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Near Field Acoustic Levitation Sliding Contact

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Abstract: The paper presents an investigation into producing self-levitation effect using piezo-electric actuators (PZT). Self-levitation has been demonstrated and results are presented and discussed. A relationship between the levitation distance and weight of the levitating sample has been found. In addition, the orientation and position of the PZTs has been found to affect the levitation distance. Modal shapes of the vibration plates used have been produced through modelling and found to accurately correlate with the experimental results found. Additional evidence suggests that the type of vibration plate material affects the separation distance, possibly due to the material's properties of acoustic reflection.

1. Introduction

Increasingly in modern technology the demand for engineering components is to become smaller and smaller. This opens up a completely new area of micro technology and precision engineering in the nanometre scale. One of the main problems with manufacturing components at such a small scale with equipment such as laser cutters, optical scanners and silicon chip production tools is the accuracy of any movement at this scale. Static friction has a major effect on controlled precise movements at the nanometre scale. Near frictionless operation of machinery for nanometre accuracy is a definite pre-requisite.

Producing frictionless movement can be achieved with several methods. Lubricating oil can be used to reduce friction but small accurate movements can be affected by the viscosity of the lubricant. Current compressed air tracks are available but these require a constant clean supply of compressed air and the air tracks require hose feeds and porous pads making the system bulky. Magnetic frictionless systems are available but these are also costly and require the use of large magnets or coils to produce the magnetic fields. In addition, the magnetic fields produced by this equipment are undesirable in many applications relating to nano-technology. Dynamic bearings do produce a frictionless surface when in operation however, they do not perform well in static conditions as when the surfaces stop moving relative to each other and the separation between them is lost.

Near Field Acoustic Levitation (NFAL) [1, 2, 3] is an interesting alternative for near frictionless operation of high precision machinery. NFAL is produced when rapid vibrations between two surfaces close together in a compressible fluid medium such as air create a load carrying gas film. This gas film has a pressure greater than the ambient pressure and so can support a load. There is no need for large quantities of clean compressed gas or the production of magnetic fields. All that is required is the production of rapid vibrations between two surfaces to produce the effect. The production of rapid vibrations can be achieved by some form of piezo-electric actuator (PZT) as the frequency required is particularly high. The separation between the two surfaces can be very small indeed, in some cases down to a distance of just 10 μm.

The frictionless operation of the levitating surface along with the small dimensions of the separation distance between the two surfaces makes the NFAL effect an alternative for separation distance techniques within computer hard disks. Within the computer industry the demand for larger data capacity storage devices, means that the density of transistors is much higher on a hard disk platter and in order for the disk head to read the data it must be extremely close to the rotating platter. Current aerodynamic methods of separation of the platter and head are reaching their limits. The possibility of the head levitating due to ultrasonic vibrations above the hard disk platter may be an interesting and plausible method. If the separation between the head and the platter can be kept extremely small down to 6nm, rather than the current distances of 76 nm to 500 nm, the density of data storage elements on the hard disk platter will increase from the current 10Gb/in^2 to 100 Gb/in^2 [4].

Acoustic levitation of solids has been suggested for use in non-contact transportation of glass substrate of LCD in its manufacture [1]. Since the acoustic levitation effect can be used to move objects as well as cause them to levitate, many other applications would be applicable to acoustic levitation where relatively light objects need transporting accurately.

This paper reports on a sliding contact operating on NFAL principle. The ultrasonic frequency range used is inaudible so operation of any NFAL contact should be kept within this region if NFAL is to be recognised as a plausible method for use in industry.

The main objective of the study presented was to find a proof of evidence demonstrating that the NFAL contact is practically feasible and operates due to the emission of an ultrasonic acoustic wave from a parallel surface. Once the acoustic levitation concept was confirmed it was then possible to investigate relationships between the levitation effect and various parameters affecting it.

2. Experimental set up

In order to investigate the possibility of self-lifting generation due to NFAL a plain rectangular piece of material was rigidly clamped at each end as shown in Figure 1[5]. The initial dimensions of the rectangular plate were 200x100x5 mm and it was made from aluminium. The plate had two foil-type piezoelectric actuators on the underside of it, which produce Poisson’s ratio contraction effect when operated. In addition, these two PZTs generate an ultrasonic acoustic wave from the surface of the plate to allow small mass objects to levitate utilising the NFAL effect.

Experimental set up, in the form of a computer generated 3-D image, is shown in Figure 2. The test rig main structure is made of mild steel and holds the vibrating plate clamped in the horizontal plane. The vibrating plate is clamped at both ends to the steel supporting structure with the help of four bolts and a steel strip at each end. In addition, the base of the rig is made from twenty millimetre thick mild steel, this additional mass aids in the stability of the structure. The vibration of the plate will inevitably be passed onto the rig, which cannot be permitted to move around during operation; the large mass of the clamping structure makes it more difficult for the vibration of the plate to cause movement of the clamping rig.

The three feet to the base are adjustable so that the testing rig can be balanced with the use of a spirit level when set up on a bench. This is necessary as the levitating sample will be very sensitive to even a slight incline and this will cause the sample to constantly slide to the edges of the vibrating plate. Including the adjustable feet in the design of the testing rig enables the level of the plate to be set to horizontal on most laboratory benches.

The vertical acrylic plate on the side of the rig base has the function of holding a 4pin socket for the connector to plug into. This makes the rig easily detachable from other equipment. In addition, this means that when the wires are connected to the PZTs and the socket they receive no disturbance. Any disturbance through the wires connected to the PZTs could damp the vibrations of the element and lead to a wire breakage.

Vibrating plates used in experiments are the 1mm aluminium plate, 1.9mm aluminium plate 1.55mm titanium plate, and the 1.1mm steel plate. The 1.9mm aluminium plate was tested first and good results were obtained. The 1mm aluminium plate was then tested, as thinner plates should lead to higher amplitude of vibrations due to the lower mass of the plate being accelerated and the increase in deformation. The high carbon steel plate was chosen to obtain ground steel gauge plate, as it was thought that the smooth ground finish would increase the NFAL performance. The titanium plate was tested because titanium has certain elastic properties[i] that were thought to be favourable to the NFAL effect.

The floating samples used for the experimental testing had to have five very important features.

(i) The sample needed to be as flat and smooth as possible on the side facing the vibrating plate.

(ii) The samples needed to be relatively light. The amount of weight per unit area that can be supported by the NFAL effect may be very small with the small size of the PZTs driving the plate.

(iii) The floating samples needed to be rigid. If the samples were not rigid then the acoustic waves emitted from the vibrating plate would be partially absorbed by the sample. The levitating sample is a reflector of ultrasonic acoustic waves produced by the vibrating plate, this is a fundamental part of the NFAL principle, having a rigid sample will greatly improve the performance of the NFAL effect observed.

(iv) The sample had to be at least 1.5 wavelengths of the flexural wavelength of the vibrating plate to levitate stably. Through modelling, it was discovered that the floating sample would need to be at least 30mm in most modes of vibration for all of the plates.

(v) The top surface of the sample had to be metallic. The proximity probe, used to measure separation, can sense only conductive surfaces.

The most readily available samples that were found to cover all of these criteria were glass discs of 49.5 mm diameter and 3 mm thick and acrylic discs of 49.5 mm diameter and 6 mm thick. Both of these samples agree with all of the above conditions, apart from neither of the samples were metallic.

To use the glass and acrylic samples with the proximity probe the upper surface of the sample needed to be metallic. This was overcome by having both of the samples gold plated. The gold plating technique produces a very thin layer of less than 0.1 μm. However, the layer is sufficient to be detected by the capacitance proximity sensor and thin enough not to affect the sample's smooth surface.

Foil type PZTs were used and they are known to change length when a voltage is put across them in order to vibrate the plate on the rig. These PZTs are capable to operate at ultrasonic frequencies and were suitable for this application. The PZTs were bonded to the plates with epoxy resin in the manner shown in Figure 3. Initially, two PZTs were used. Their positions were decided as the best position over the plate in regards to the most flexural part of the plate, one element in the centre of each half of the plate less the clamped ends of the plate. Also the orientation of the PZTs was chosen to be lengthways as in this direction the plate has more material and so is more flexural.

3. Modelling and modal analysis

The 1.9mm thick aluminium plate was modelled using the finite element analysis programme ANSYS. Two models were created to investigate the behaviour of the plate around the ultrasonic frequency range.

3.1 Modal analysis

The first model was a modal frequency sweep of the plate. The plate was drawn in ANSYS and then a frequency sweep was done about a range of frequencies, which was set to 20 kHz– 40 kHz, as this is the range of the PZTs used. Through this frequency sweep, ANSYS detected the theoretical resonant frequencies of the plate with the given material properties of density 2600kg/m^3, Young's modulus 70GPa and Poisson's ratio 0.33. ANSYS also used the dimensions of the plate. The plate model was fixed at both longitudinal ends of the plate for 20mm from both ends. This was done by restraining the areas of the plate model surface for this distance in all dimensions. The elements used were solid brick 20 node "type 186" for the plate central area and solid tetrahedral 10 node "type 92" for the clamped area of the plate.

ANSYS was then used to display each of the detected resonant frequencies showing the deformed modal shape at that resonant frequency. This deformed shape does not have dimensions of deformation as no applied force is specified in the computing of the modal shapes, the distances shown in the deformation of modal shapes is relative distance. The deformed shape shows an estimate of what that mode of resonance of the plate will look like in terms of flexural vibration.

3.2 Structural deformation

The second model was a structural model of the plate. The plate was drawn in ANSYS as in the previous model with the same boundary conditions. Then forces of 10N per PZT were applied to the model of the plate in the positions where the PZTs are attached, across 3 nodes. By modelling the forces produced by the PZTs, the stress within the plate model can be examined and the deformed plate can be analysed. This model gives an indication of the way in which plate is forced to vibrate and the dimensions at which the plate will deform when the forces are applied. The structural model was used to understand how the plate is excited by the PZTs and whether the position of the piezo-actuators can be optimised to give better experimental results.

The structural model of the 1.9 mm thick aluminium plate, Figure 4 shows that the compressive forces applied by PZTs to the underside of the plate model deform the plate in this manner. The four protuberances on the surface of the plate model are directly above the positions of the forces representing the PZTs in the model; the deformation shown in the model is to an exaggerated scale.

Figure 5 shows that the displacement perpendicular to the surface of the plate has

a maximum value of 0.233 μm. The maximum displacement within the plate is found where the longitudinal PZTs are positioned.

When the PZTs are driven with a sinusoidal signal the forces are applied in an oscillatory manner, the deformation will occur as shown in Figures 4 and 5. The plate will also deform similarly in the opposite direction with respect to the surface, reciprocally every cycle of the sine signal. This deformation of the plate will excite it, vibrating it to the supply frequency of the PZTs.

The shape of the deformed plate as seen in this model will not necessarily be the shape that the plate will vibrate at. Flexural vibrations of the plate are at maximum displacement amplitude when the vibration of the plate is at a resonant frequency of the plate. To achieve maximum resonant frequency displacement amplitude, the position of the applied forces to the underside of the plate is critical. If the position of the PZTs deforms the plate in a shape that is similar to the modal shape of the plate at the applied frequency, then the resonant vibrations of the plate will be of higher displacement and more forceful, this should produce a better NFAL effect.

By examining Figures 4 and 5 it can be seen that the PZTs deform the plate differently when orientated in different positions. Relating the position of the PZTs to the optimum position is partly a trial and error process as the modes of vibration of the plate have been modelled but it is difficult to perceive which modes will be better at producing the NFAL effect without experimentation. This is due to the displacement values of the modal structure being given in relative distance rather than actual distances. This structural model of the plate will be compared with the results to attempt to find optimum positioning of the PZTs.

4. Experimental apparatus and procedures

Flow chart, shown in Figure 6, illustrates the experimental set up of the apparatus. The flow chart shows the various components used throughout the experiment and the connections between them.

The apparatus, as used during experimental investigations, is shown in Figure 7. The input equipment as shown in Figure 6, consists of an 110V transformer and a sine wave signal generator. The 110 V transformer has to be used to drive the ultrasonic PZT amplifier and the PZT monitor. The sine wave signal generator is needed to create the sinusoidal frequency required to drive the PZTs attached to the plate. This sine wave generator is operated between the frequency range of 10 – 60 kHz and it goes well into the ultrasonic region. This is also useful for application purposes as in ultrasonic region the NFAL does not emit audible noise.

Two experiments of fundamental importance for the concept of NAFL were carried out, namely (i) voltage amplitude versus levitation distance and

(ii) supported load per unit area (surface density) versus levitation distance.

In order to find out the relationship between the voltage amplitude and levitation distance, the following steps were taken:

1. Both the surface of vibration plate and the sample to be levitated were thoroughly cleaned. Then the gold plated sample, either glass or acrylic disc, was positioned in the centre of the vibrating plate with the proximity probe directly above it. The amplitude of the input signal to

the amplifier was increased until the amplitude of signal to the PZTs was at 160 V as measured on the oscilloscope screen.

2. The proximity probe was then lowered to get a reasonable reading of voltage. The voltage had to be low enough to fit on the oscilloscope scale with a high resolution so that all of the distance measurements consisted of measurements of at least 20% of the vertical height of the oscilloscope screen.
3. The first reading of the maximum separation distance was found by lowering the amplitude of the input signal to zero, as shown in Figure 8. The difference in voltage of the horizontal line (the proximity probe output) was recorded and is directly proportional to the levitation distance. This difference in voltage between the two conditions is the "separation voltage". Then the amplitude was increased again to the same point of 160 V, and lowered again to zero, here another reading was taken. This was repeated 4 times so that an average of the four readings could be used for results processing.
4. Now to take further readings, the amplitude of the signal input voltage was reduced by the step length (typically 10 V per step was used) and four results were recorded for each amplitude voltage in the same manner as the maximum separation voltage described step 3. Throughout the decrease of the amplitude of the input signal voltage, the proximity probe was lowered to ensure the measurement resolution was kept to 20% of the oscilloscope screen per measurement. In addition, the levitating sample was lightly touched with a small piece of plastic before each amplitude change to ensure

that the sample was still levitating and was not getting stuck on the surface of the plate by any contaminants.

Relationship between supported load per unit area (surface density) versus levitation distance was established utilising procedure described above. In addition to that the following steps were taken:

1. The first voltage reading is proportional to the separation distance of load per unit area of the levitating sample. For this first reading the load per unit area (surface density) was simply the weight of the sample divided by the area of the bottom surface of the levitating sample.
2. The next reading was carried out as described in step 3 above. The amplitude of the input signal voltage was not changed and stayed at 160 V. However, a mass to increase the load per unit area was placed on the levitating sample. This slightly decreased the separation distance between the levitating sample and the vibration plate.
3. This procedure was repeated for the required loads to be tested to give a set of results to analyse the separation distance versus load per unit area. Masses used to vary the load per unit area were from 1 g to 15 g in 1 g intervals. Afterwards, 5 g intervals were used until the suppression of levitation, which happened, typically, around 80-90 g.

5. Results and discussion

The testing began with 1.9 mm thick aluminium plate and the lengthways orientation of the PZTs. A preliminary experiment was carried out according to the experimental procedure described earlier.

Gold plated glass disc was used as levitation sample and the plate was operated at a resonant frequency of 25.6 kHz, which was found to be the most powerful ultrasonic resonant frequency.

5.1 Effect of PZT orientation

The experimental findings showed that the levitation distance of the floating sample was less than 5 µm at full peak to peak voltage. In order to increase the levitation distance of the floating sample two additional PZTs were added to the vibration plate laterally across the centre of the plate now giving the plate 4 PZTs. The levitation distances obtained with the additional elements were much higher. The results of the different orientations of the PZTs are shown in Figure 9. It is clearly shown that the levitation distance is almost entirely dependant upon the laterally aligned PZTs and the longitudinally aligned elements do not contribute much to the NFAL effect. As the graph shows, the levitation distance versus input voltage amplitude relationship seems to be a reasonably linear for the laterally applied PZTs when just the values above the 5 µm separation distance are considered. This can also be said for the PZTs orientated longitudinally for voltage amplitudes greater then 120 V peak to peak. However, the separation distances achieved with this orientation of the PZTs is far less than the laterally orientated ones. In fact, the levitation distances attained do not even go above the critical separation distance of 5 µm and so these results could be disregarded altogether as true levitation of the sample may not be fully achieved here and there may still be contact with the vibration plate below.

The reason for the orientation of the PZTs affecting the performance of the NFAL so dramatically is thought to be that the lateral PZTs excite the plate in this mode of vibration much more. This can be clarified by looking at the modal shape of the plate at the frequency of 25.6 kHz, shown in Figure 10. This figure demonstrates the modal shape of the plate when at its resonant frequency of 25.6 kHz. To achieve a pattern depicting the modal shape of the vibrating plate, caster sugar was simply poured onto the plate and the sugar particles gathered around nodes – the points between the oscillating crests and troughs of a standing wave of the flexural wave of the plate. The sugar particles gathered here because the nodes are stationary positions of the plate and so permit the sugar particles to reside. This mode appeared to displace the most perpendicular to the surface of the plate in comparison with other resonant frequencies found between the frequencies of 20-50 kHz. This was found both with the maximum levitation distance achieved at this frequency and the sugar particles being most vigorous at this frequency, as they are forced off the oscillatory parts of the plate. The experimental modal shape at this frequency agrees well with the modal shape found within FEA modelling at a frequency of 25.955 kHz (see Figure 11). This is the only modal shape found that has eight longitudinal nodes of flexural vibration and the frequency is very close (within 1.4%) to the frequency found during testing.

The deformed shape of the model (see Figure 12) shows, in an exaggerated scale, the modal shape of the plate when vibrating at the frequency of 25.96 kHz model. It can be seen from Figure 12 that the reason that the PZTs excited the plate in this mode much better when mounted laterally, is because the force of the elements was applied across the peak of a flexural wave. Unlike in the longitudinal direction, this orientation of the PZTs resulted in plate deformation similar to the plate’s modal shape at this frequency. This explains why the lateral PZTs produced a levitation distance that is over 6 times higher than that obtained with the longitudinal PZTs. The best position for the elements to be in would be centred on a crest of one of the peaks/troughs as the shape oscillates between the two. In this position the maximum displacement of the PZT can be utilized as this position of the flexural wave is where the maximum lateral displacement occurs (see Figure 13). The crests of the flexural wave of the plate are shown to be the most laterally displaced positions locally over the length of a PZT (10mm) in Figure 13.

Positioning the lateral PZTs centrally over the crest of the plate flexural waves could increase the levitation distance of the NFAL effect even further, as the current position of the elements is not centrally over the crest of the waves. If the NFAL effect were to be increased even further, then several PZTs of the same dimensions used in this experiment could be positioned on the underside of the plate placing each PZT over the crest of one of the flexural waves of the plate.

5.2 Load carrying capacity

Aluminium plate with 1.9 mm thickness was used and operated at the frequency of 25.6 kHz. Levitating specimen was the gold plated glass disc. The results obtained from the testing are shown in Figure 14. This figure shows the combined mass of the levitating sample versus the separation distance achieved for the fixed voltage input amplitude. It appears that the levitation distance is inversely proportional to the square root of the weight per unit area of the floating specimen in al flexural modes, that is,

$$L = k\frac{1}{\sqrt{m}} \tag{1}$$

where L is the separation distance, m is the mass of floating specimen and k is a constant. In order to prove the correlation with the above equation the results shown in Figure 14 were re-plotted but this time in a graph of levitation distance versus the inverse of the root of the total mass on the levitating object. It is seen from Figure 15 that a linear relationship was obtained.

The levitation distance was found to be proportional to the inverse root of the total mass of floating object with the proportionality constant k equal to $1*10^{-4}$.

5.3 Effect of vibrating plate material

In order to ascertain the effect of plate material on levitation two additional plates, 1.6 mm thick titanium plate and 1.1 mm thick steel plate were made and tested. In Figure 16, the results obtained are compared with the set of results found for the aluminium plate of 1.9mm thickness.

As the results show, the 1.9 mm aluminium plate produces the largest separation distances. The 1.1 mm steel plate produces the next highest separation distances and then the 1.6 mm titanium plate produces separation distances that have been recorded but are all below the 5 μm level.

In the attempt to understand the differences between the NFAL effect when using these materials, the mass of each plate must be taken into consideration. The masses involved were: 172.9 g, 144.8 g, and 103.5 g for steel, titanium and aluminium plates respectively. Lighter plates should give better NFAL effects as they can be accelerated greater with the same force and so the flexural wave should have higher amplitudes of displacement. This appears to be true at first as the aluminium plate did produce the greatest vibrations however the steel plate, which is the heaviest plate of the three, is not the worst plate in regards to levitation distance. The distances produced with the steel plate were higher than the ones produced with the titanium plate.

The reason for this non-correlation of mass of plate versus levitation distance may be because the modal shape for each plate is dependant on the dimensions of the plate and the material properties namely the Young’s modulus, Poisson’s ratio and the density of the material. In order for any material to produce a large NFAL effect the plate must have a modal shape at an achievable frequency with a given equipment, the PZTs must by positioned and orientated in an optimal way so that maximum displacement of the plate is possible perpendicular to the surface of the plate. The 1.9mm aluminium plate achieved these goals better than the other plates and so outperformed them by producing a larger separation distance.

6. Conclusions

Based on obtained results the following conclusions can be drawn.

(i) Existence of NFLA effect has been experimentally confirmed.

(ii) For the 1.9mm aluminium plate, a reasonably linear relationship was found to exist between the PZT input voltage and the levitation distance at the frequency of 25.6 kHz. This can also be said for the titanium, and steel plates at their respective frequencies.

(iii) A relationship between surface density and separation distance for the 1.9mm aluminium plate at a frequency of 25.6 kHz was found to exist, as given by equation (1).

(iv) The orientation and position of the PZTs was found to be one of the most important factors controlling the effectiveness of the NFAL phenomenon. It has been found that attaching the elements in a suitable position on the plate is dependant upon the modal shape produced at the operating frequency of the vibrating plate and the dimensions of the PZTs.

(v) Computer modelling results of modal shape agree well with experimental findings. Both the modal shape and the frequency at which it is produced show excellent correlation.

(vi) Vibration plate material greatly affects the separation distance created with the NFAL effect. This is because the modal shape and resonant frequencies, closely governing the NFAL effect, were also altered by the material.

7. References

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Figure captions

Figure 1 Piezoelectric driven plate and levitating sample.

Figure 2 Three-dimensional drawing of testing rig.

Figure 3 Vibration plate with four PZTs bonded to the underside of the plate.

Figure 4	Structural model of 1.9mm thick aluminium plate, deformed with 4 PZTs.
Figure 5	Contour plot of Z-axis displacement, 1.9mm aluminium model.
Figure 6	Flow chart of the apparatus and connections between its main components.
Figure 7	Apparatus set-up.
Figure 8	Oscilloscope output screen, no levitation (right), levitating sample (left).
Figure 9	Graph of separation distance versus voltage across PZTs, for three orientations of the PZTs, at 25.6 kHz.
Figure 10	The pattern of sugar upon the plate when resonating at 25.6 kHz.
Figure 11	Modal shape of the plate at 25.955 kHz.
Figure 12	Exaggerated model of the modal shape of the plate when excited to resonant frequency of 25.955 kHz.
Figure 13	Contour plot of lateral displacement when in modal shape at frequency of 25.955 kHz.
Figure 14	Separation distance versus total mass of levitating sample.
Figure 15	Separation distance versus inverse root of the total mass of the levitation object.
Figure 16	Separation distance versus applied voltage input for aluminium (1.9 mm thickness), titanium (1.55 mm thickness) and steel (1.1 mm thickness) plates.

Figures

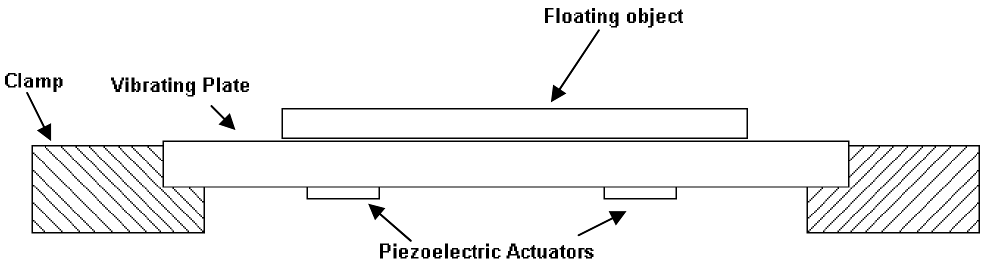


Figure 1

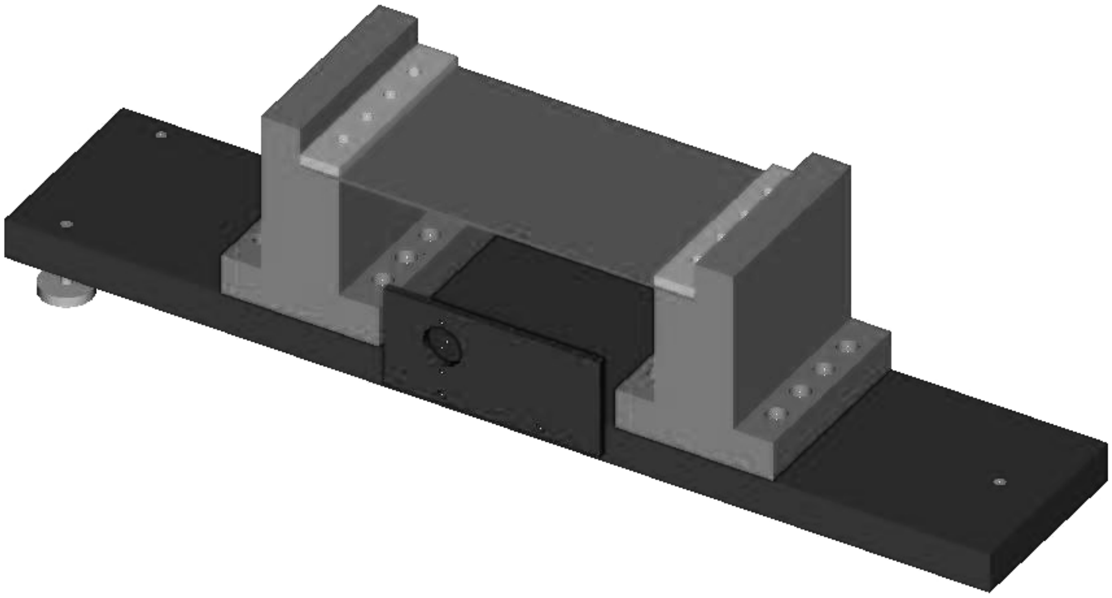


Figure 2

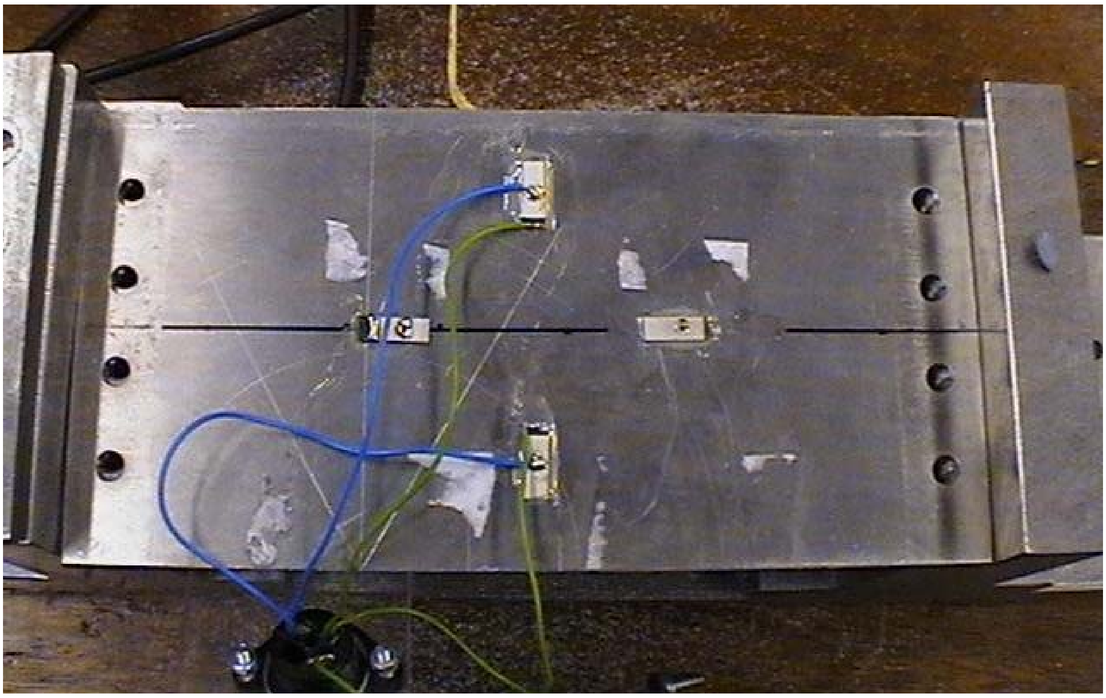


Figure 3

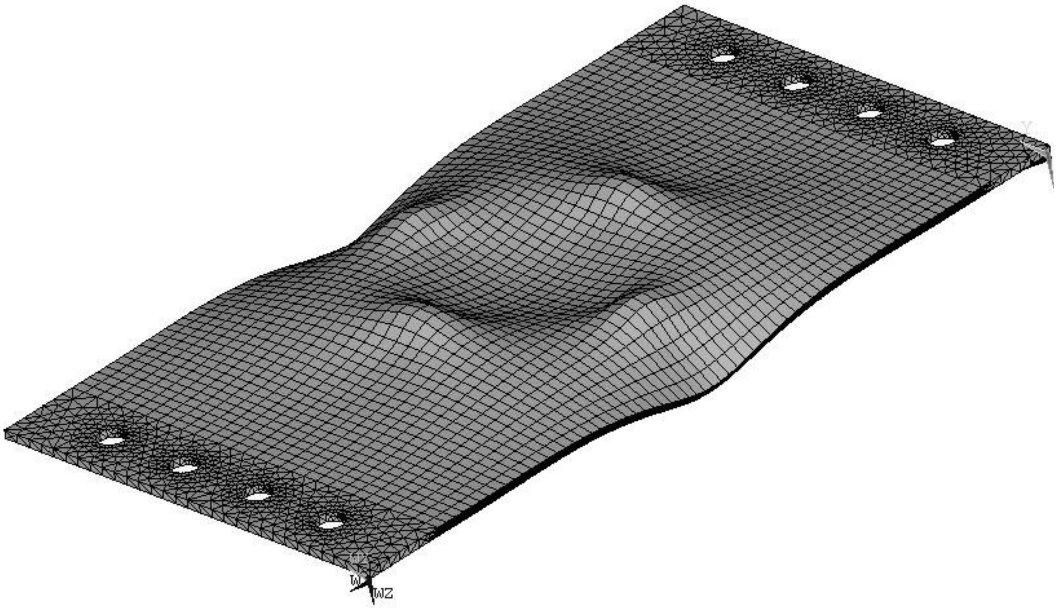


Figure 4

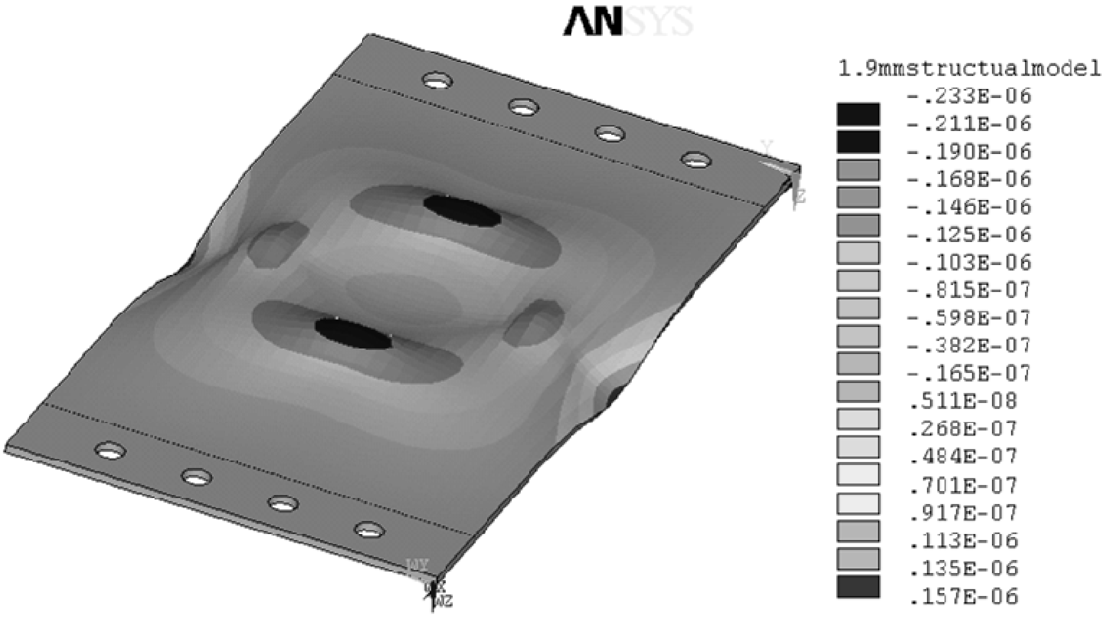


Figure 5

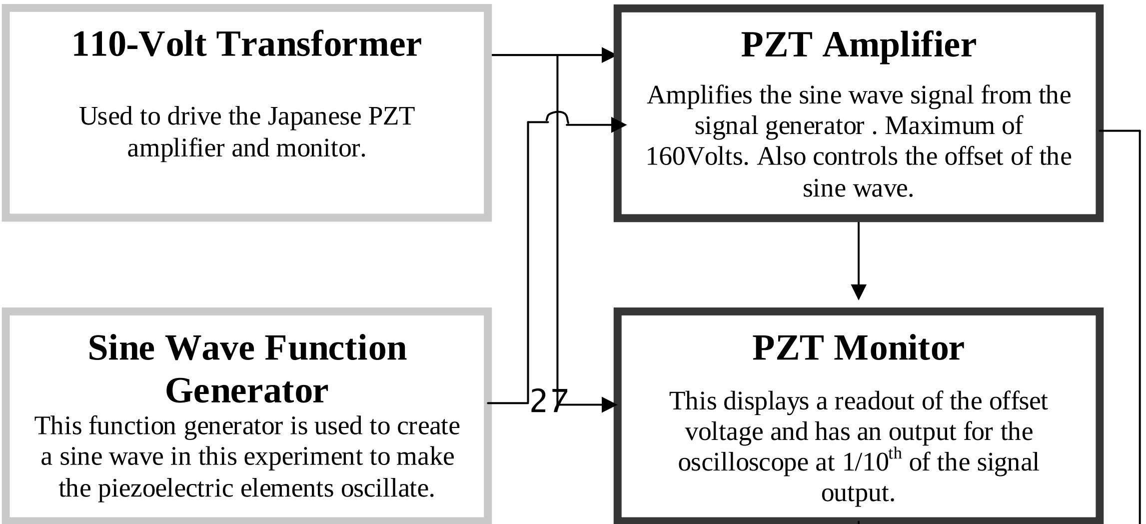

110-Volt Transformer
Used to drive the Japanese PZT amplifier and monitor.
PZT Amplifier
Amplifies the sine wave signal from the signal generator . Maximum of 160Volts. Also controls the offset of the sine wave.
Sine Wave Function Generator
This function generator is used to create a sine wave in this experiment to make the piezoelectric elements oscillate.
PZT Monitor
This displays a readout of the offset voltage and has an output for the oscilloscope at 1/10th of the signal output.

Figure 6

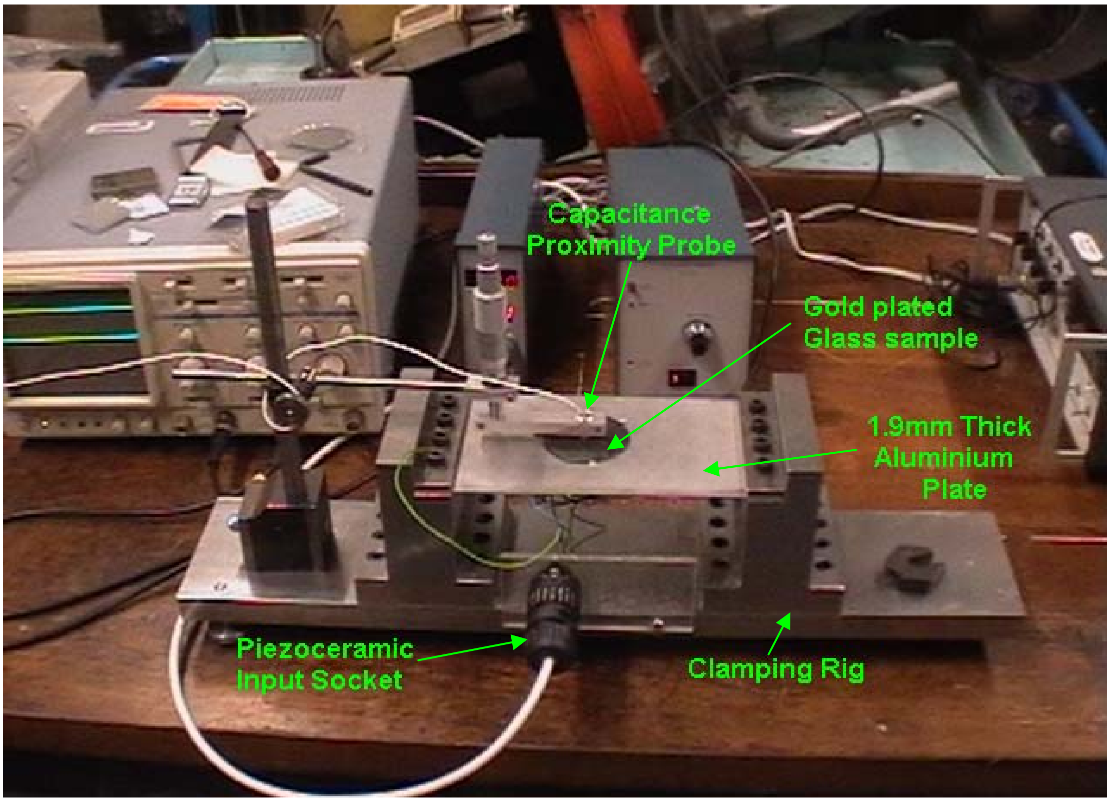

Capacitance Proximity Probe
Gold plated Glass sample
1.9mm Thick Aluminium Plate
Piezoceramic Input Socket
Clamping Rig

Figure 7

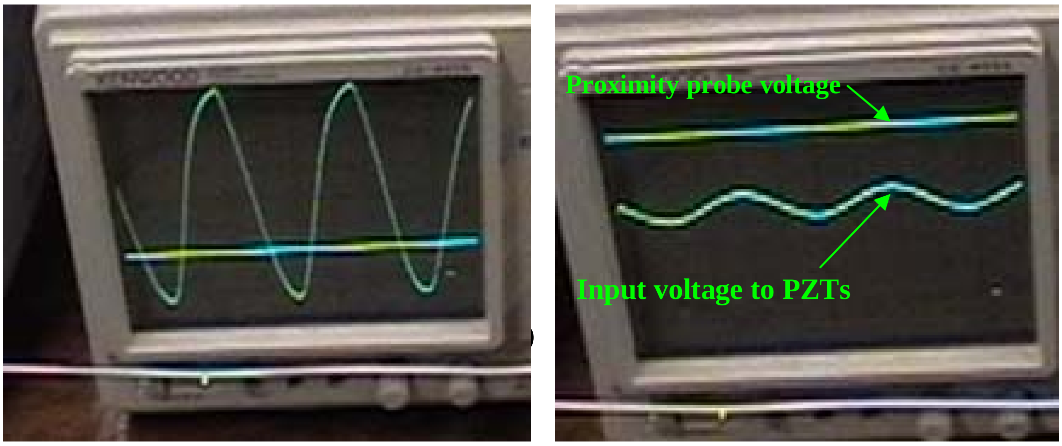

Proximity probe voltage
Input voltage to PZTs

Figure 8

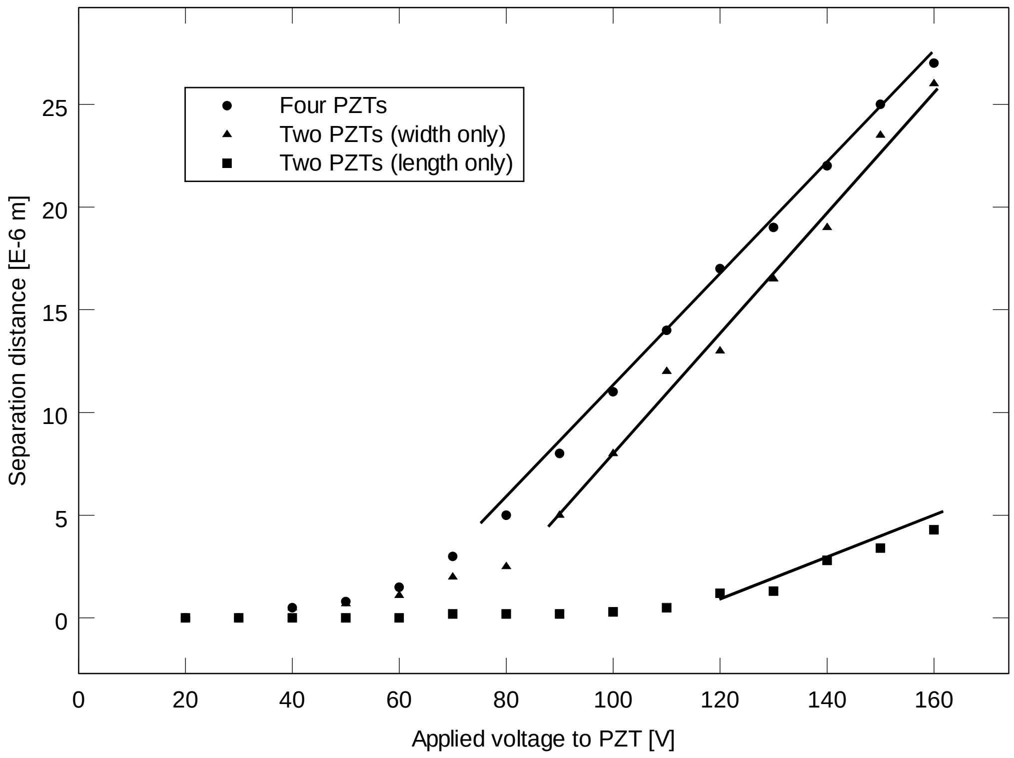


Figure 9

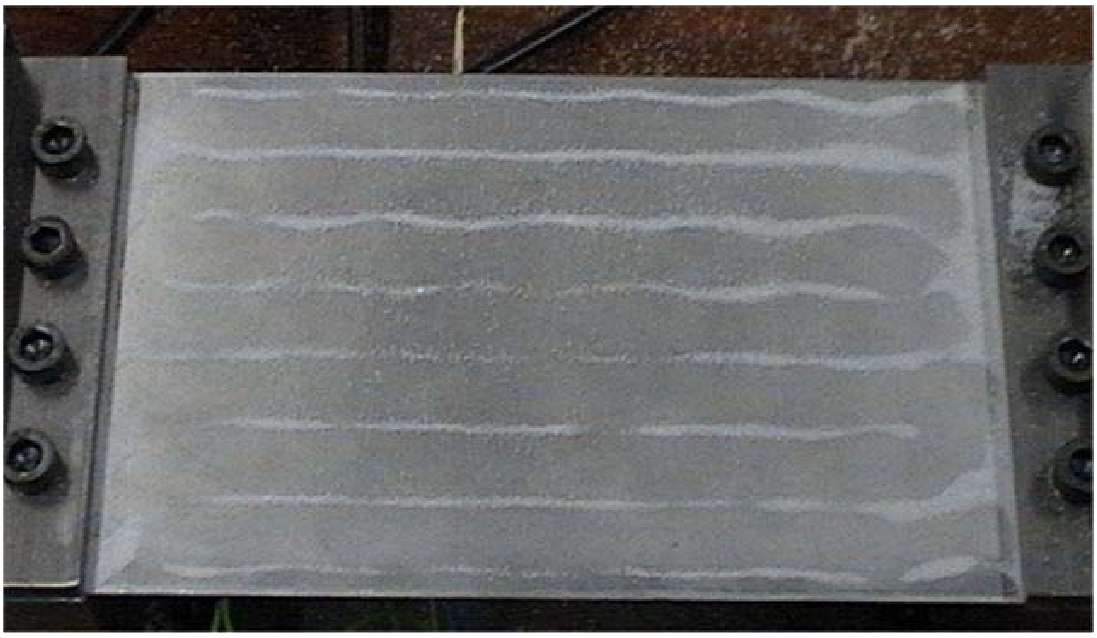
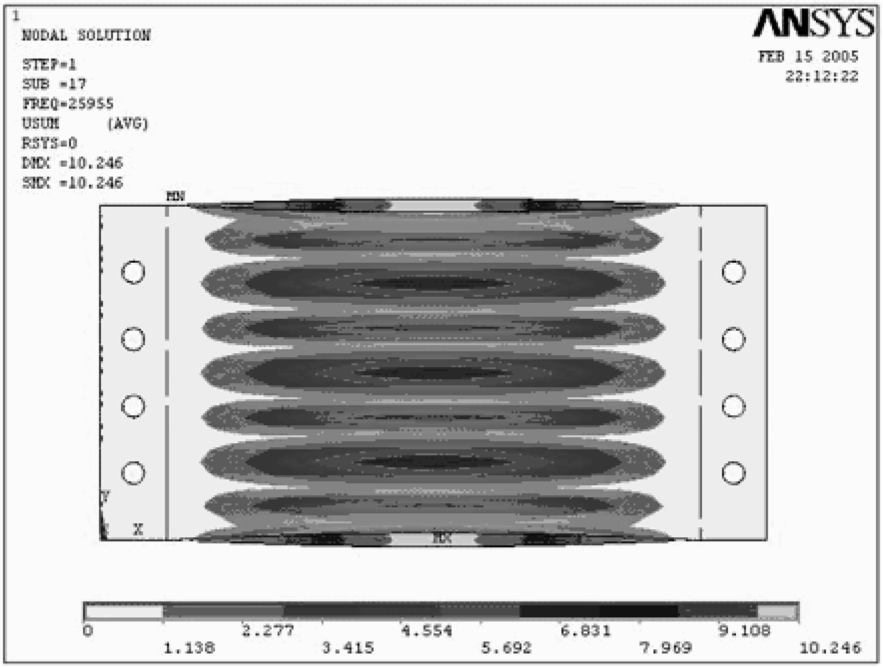


Figure 10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RSYS=0
DMX =10.246
SMX =10.246
ANSYS
FEB 15 2005
22:12:22
MN
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X
0
1.138
2.277
3.415
4.554
5.692
6.831
7.969
9.108
10.246

Post print from a paper that appears in the Journal of Applied Mechanics, Volume 74, Number 4, July 2007, pp. 816-820

Figure 11

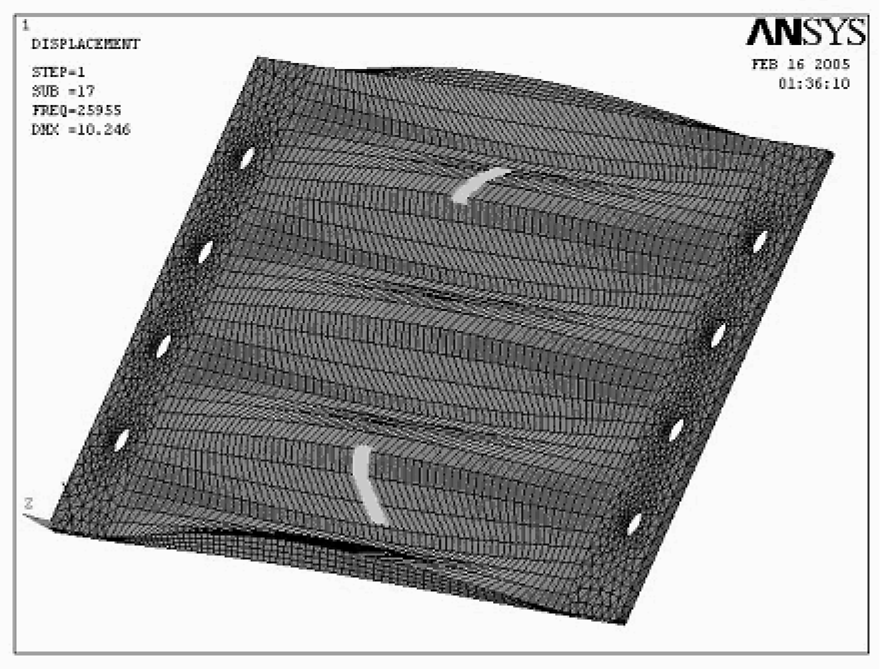

Figure 12

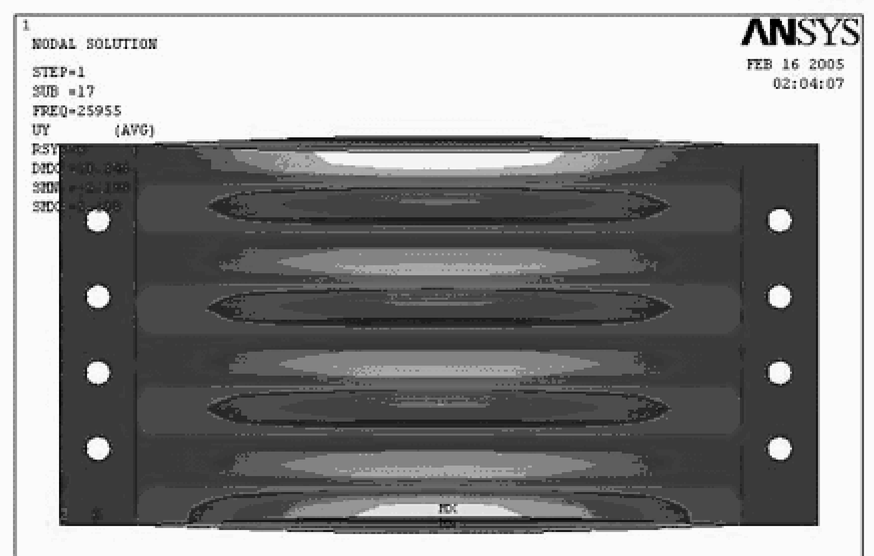

Figure 13

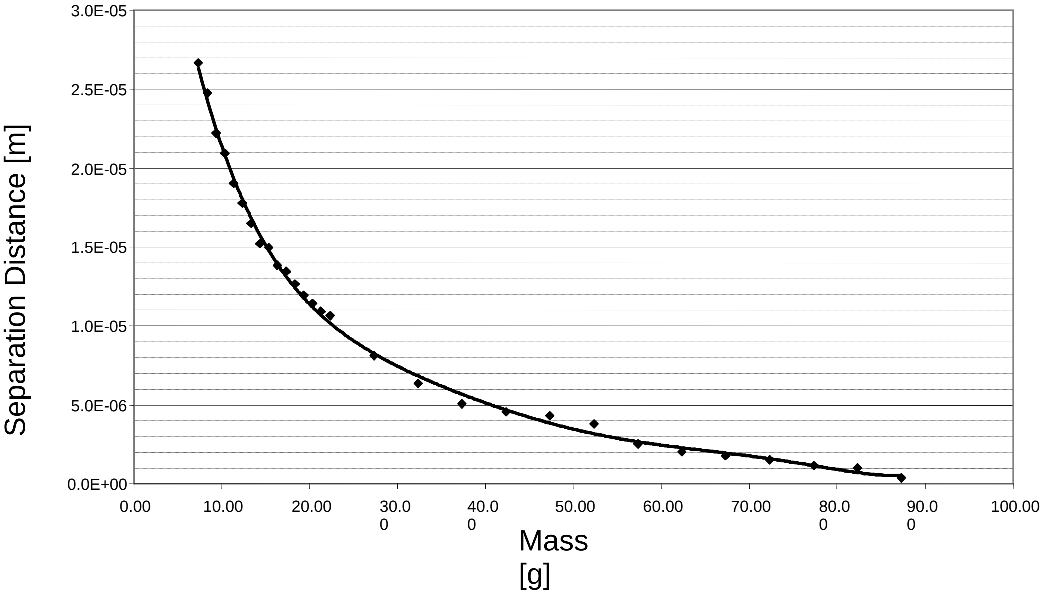

Figure 14

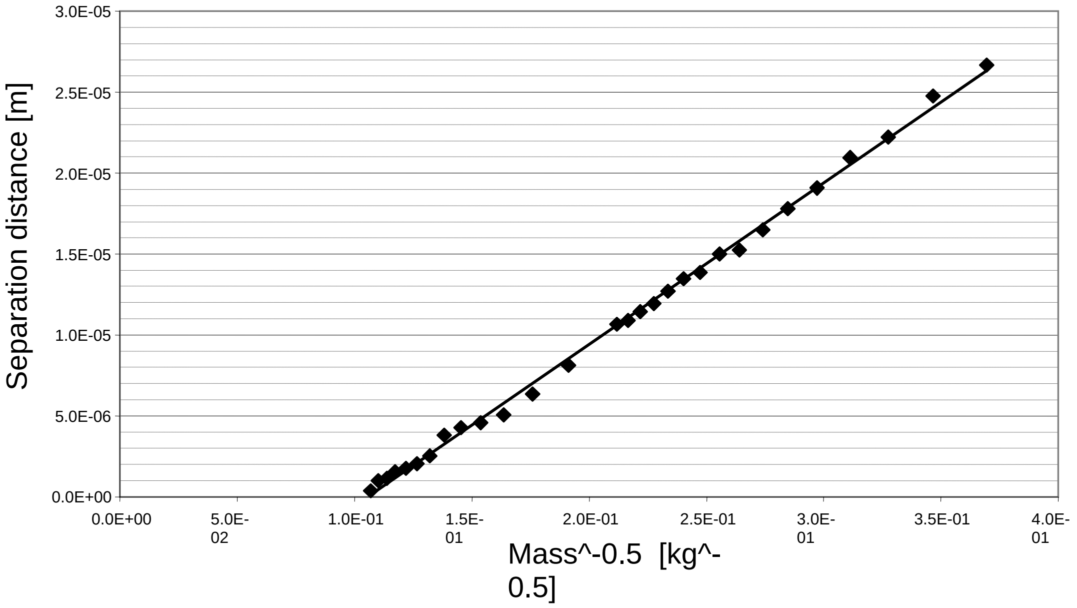
Separation distance [m]
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
0.0E+00
5.0E-02
1.0E-01
1.5E-01
2.0E-01
2.5E-01
3.0E-01
3.5E-01
4.0E-01
Mass^-0.5 [kg^-0.5]

Figure 15

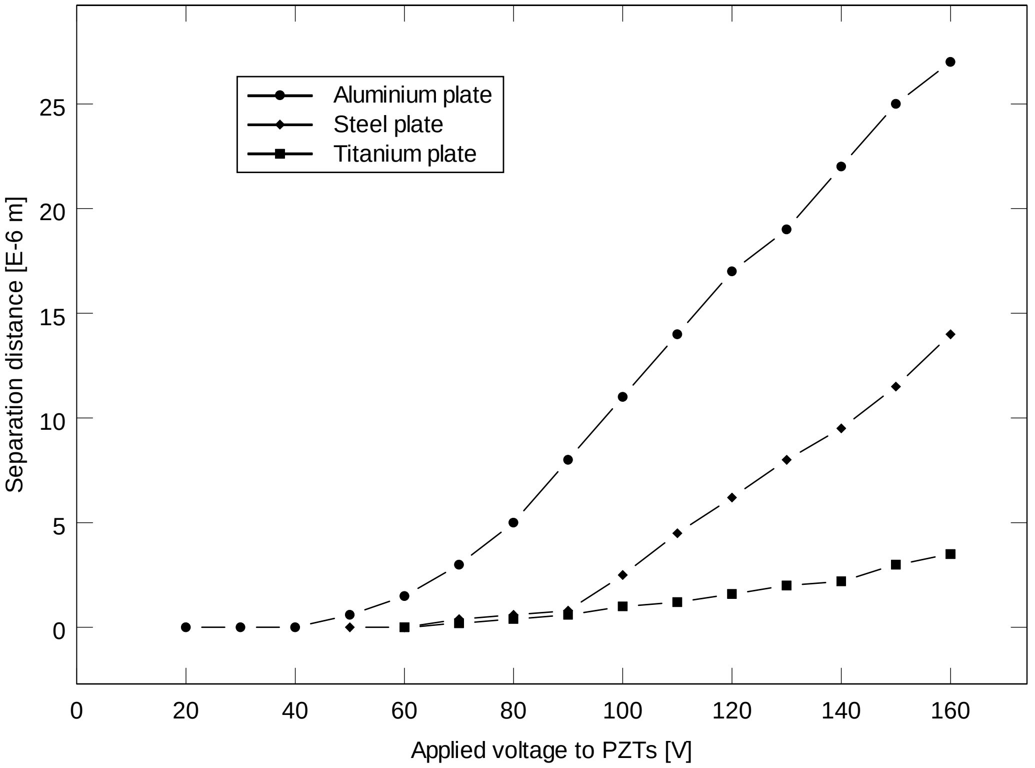
Aluminium plate
Steel plate
Titanium plate
Separation distance [E-6 m]
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
Applied voltage to PZTs [V]

Figure 16