mechanism transferring pressure to the piezoelectric diaphragm through a 3D printed pressure pad. A load spring maintains an upward pressure on the actuator rod and on the diaphragm through the parallel mechanism. A preload adjuster centres the parallel mechanism at its resting position and provides a small force on the piezoelectric disc after the spring load has been removed. The CNC machine is programmed to start a probe moving towards the actuator from 1mm above it and to continue for 0.5mm after striking the actuator. This was done to eliminate the effects of the acceleration and deceleration times which are a feature of CNC programs.

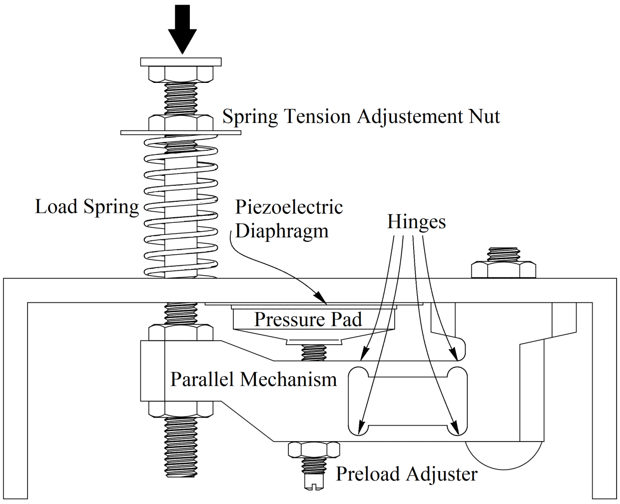

Figure 1. Test equipment for obtaining response data.

In order to check for loss of sensitivity in use including that at higher temperatures, a test rig was fabricated to stress piezoelectric discs by alternately applying a pressure to the disc and relaxing that pressure over a large number of cycles and over a range of temperatures. The rig consists of an aluminium block having a flat surface on which the piezoelectric disc is mounted and a pressure pad having a flat surface of the same diameter as the upper electrical contact of the disc. A force generated by a spring is applied by way of an actuator rod and a parallel mechanism to the pressure pad; an electrical solenoid acts to relax the major part of the pressure on the piezoelectric disc at regular intervals.

Provision is made to adjust the pressure on the pad due to the spring, the pressure due to the elasticity of the joints of the parallel mechanism and the mechanical travel of the armature and actuator rod. The rig, shown in **Figure 2**, is mounted on a stand which also carries a dial indicator for checking the travel of the actuator rod and the pressure pad adjusting screw during adjustment. An upward force is applied through the return spring adjusting eye with a spring dynamometer to set the spring pressure. Adjusting the preload applied by the parallel mechanism is done by lifting the free end of the parallel mechanism with a spring dynamometer with the solenoid operated. During commissioning of the rig the following were found to be usable values: Force applied by the parallel mechanism alone to the piezoelectric disc 0.5N; force applied through the actuating rod 4.5N when lifted 0.25mm from its resting position; Armature to Solenoid clearance in the non-operated state 0.8mm; overtravel of the actuator rod from the point that pressure is relaxed to full travel of the solenoid 0.3mm. The dial indicator is removed during cycling tests.

The temperature of the piezoelectric disc is maintained by a resistance heater in the heater block and a thermocouple temperature controller [12]. The voltage generated by the piezoelectric disc was recorded by a Digital Storage Oscilloscope [13] and a X10 probe.

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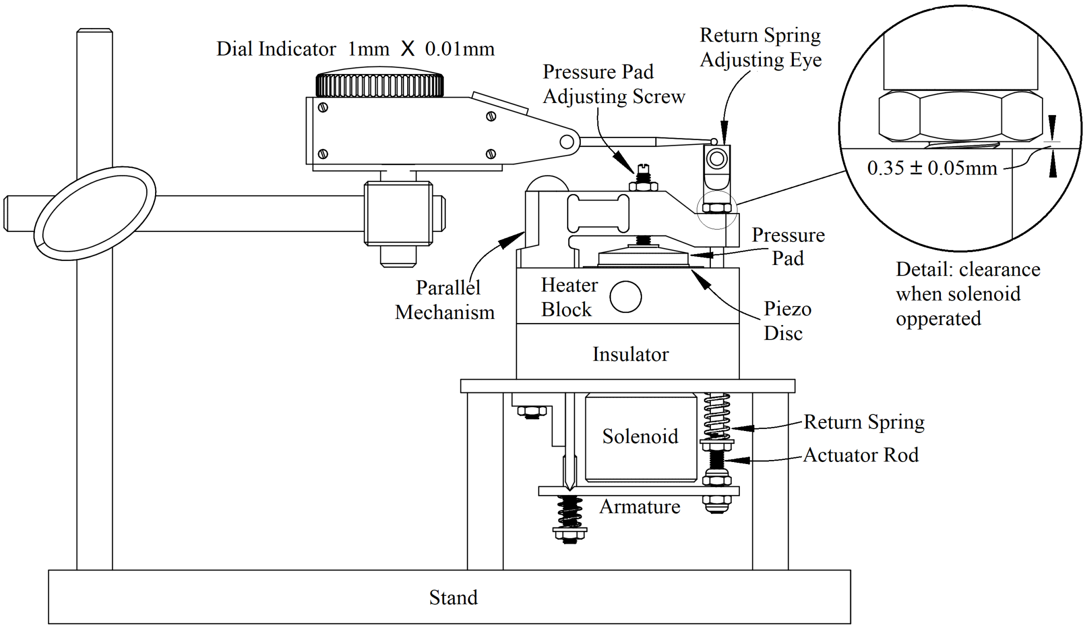
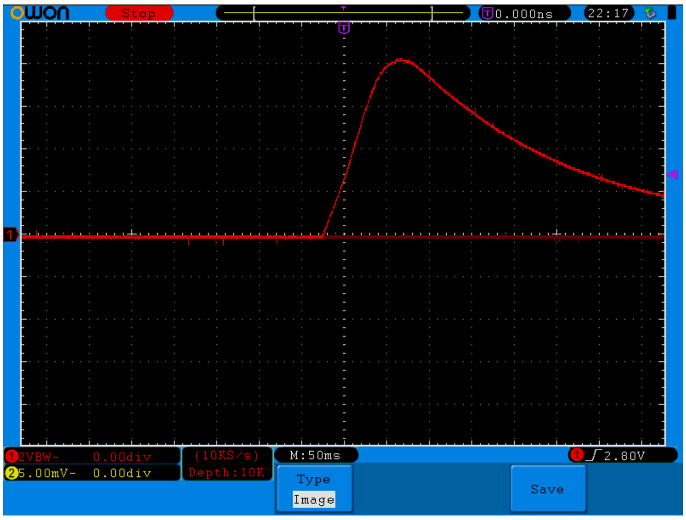


Figure 2. Test equipment for obtaining temperature response and ageing data.

3. Results

3.1. Electrical response of Piezoelectric Diaphragms.

A first batch of 10 piezoelectric diaphragms were obtained on eBay, the manufacturer of these is unknown but they were similar in size and appearance to Murata 7BB-27-4LO. The traces below were all from one of these diaphragms fitted in the Electrical Response Jig shown in **Figure 1**.



1 2VBW- 0.00div
2 5.00mV- 0.00div
(10KS/s)
Depth:10K
M:50ms
1 ∫ 2.80V

Figure 3. 1mm per second with pre-travel and after-travel.

In **Figure 3** the probe strikes the actuator at 1mm per second and the peak voltage obtained from the piezoelectric diaphragm was 8.1 Volts which occurred 90ms after the first contact. Oscilloscope settings were 5V per cm vertical with trigger set to 2.4V and horizontal was set to 50ms per cm.

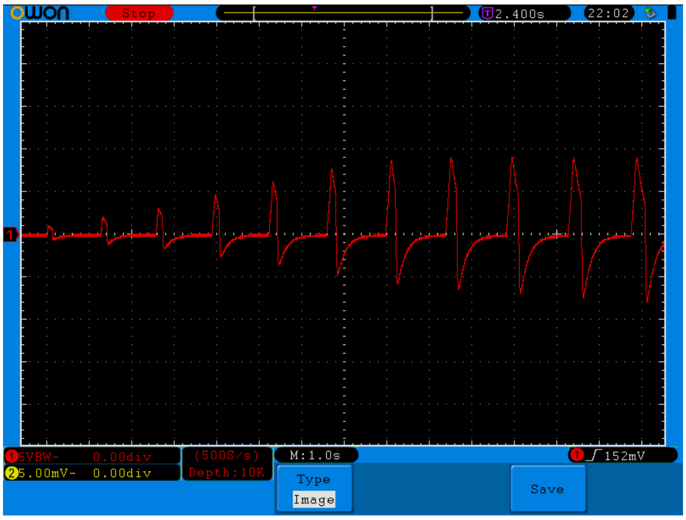


Figure 4. Cycling 1mm per second with increasing travel.

The probe strikes the actuator and over-travels by 20μm each cycle from 20 to 220μm. The voltage response is shown in **Figure 4**. Note that the travel at greater than 120μm is more than the 90μm implied by the first test. This is thought to be due to the deceleration phase from the CNC software.

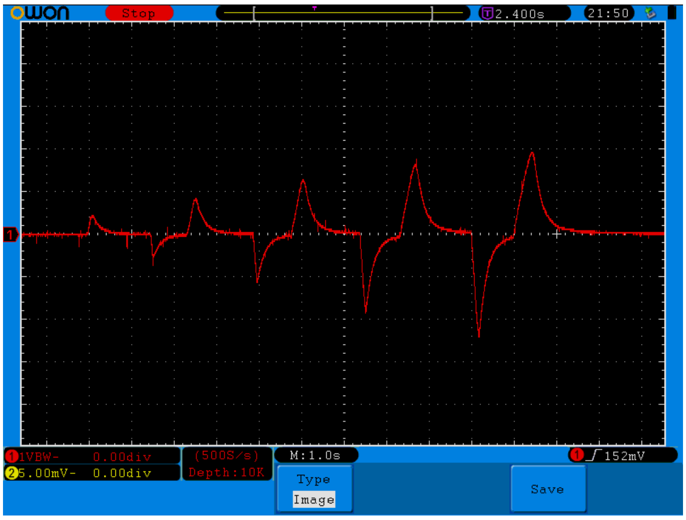


Figure 5. Cycling 2mm per second with increasing force.

To obtain data on the force response the solid probe was replaced with a light spring and travel was set so that with each cycle the force applied by the spring was increased by 20 grams force to a maximum of 100 grams force. To obtain the required spring rate an Entex stock no. 3352 spring was shortened to give a rate of 125 grams per mm. The resulting voltage is shown in **Figure 5**, the available voltage being significantly reduced by resistive leakage through the oscilloscope probe

The remaining nine piezoelectric diaphragms were all checked for basic voltage output and did not differ visually from the first one shown in **Figure 3**.

3.2. Cycling tests to determine service life

Using the test equipment shown in **Figure 2**, a Murata 7BB-27-4LO piezoelectric diaphragm was mounted and subjected to 100,000 cycles of pressure at 5N relaxed every 5.4 seconds to 0.5N for 2 seconds. After an initial hour to allow the equipment to settle the output was monitored and recorded every 25,000 cycles. The temperature was checked when each reading was taken and remained within 20°C±2°C at each reading. The first and final oscilloscope records are shown in **Figure 6** and the peak value graphed and shown in the top (blue) trace in **Figure 7**. During this test the peak voltage fell from 25V to 23.2V

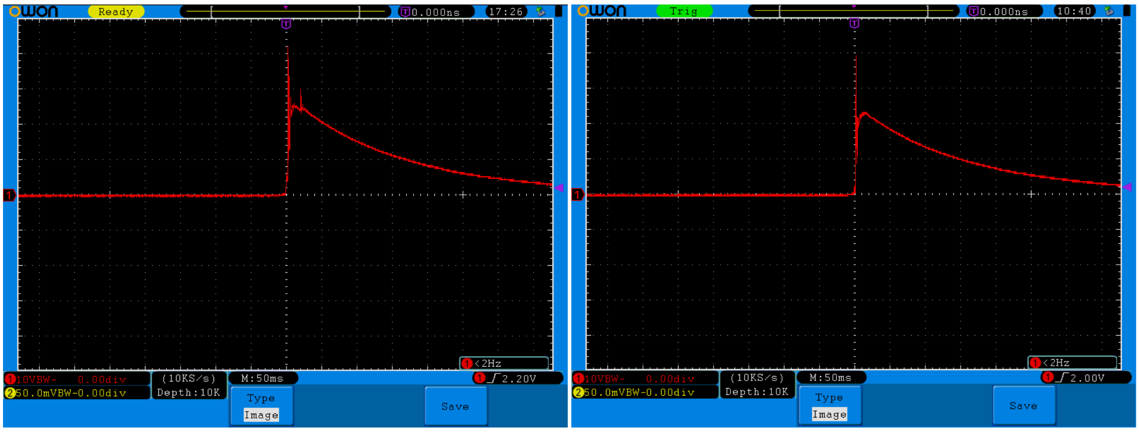


Figure 6. Peak amplitude after 1 hour (642 cycles) and after 100,000 cycles.

To investigate any change that may occur at higher temperatures the piezoelectric diaphragm was replaced with a new Murata unit and the temperature of the heater block raised to 50°C. 50,000 cycles were applied at the same pressures as the ambient test. The peak amplitude increased from 12.0V to 13.5V over the duration of this test.

As the increase had been unexpected, a further new Murata piezoelectric diaphragm was fitted and the temperature increased to 80°C. At this higher temperature the peak amplitude increased from 3.8V to 6.0V over the duration of the 100,000 pressure cycles, this change being plotted in the red line in **Figure 7**.

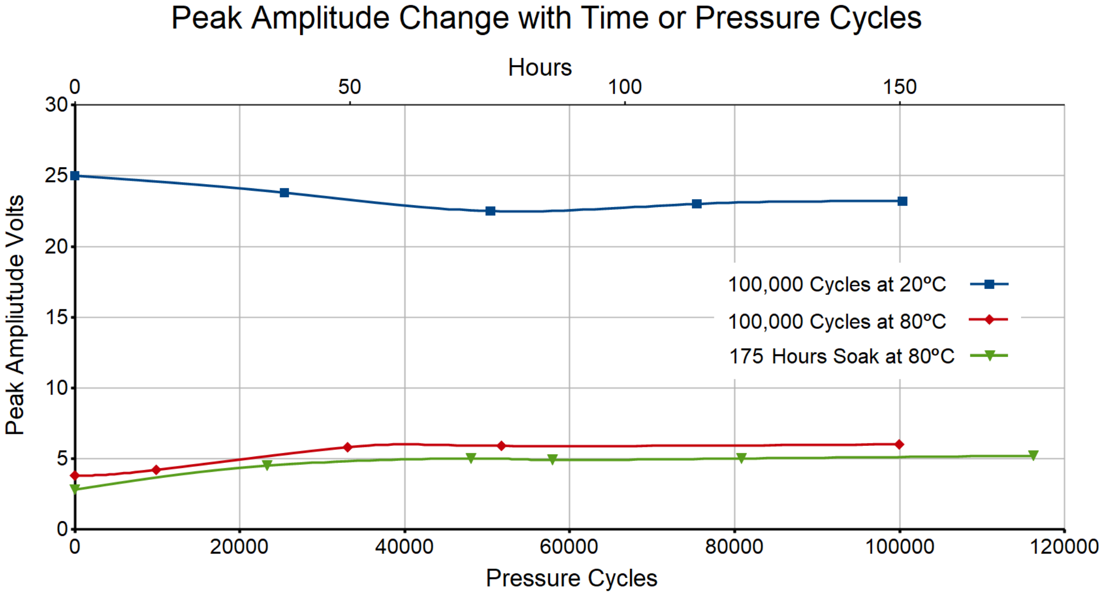


Figure 7. Change of peak amplitude with temperature and number of pressure cycles

To determine if the increase was an effect of the temperature alone a further test was devised. Using a new piezoelectric diaphragm the rig temperature was rapidly bought up to 80°C while the diaphragm was maintained at a pressure of 5N without pressure cycling. At several points the solenoid was operated for long enough for three pressure cycles to be applied and the resulting voltage to be recorded, about 15 seconds. The resulting peak amplitudes, recorded over 175 hours and plotted in the lower (green) trace in **Figure 7**, indicate that the higher temperature is the principle cause of the rise in output.

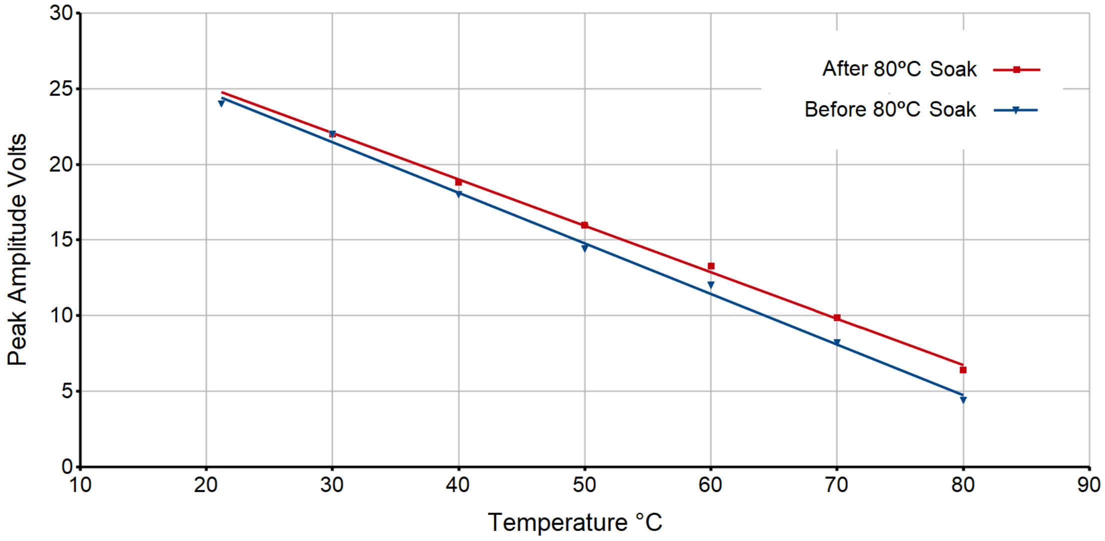


Figure 8. Effect of temperature on peak response before and after 50,000 pressure cycles at 80°C

In previous tests [10] a relatively rapid decline in sensitivity of piezoelectric diaphragms with increasing temperature was found. A new test was conducted in order to better categorize this in combination with the observed increase in high temperature sensitivity over time. A new piezoelectric diaphragm was fitted to the temperature response rig **Figure 2** and the pressure cycled as in earlier tests. The temperature was bought up rapidly in 10°C steps to 80°C and the peak amplitude at each interval was recorded. The test was continued for 50,000 cycles with the temperature held at 80°C after which the heater was turned off and peak amplitude recorded every 10°C down to 30°C. The results of this test are plotted in **Figure 8**, the lower (blue) line showing the peak values before the heat soak and the upper (red) line showing the peak values after the soak.

4. Discussion

4.1. Piezo Electric Nozzle Contact Sensing by use of drilled piezo ceramic discs.

A further development in the use of piezo electric sensing systems, as discussed here, was made by Simon Khoury. At the time (Jan 2017) the use of piezo electric sensing of nozzle contact by placement of piezoelectric discs either beneath a 3D printer's build stage, or somewhere upon its print head assembly, was already known. However the system of placing the discs below the build stage, required at least three piezo discs, sometimes four, so was considered more complex than necessary.

The build stage assembly is frequently mounted on a moving axis, the Y-axis in some cases (I3-type printers and their derivatives) or the Z-axis (for example corexy style printers) which results in two potential issues: Firstly, if the axis in which the piezo electric diaphragms moves, and such movement is required to bring the printbed and nozzle into contact this can, depending on the design and the quality of linear motion components, create mechanical noise which reduces the sensitivity of the apparatus. As such, the scheme of placing the sensors under the build stage is especially suitable on a delta printer, where the bed is fixed in place, but less satisfactory on other designs with moving build stages especially in the z-axis direction; secondly the stability of the build stage resting on mounts containing piezoelectric diaphragms, can be affected in this scheme, resulting in a mobile build stage, which inevitably causes reduction in print quality. Mounts are either more stable though more complex and expensive to build, or less stable but often cheaper and easier to construct. It is required that as much of a 3D printer be as rigid as possible in use including the build stage and its substructure, primarily to ensure the accuracy of the printed objects, and secondarily to enable accurate probing to take place. Additionally since 3D printers enhance the adhesion of the deposited polymer to the printbed by the use of heat, usually in the range of 55^{o}C to 115^{o}C, the possibility that the piezoelectric discs would heat up in use existed, which would cause undesirable changes in performance (reduced sensitivity or erratic triggering.) This lead to the realisation that a simpler method of using piezoelectric discs as sensors for nozzle contact was possible.

The key innovation, was to drill a hole through the centre of the piezoelectric disc, in such a way that it would still function adequately afterwards. Indeed, the cutting by either spur point drill bit, utilizing moderate force and low rpm, or use of CNC/lathe to cut the hole in the disc resulted in a hole through the upper conductor, ceramic and lower brass body of the disc of good quality. A hole of between 4.5mm and 5mm was chosen to minimize the amount of ceramic material removed, which generates the voltage during deformation, and to allow the 3D printing polymer (filament) to pass through the disc. In the case of the more common 1.75mm diameter filament type, a PTFE guide tube (2mm ID 4mm OD) was used to surround it, which prevents undesirable flexing of the filament as it is driven into the melting chamber above the printers nozzle (hotend). In the case of a 3mm filament no guide tube was used (as this filament is stiffer due to its larger diameter). It is noteworthy that piezo-ring devices already exist with holes centrally located but the cost of these devices is several orders of magnitude higher than for piezoelectric discs such as the Murata 7BB series, and they are available only from specialist suppliers.

Having determined by test probing, and testing of various drilled piezo electric discs on an oscilloscope, that the disc still functioned as it did when un-drilled, albeit with a reduction in voltage generated equal to the proportion of ceramic material removed, but well within the range at which detection with high sensitivity is possible, the next step was to mount the disc above the extruded polymer heater assembly.

An extruded polymer heating assembly referred to generally as a hotend, typically consists of a metal block with an electrical heating element placed into it, a nozzle threaded into the metal block through which the polymer is extruded, and a thermistor or PT100 sensor to provide closed loop control by PID of the temperature. This is attached to an externally threaded metal tube (ceramic/polymer in some types) which is threaded into the metal block (hotend) at one end, butted tightly against the mating surface of the nozzle, and at the other end into a (typically) aluminium heat-sink (correctly known as a coldend), the purpose of which is to prevent the heat in the hotend, often between 180^{o}C and 270^{o}C) from rising by conduction to the print-head, which can often be made of printable polymers, such as ABS, to enable parts to be printed by the machine itself. These polymers would soften at around 130^{o}C, and deform without the heatsink, and typically a fan with duct to pass air through it.

Construction of the sensor units shown in **Figure 9** consisted initially of two 3D printed polymer (ABS) components and a piezoelectric disc (Murata 7BB 27mm). The lower part incorporated a clamp that held the heat-sink mentioned above with its hotend attached, and which incorporated a surface on its upper aspect which contacted the piezoelectric disc. The upper part on its lower aspect incorporated a surface for contacting the piezo electric disc, fixing holes for attachment to the lower part and some method of attachment to the print-head. As such the design, in its most basic form, is a piezo electric disc (with the hole drilled) sandwiched between two 3D printed polymer parts - one attached to the printhead and the other to the hotend/coldend assembly. The filament can pass through the sensor assembly and piezoelectric disc due to its centrally drilled hole, and into the heat-sink, hotend and reach ultimately, the nozzle.

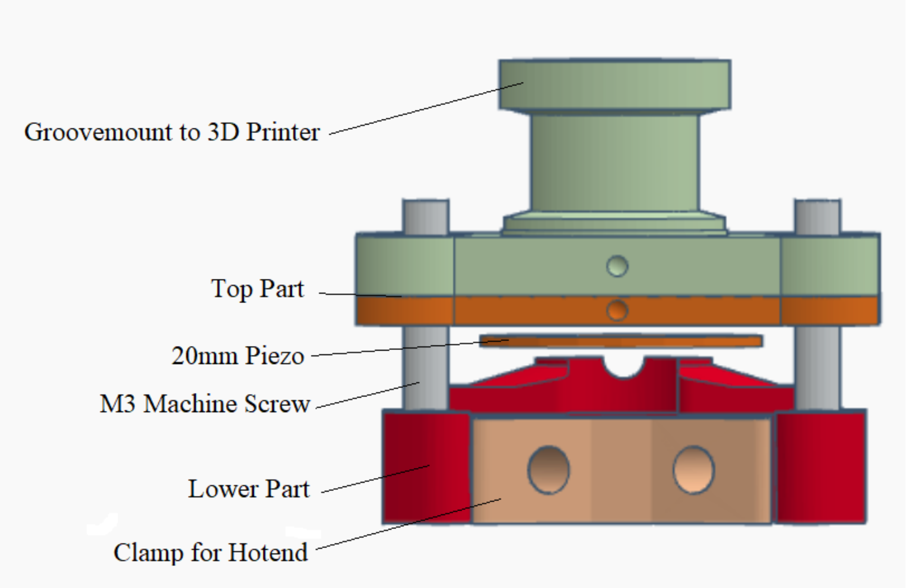


Figure 9. Piezo Z Probe

When the nozzle and printbed are brought together so that contact occurs, a force is generated which is transmitted directly upwards through the assembly. The force required to register contact is only in the order of 10-15g depending on the hardness of the printing surface on the build stage, of which many types are in common use. This force can be modified by changing the speed at which the nozzle and printbed are brought together during probing. When this occurs a voltage is generated by the piezoelectric diaphragm which can be detected by the amplifier circuit referred to elsewhere.

One of the key requirements of a sensor within a mounting system for the hotend/coldend assembly is for the hotend/coldend assembly mounted using it, to be as rigid as possible. Having lateral movement of the nozzle greater than 20-30μm during printing is highly undesirable, and would result in low accuracy printing, especially during the deposition of external perimeters. As each layer of material is deposited its upper surface is rarely uniform enough for the nozzle not to occasionally contact it when it passes over during printing of the next layer. Vertical movement of the nozzle is also undesirable but so long as it is less then 100μm, its effect on the accuracy of the print is acceptable. The sensor unit's design therefore is a compromise between having high sensitivity for nozzle contact which would be achieved by having a relatively loose assembly which allows for greater compression/flex in the piezoelectric disc, yet an unstable nozzle, and having an extremely tight assembly which would have much less sensitivity due to pre-loading of the piezoelectric disc, but exhibit greater nozzle stability.

Another aspect considered was that in the first prototype shown here, which used a 27mm piezoelectric disc, the mechanism by which force was imparted to the piezoelectric disc was by uniform compression. Whilst this achieves reasonable sensitivity, greater sensitivity can be achieved by flexing the disc. In this version four screws were used to hold the assembly together. This allowed a reasonably firm assembly to be constructed. Another version with three screws holding the assembly together was deemed to be too flexible and polymer pins were introduced alongside the screws, the idea being that the lower part could slide on the pins, the pins acting to limit lateral movement in the assembly and attached hotend/nozzle. This was later designed-out as the unit became smaller and this lateral movement was reduced.

Later versions shown here used a flange on the uppermost aspect of the lower part which engaged the piezoelectric diaphragm just lateral to the hole drilled into it and was 8mm internal diameter and 10mm external diameter. The upper part of the assembly incorporated a recess, with a lip into which the piezoelectric diaphragm sits. As such when these two components are attached to one another the diaphragm is bent centrally against its upper support and placed in light pre-load. This enhances sensitivity whilst achieving much less movement laterally at the nozzle. Another change was to make the unit smaller, in order to do the size of piezoelectric disc reduced from 27mm to 20mm.

5. Conclusions

The reliability, sensitivity and repeatability of piezoelectric diaphragms has been demonstrated and the cyclic tests have indicated that a long service life may be expected. Piezoelectric diaphragms have other useful characteristics such as robustness, high availability and low cost. Some weaknesses such as the variability of response, temperature drift and polarization are known and are largely due to the uses described here relying on parameters not specified for manufacturing. Despite the foregoing, the output from these components is so large that even a poor quality piezoelectric diaphragm is able to give an output much greater than is needed for accurate detection of the 3D printer build surface.

In order to promote the widespread adoption of this technology and method of probing the build stage of a 3D printer, the company Precision Piezo [14] has been formed which has during its first 6 months of operation some 125 units have been sold. These have been performing extremely well and the number of potential applications increases daily. It is open source in nature and rooted in the RepRap community where ideas such as this continue to be discussed, developed and shared for the good of all.

Acknowledgments: This work is unfunded, the participants having covered their own material and equipment costs. Where monetary transfer between participants has been needed or where items have been sold the income has been limited to not more than the costs. MDPI has waived the Article Processing Charge.

Author Contributions: Mike Simpson designed the experiments to investigate electrical response and service life of piezoelectric diaphragms; Simon Khoury designed several practical implementations of Z probes using piezoelectric diaphragms and maintains them in the public domain.

Conflicts of Interest: Mike Simpson declares no confilct of interst: Simon Khoury declares that he has a financial interest and is trading as "Precision Piezo". All information required to construct piezoelectric systems described in this article are open source and no patents are held nor copyrights enforced.

Abbreviations

The following abbreviations are used in this manuscript:

MDPI: Multidisciplinary Digital Publishing Institute
FFF: Fused Filament Fabrication
ABS: Acrylonitrile Butadiene Styrene

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