Design and Development of Sensor Array Consist of Piezo Element for Fluid Jet Polishing Application

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1 Abstract

The Fluid Jet Polishing (FJP) is new in the field of optical fabrication or glass precision and is used as an alternative tool for polishing process. Shaping and finishing concave section of aspheric of glass is very challenging in optical fabrication. The current sub aperture polishing method is using small polishing tool to be in contact with the surface of work piece. As optical design become more complex in geometries, new alternative process is searched and continuously developed. Fluid jet polishing using abrasive waterjet is a newcomer in this field and it is believed to has more advantageous in sub aperture polishing method once the method is esTablelished. The jet profile and its parameter near impact wall are major point of interest in this study. A 3D finite-element model is developed as part of investigation. The piezoelectric patches are surface bonded on quadrilateral thin plate and supported withspring damper elements. The main goal of this paper is to investigate mechanical characteristics ofpiezoceramic array on membrane and the effect of force excitation using small motor and electricexcitation on the system. The system setup produced small vibration displacement and does not displace the plate beyond elastic strain region. The results show the linear behavior of piezoceramicand the correlation between electric excitation, motor vibration and displacement at the centre of theplate at different frequency range. The mode shapes and natural frequencies at low frequency spectrum are also presented. Therefore, the results can be used as reference to further develop fluid jet system with aid of piezoelectric patches.

2 Literature Review

2.1 Theoretical Basis

Fluid Jet Polishing is shaping and finishing technique that was developed in year 1998 by Oliver W. Fähnle [OLIV98],[OLIV98b]. The principles of operation is originates from two different techniques: abrasive water jet cutting and bowl feed polishing.[OLIV03]. In fluid jet cutting, the pressure used during operation is high which producing high speed of slurry and it is able to cut both ductile and brittle material. The resulting surface is not very good compare to bowl feed polishing where excellent surface quality can be obtained because the force that presses the abrasive particle is much smaller. Bowl feed polishing uses deformable tool which immersed in the slurry. During operation the tool is in contact with the glass and no slurry is added once the process has started. Due to the rotary speed of the tool with respect to the workpiece, the abrasive particles in the slurry slowly move towards the edge and fall over.

The idea of Fluid jet polishing is using the mixture of fluid and abrasive particles as a medium and using slurry which will be in contact with glass surface at sufficient pressure in order to shape and polish the surface. Therefore FJP operates at lower pressure compare to abrasive water jet cutting and due to the fact that particles move relatively slowly over the surface compare to the velocities in abrasive jet cutting, the resulting surface quality is much better than in the case of abrasive jet cutting. Abrasive slurry jet (ASJ) cutting systems operate at pressure typically at several hundreds of bar [OLIV98]. FJP in the other hand is operated at low pressure and for my study, operating pressure of 20 bar is used.

2.2 The setup of FJP

The setup consists of slurry in a tank, stirrer, nozzles, hoses and pump. An overview of the setup can be found in Figure 2-1. In a tank, water and abrasive particles are mixed by mechanically stirring. The water mixed with particles homogeneously and it is referred to as the slurry. The slurry is pumped from the tank by means of a low pressure pump (0-20 bar) and guided through a nozzle. The nozzle is positioned above the surface of glass where the standoff distance and the angle can be chosen freely. The sample which is in this case is glass can be rotated in one direction with respect to the nozzle. After processing the surface, the slurry is collected and guided back to the tank, filtered and then the slurry can be used again.

The setup is realized using a computer numerically controlled (CNC) machine where a pump and tank is connected externally with pipe. The tank consists of stirrer where the speed can be controlled. The pipe is connected to the upper spindle where the nozzle can be mounted and the slurry could flow through it and forced to return to the tank after processed the glass.

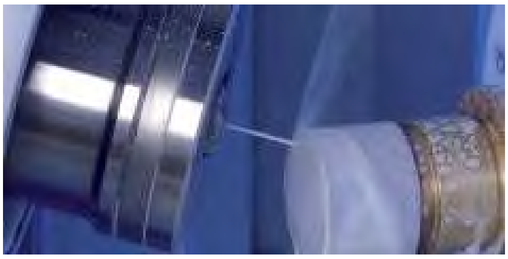


Figure 2-1:Nozzle and workpiec

2.3 FJP and classical Polishing

To see the difference between classical polishing of glass and Fluid Jet Polishing, the local pressure between both processes is estimated. Assume that local pressure have same order of magnitude and interaction time is deduced. In classical case, if load F of 10 kilograms is applied to a pad with surface area of 10 cm² and only 10% of the pad is covered with abrasive particles that actually make contact with the glass surface. The local pressure, p, equals

$$p = \frac{m.g}{A} \qquad \text{Equation 2-1}$$

where A is the effective area of contact [m²] and g is the gravitational acceleration [m/s²]. The calculated pressure exerted on the contact surface is 981 kPa.

In the case of FJP, we have velocity of 49 m/s, a cross section of nozzle orifice of 0.61 mm², a density of the abrasive of 7280 kg/m³, and a 4.8 % weight concentration of abrasive is added to the slurry. The mass of this abrasive is equal to 43g (detail calculation in section 3.3).

The following equation is valid

$$F_{t.}\Delta t = m.\Delta v \qquad \text{Equation 2-3}$$

Where F_t is the force the particles transfer during time Δt, m is the abrasive mass, and Δv their change in velocity. The maximal velocity change will occur when the particles come to a complete stop, from their initial velocity of 49 m/s. The exerted pressure p equals the force that the particles transfer per unit time, divided by the surface area, A.

$$p = \frac{F_t}{A} = \frac{m\Delta v}{A\Delta t} \qquad \text{Equation 2-4}$$

From this equation we find for the average interaction time is equal to 3.5 s.

$$\Delta t = \frac{m\Delta v}{Ap} \qquad \text{Equation 2-5}$$

This estimation is an upper limit since we have assumed that all particles make contact with the surface, and that they transfer all of their kinetic energy to the surface.

2.4 Advantage and disadvantage of FJP

To understand more about FJP, the advantages and the disadvantages are listed. FJP is a new polishing method that has lot of advantages. However, it also has disadvantages since it is still in development phase.

2.4.1 Advantage of FJP

The main advantage compare to the classical polishing method is the tool does not erode over time with assumption of nozzle wear is minimal and will not influence spot shape. The tool in this case is referred to the slurry which contains abrasive particles hitting the effective area of surface and it does not referred to the nozzle. Since the tool does not erode, so the machining spot shape is constant.

Beside able to reduce roughness, this method can be use for shape corrections. Complex geometries such as aspheres can be polished with FJP because there is no direct contact between pad and work piece. The time of contact between slurry and surface is called dwell time and if the dwell time can be controlled for every point on the surface, then the same amount or material can be removed everywhere.

The setup of the process without CNC machine may work and it is not expensive. However the control element will increase the price. Moreover if nozzle which last longer can be designed, then the cost of the process is cheaper than conventional process. Moreover the slurry is recycled and therefore it is environmental friendly.

Heat generated due to friction can be ignored since the medium being used is water. The cooling and polishing during the process eliminate heat generated from friction between particle and surface.

The removal profile can be optimized by choosing specific nozzle and impact angle. Various removal spot profile size is possible. The processing speed can be increased by using several nozzles simultaneously. Concentration of the abrasive particle can be varied and different material removal rate can be obtained.

2.4.2 Disadvantage of FJP

The major disadvantage of FJP using current nozzle is the formation of ring shape area where most material is removed from the edge whereas hardly any material is removed from the centre. Figure 2-2 shows symmetrical spots with shape of a ring after it is operated at certain time and with certain standoff distance. The result shows that the middle area of the spot is the least removal area compare to the edges where deeper material removal is found.

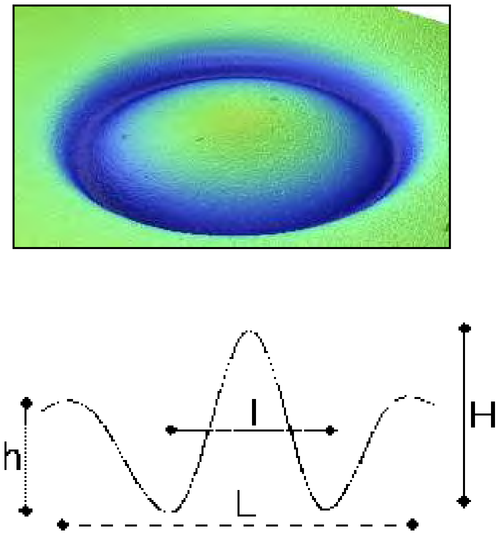


Figure 2-2: Ring shape on lens surface

A second disadvantage is wear due to the abrasive. Parts of the setup including nozzle head have to be repaired or replaced on regular basis.

2.5 State of the Art of Nozzle Design for Abrasive Water Jet Polishing.

Generally the nozzle design can be classified base on the working principle. A typical nozzle design worked based on shear flow principle where the fluid and particle stream along the axis as it enter the nozzle inlet and keep flowing and accelerate until it projected out of the nozzle. The inlet diameter is generally multiple times bigger than the nozzle orifice.

In some design, abrasive particles are injected to the fluid stream from different feed line and the feed rate of the abrasive particles can be varied. However these designs are mostly found in the nozzle used for fluid jet cutting. One of the reasons is to minimize the erosion on the parts between pump and nozzle. The abrasive particle in fluid jet cutting flow at higher speed and due to erosion, it have to be exchanged more frequently if the abrasive and the particle share the same feed line from the beginning. However the biggest advantage of different abrasive feed line is the erosion can be control through variation of particle mass flow rate. A study for fluid jet cutting is conducted and it shows that as the mass flow rate of the particle is increase, the erosion will also increase. However if the abrasive concentration is very high, then the efficiency of a jet could decrease as the water jet has to accelerate more particles through the small tube [MOST09]. In the fluid jet polishing, the abrasive particles are mixed in the tank and the slurry is pumped to the nozzle. A typical concentration of the particle contents in the slurry is 5% to 10% [OLIV99]. In this study erosion model using numerical simulation is not made because the model depends on the empirical data.

In some design, the shape of accelerating tube is proposed to increase the velocity of the medium. In a study, a length of cylindrical section work as accelerating tube located at the nozzle exit is varied. It was found out that for a certain diameter and pressure, there is optimum length where the velocity of the particle is the highest [GUIH08]

A second type of nozzle is a nozzle that works with the swirl flow principle. Not many designs can be found that make use of swirl flow for fluid jet polishing. The design is normally difficult to manufacture and it is normally be using additive layer manufacturing technology and being used as prototype. Moreover it is still in the research phase. Oliver w. Fähnle in his study used coil-like shape in the nozzle exit and the water will have to follow the contours of the threaded nozzle [OLIV02].

3 Introduction

The Fluid Jet Polishing (FJP) is new in the field of optical fabrication or glass precision and is used as an alternative tool for polishing process. Shaping and finishing concave section of aspheric of glass is very challenging in optical fabrication. The current sub aperture polishing method is using small polishing tool to be in contact with the surface of work piece. As optical design become more complex in geometries, new alternative process is searched and continuously developed. Fluid jet polishing using abrasive waterjet is a newcomer in this field and it is believed to has more advantageous in sub aperture polishing method once the method is esTablelished.

Detecting fluid jet polishing impact and impact wall displacement is the purpose of the study. The application of Active Vibration used to measure the displacement after the impact. . Recent advantages in computer technology, however, have now made it a practical solution to generate experimental setup of the study.

The displacement and vibration detection can be control using classical PID regulator. An approach for active damping is made by the use of a classical PID regulator. First the system has to be identified and characterized to select appropriate gain values. The necessary information about the controlled system is obtained by a so called offline identification of the system. Therefore in a first step a FEM model is created to get the necessary knowledge of the system under different environmental conditions, e.g. at different frequencies.

4 Experimental platform

This chapter will describe the experimental platform both for the PID and the adaptive approach.

4.1 Mechanical setup

The spring mass system contains a membrane made out of stainless steel, two piezoelectric bender elements and an acceleration sensor in the middle. The membrane with a thickness of 0.5mm is fixed with 4 shock absorbers on a massive aluminum block (200x200x20mm) to decouple any vibrations from ground. In older investigations a vibration motor was used in the middle to excite the membrane to vibration. But problems with the reproducibility and the signal handling lead to quit this method. Now one piezoelectric element is used to excite the membrane, the other one is to control the vibration. The acceleration sensor monitors the residual vibration [Figure.4-1].

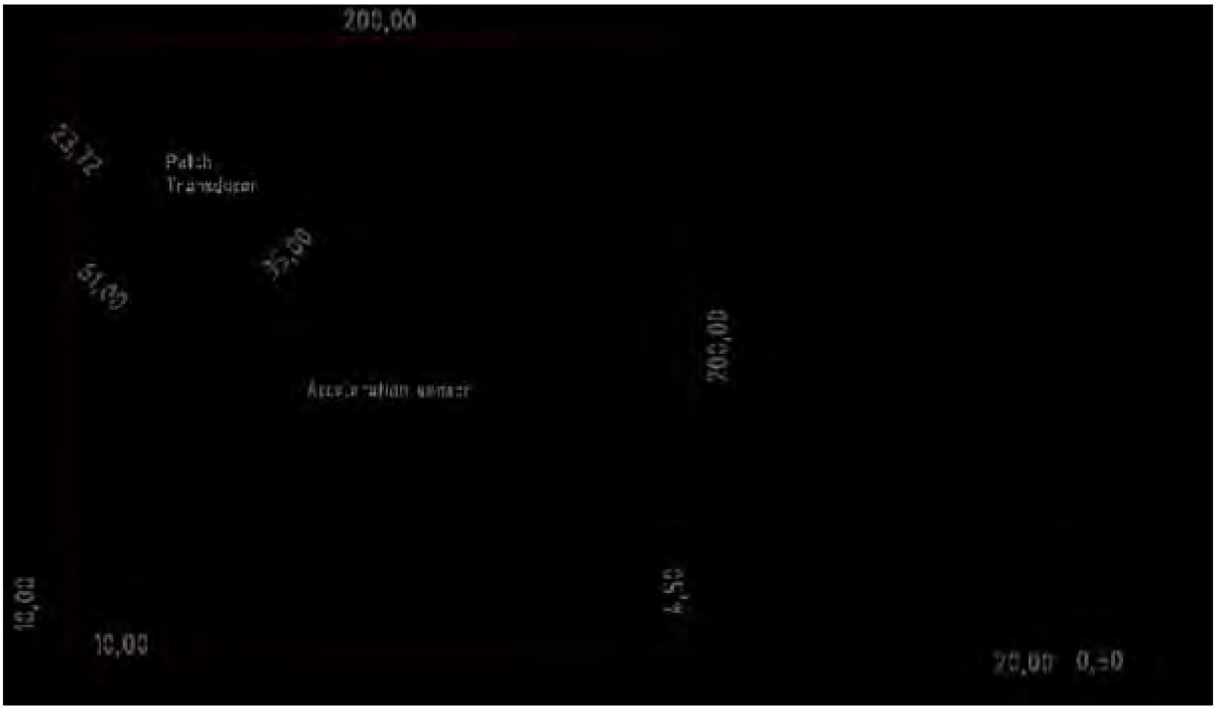


Figure.4-1 [Mechanical-setup]

4.1.1 Estimating the best position of the piezoelectric elements

To estimate the best, this is to say the most efficient positions for the piezoelectric patch-transducers an experimental modal analysis has to be performed. The vibration-motor is used as source for the vibration. Because of the almost linear relation between the motor and its revolution one can induce vibrations with various vibrations exactly in the middle of the membrane simply by changing the motor voltage. The appearing shapes (powder colored in cyan) are defined by the anti (nodes) of the waveforms in the material and show the distribution of the vibration [Figure. 4-2]. The motor voltage and the frequency of the vibration is colored in red.

Figure. 4-2 [Experimental modal analysis]

Within a voltage-range of 0.0V to 1.5V the shape of the mode is similar with a cross-section of a tube. With increasing voltage the thickness of the shape decreases. This result leads to the assumption that the most efficient position for the patch-transducers is somewhere in the middle between the middle and the border of the membrane.

4.2 Electrical setup

The mechanical system has first to be excited and second to be controlled. For that purpose one of the piezo elements creates a disturbing vibration on the membrane and the second one creates a counter vibration signal. Both elements are driven independently via a 2chn piezo amplifier. The residual vibration in the middle of the membrane is acquired by a 3-axis acceleration-sensor ADXL330EB from AnalogDevices, but certainly only one axis (Y-axis) is needed [Figure. 4-3].

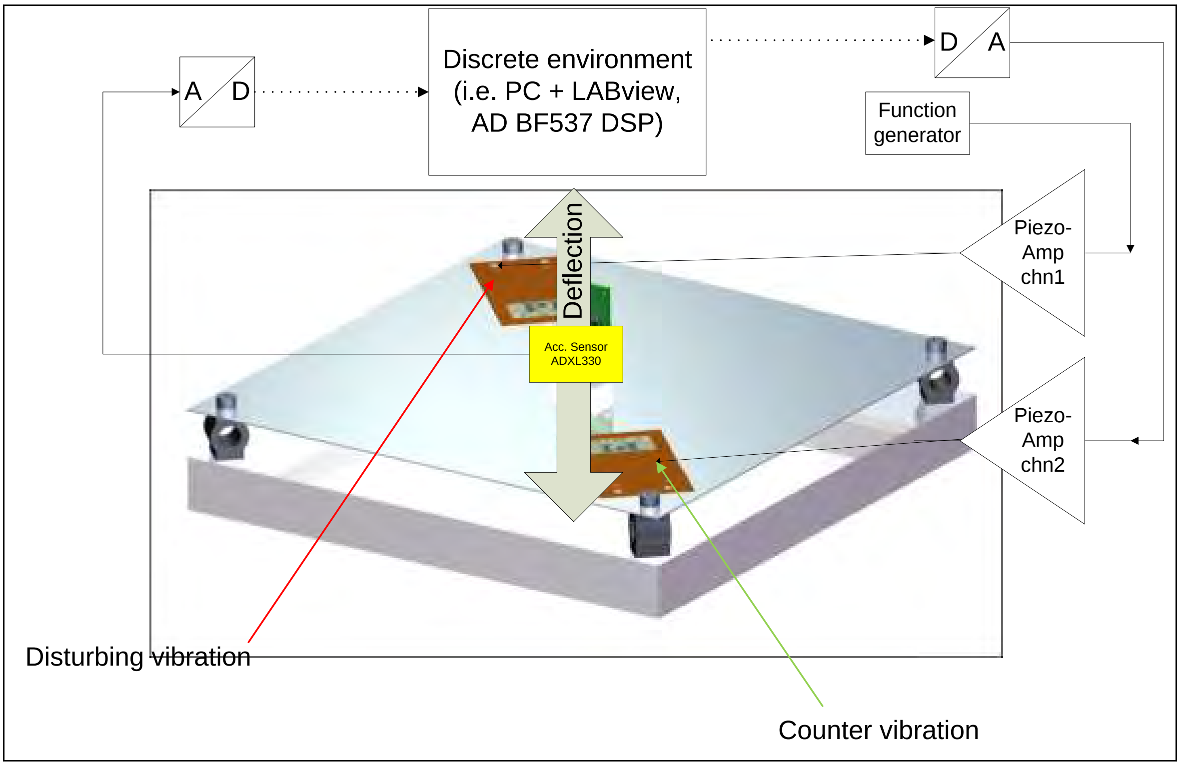


Figure. 4-3 [Electrical-setup]

The sensor output and the amplifier inputs are connected via ADC/DAC to a discrete control system later.

Due to the fact altogether 3 different approaches are tracked, this setup will be adjusted adequately. For the vibration control with the general PID approach just as the adaptive approach with DAQ devices the signal conversion will take part in the standard DAQ data acquisition hardware offered by National Instruments. The signal processing will be realized accordingly using the graphical programming language of National Instrument´s LabVIEW.

The last approach, running an adaptive vibration control on a BF537DSP, is absolutely autonomous from the environment mentioned above. Here the signal conversion will take place in a special DualVoiceBand-codec interfaced directly to the DSP. Also the signal processing runs on the DSP.

5 Experimental modal analysis

After both piezoelectric bender elements are glued on the membrane, some investigations about the system-behavior have to be made. Mainly for the PID approach it´s necessary to know the properties of the system at different frequencies. Following picture shows the different modes of the membrane (colored in cyan) at various frequencies. Only one piezoelement is driven with a sinusoidal signal with amplitude of 1V [Figure. 4-4]. One can see that in the lower frequency range (10Hz-200Hz) the mode´s shape is more or less constant whereas in the higher frequency range it changes.

Figure. 4-4 [Modal analysis at different frequencies (experimental)]

6 FEM system simulation

In the simulation study, software ANSYS educational version 12.0 is used. The simulaton tasks focus on validation of best position of piezo elements on plate, understanding behavior of the system and finding transfer function of the system at low frequency spectrum. In modal analysis the natural frequencies and corresponding mode shapes are presented. The results from modal analysis are then compared with the experimental result. By numerical simulation in harmonic analysis, the effects of the system in actuator mode at appropriate electric excitation from piezoelectric actuator are investigated and appropriate transfer functions are developed.

6.1 Modeling of the system

Simulation model is built base on the undergoing experimental model. It consists of 200 mm x 200 mm rectangular steel plate of 0.5 mm thickness supported by polymer structure mounted on rectangular steel base plate. There are two piezo patches of thickness 0. 4 mm which are bonded on the top side of the plate with a 0.2 mm adhesive layer

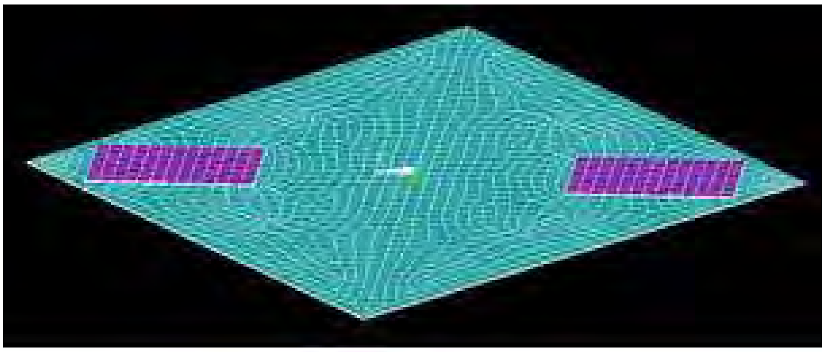


Figure. 5-5 [FEM model of the system]

[Figure. 5-5] above shows the specimen structure modelling by ANSYS. A 3-D element ‘SOLED45’ with 3 degree of freedom and 8 nodes is used for modelling the plate structure and bonding layer.

A 3-dimensional coupled field element ‘SOLED5’ with 8 nodes is used for modelling piezoelectric actuators. This element allows coupled DOF of displacement and voltage.

The mass of mounting parts of the vibration motor and the sensors are considered as constant value acting at one node and it is represented by structural point mass element 'MASS 21' with 3 degree of freedom (Ux,Uy,Uz)

The supports of the plate are modelled by combination element 'COMBIN14' with a DOF in longitudinal Uz direction and have 2 nodes. The constant value of spring constant and damping ratio are defined

The base plate and the air are not to be modelled.

6.1.1 Material data for Modeling

The following equation describes the behavior of coupled electromechanical problem in the analysis. The value of stress and electric displacement depends on the stress and the electric field quantity in the system.

$\{T\} = [C^E]\{S\} - [e]\{E\}$

$\{D\} = [e]^t\{S\} + [\varepsilon^s]\{E\}$

Where

$\{T\}$ = Stress vector (six components x, y, z, xy, yz, xz)

$\{S\}$ = Strain vector (six components x, y, z, xy, yz, xz)

$\{D\}$ = Electric displacement vector (three components x, y, z)

$\{E\}$ = Electric field vector (three components x, y, z)

$[C^E]$ = Stiffness matrix evaluated at constant electric field, i.e. short circuit.

$[e]$ = Piezoelectric matrix related to stress over electric field.

$[e]^t$ = Piezoelectric matrix relating stress/electric field (transposed).

$[\varepsilon^s]$ = Dielectric matrix evaluated at constant strain, i.e. mechanically clamped.

For piezoelectric element there are four important parameters describing the physical behavior which are given by manufacturer's data. There are density, relative permittivity, piezoelectric matrix and stiffness matrix.

The Piezoelement used for experiment is PIC252. The data for PIC252 cannot be found in internet site from manufacturer's data. For the purpose of simulation, the data is get from manufacturer and it is told that the material coefficients for PIC252 are the same with PIC255. From manufacturer's supplied data, the coefficient given need to be converted because ANSYS only accepted a certain form of input. Only certain coefficient from the manufacturer's data will be used. The manufacturer's data and the needed data for ANSYS are presented below.

In Ansys input form for stiffness matrix :

Stiffness Matrix c $[Gpa]$: $\begin{pmatrix} 123.00 & 76.70 & 70.25 & 0 & 0 & 0 \\ 0 & 123.00 & 70.25 & 0 & 0 & 0 \\ 0 & 0 & 97.11 & 0 & 0 & 0 \\ 0 & 0 & 0 & 23.11 & 0 & 0 \\ 0 & 0 & 0 & 0 & 22.26 & 0 \\ 0 & 0 & 0 & 0 & 0 & 22.26 \end{pmatrix}$

Manufacturer's data for stiffness matrix :

$$c11E = 123.00\ GPa$$

$$c12E = 76.7\ GPa$$

$$c13E = 70.25\ GPa$$

$$c33E = 97.11\ GPa$$

$$c44E = 22.26\ GPa$$

$$c66E = 23.15\ GPa$$

The symbol 'E' simply means the stiffness matrix was measured under constant electric field

Ansys input form for permittivity matrix:

Permittivity Matrix: $\begin{pmatrix} 930 & 0 & 0 \\ 0 & 930 & 0 \\ 0 & 0 & 857 \end{pmatrix}$

Manufacturer's data for permittivity matrix :

$$\varepsilon 11\mathrm{Sr} = 930$$

$$\varepsilon 33Sr = 857$$

Symbol 'Sr' means permittivity at constant strain.

Ansys input form for Piezoelectric matrix:

$$\text{Piezoelectric Matrix}, e^t \left[\frac{C}{m^2}\right]: \begin{pmatrix} 0 & 0 & -7.15 \\ 0 & 0 & -7.15 \\ 0 & 0 & 13.7 \\ 0 & 0 & 0 \\ 0 & 11.9 & 0 \\ 11.9 & 0 & 0 \end{pmatrix}$$

<u>Manufacturer's data for Piezoelectric matrix</u>

$$e31 = -7.15\ N/Vm$$

$$e33 = 13.7\ N/Vm$$

$$e15 = 11.9\ N/Vm$$

Unit [N/Vm] can be converted to [C/m²] and it will not effect the magnitude.

The density from manufacturer's data needs no conversion.

$\text{Piezo ceramics density}, \rho = 7800\ \text{kg/m}^3$

For a linear elastic calculation in ANSYS, E-modulus, density and Poisson's ratio of the steel plate and glue are needed. For steel plate and the adhesive layer, the following data are used [Table. 1].

Table. 1 [Material properties for Steel Material and Hysol Bond]

Material	$E - Modulus, (x10^9\ N/m^2)$	$Density, (\frac{kg}{m^3})$	$Poisson's\ ratio$
Steel plate	210	8030	0.31
Glue (Hysol Bond)	1.7	3261	0.34

The information about the centre mass which includes sensors and mounting plate are approximated. The stiffness and damping factor are not provided by manufacturer's datasheet and hence need to be approximated. The approximations are done by varying the value of stiffness. Increasing the stiffness of spring will also increase the natural frequency of the system and will change the mode shapes of the system. The value is then compared with experimental results. The magnitude like maximum displacement or acceleration also can be compared. The stiffness value for Spring in analysis file is 8 times larger because the line element 'COMBIN14' used in the analysis have been divided to 8 equal length through meshing. The following Tablele [Table. 2] shows the end value and valid for full model only. If a quarter model is used, the mass need to be divided to 4.

Table. 2 [Material data of centre mass and spring damper]

Material	Mass(kg)	Stiffness(N/m)	Poisson's ratio
Sensor and Mounting Block	0.084	-	-
Spring and damping element	-	10000	0.01

6.1.2 Meshing and Unit System

Since the gradient of the thin plate in thickness direction are high and 3D solid element is used, therefore three elements are used in thickness direction. According to aspect ratio, the width of an element needs to be at least five times the minimum thickness. Since the system has smooth solution, the global size is set 10 times the minimum thickness which is 1.6mm. There are 2 elements selected in thickness direction for piezoelectric element and one element for the bonding layer. To mesh the model sweep meshing method has been used, which is a combination of free and mapped meshing.

MKS unit, Kg-m-s-A-K, is used. For the dimensions of the model, "mm" is used first instead of "meter "and in later step, the model is scaled down to the meter unit to get the MKS unit. All other input parameters are in SI unit

6.2 Results of Simulation

6.2.1 General behavior of the system

To know the general behavior of piezoelectric element and how it will affect the system, static analysis is used. The static analysis is used to calculate the value of maximum deformation of the plate at different voltage excitations. The following figure shows the result of the static analysis at voltage excitation of 50 volts. At first 50 volts is applied at upper layer and the lower layer of piezoelement is set to 0 volts. For the second analysis, upper layer is set to -50 volts.

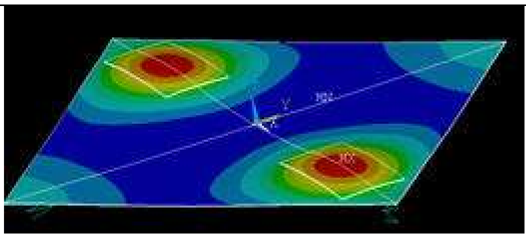
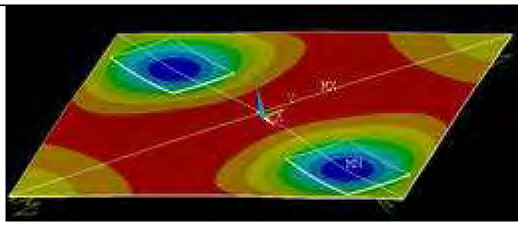
Voltage excitation: 50V	Voltage excitation:-50V
	

Figure. 6-6 [Static analysis at different voltage excitations]

At positive voltage [Figure 6-6], the piezoelectric expands laterally. Since patch is bonded to the plate, it produced extension at the upper plate and compression at lower plate. The application of an electric field along the polarization direction make the patch expand in the perpendicular direction, thus producing a local strain on the patch and bend the plate upwards. Local maximum occur at area where the piezoelectric patch are bonded with the plate. It occurred at around the centre of the patch actuator at node 21416 and node 21417.

At negative voltage[The right figure], there is contraction at piezoelectric actuator and it worked vice versa. The application of electric field opposite to the polarization direction make the piezo actuator contract in the direction perpendicular to the electric field and bend the plate downward.

6.2.2 Natural Frequency and mode shapes

The method of extraction of the mode shape from using ANSYS is modal analysis. The analysis will investigate natural frequency and mode shapes of all possible excitations. For the analysis, frequency spectrum from zero to 500 Hertz is selected and the analysis results are presented. The mode shapes are then compared with experimental results. The experiments are conducted using sand which is placed on the vibration plate. The system is then excited at particular frequency and the shape of the sand after certain time is captured using camera.

The five first natural frequencies and its corresponding mode shapes are found and Figure. 6-7-Figure. 6-11 illustrated the natural frequencies of the system and the corresponding mode shapes during simulation and experimental results used to validate the results.

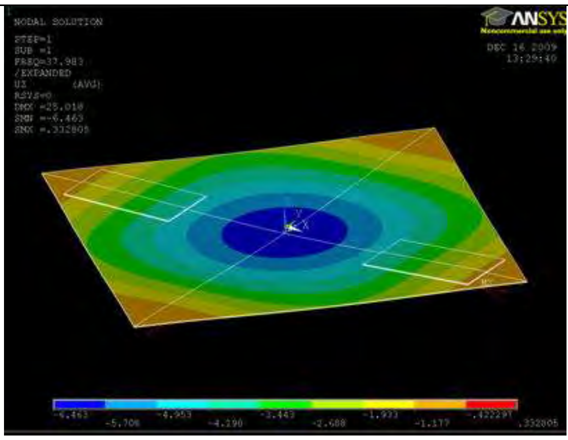
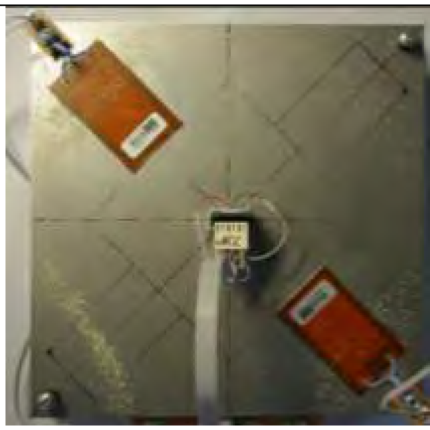
37 Hz	30 Hz,40Hz
	

Figure. 6-7 [First mode shape from simulation and experiment]

The system is excited using piezo patch with voltage excitation of 50V. The colours represent the magnitude in term of displacement. Red colour represents maximum position, blue colour represents minimum position and the green colour is the neutral position which is equivalent to no displacement. [Figure. 6-7] on the left side shows the first mode shape from both the simulation and experimental analysis. The right figure shows the shape of the sand recorded at 30Hz and 40Hz. At 37 Hz natural frequency occur and the corresponding figure shows that the centre of the plate moves downward whereas the four edges are in phase and move upward. As one can see, the green line has the shape with the sand form on the plate.

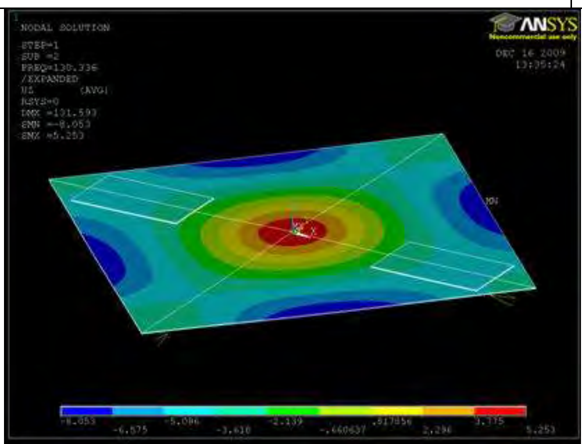
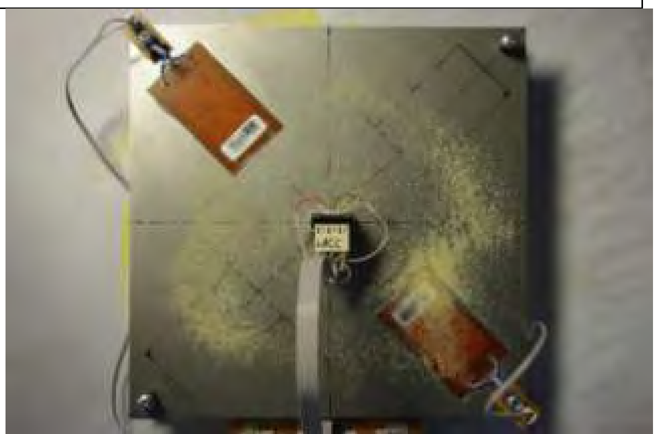
130Hz	132Hz
	

Figure.6- 8 [Mode shape at second natural frequency]