JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

VIBRATION ANALYSIS OF BORON NITRIDE NANOTUBE IN MICROGRIPPER

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Abstract : Nano robotic manipulation is mainly influenced by the performance of manipulation tools. Micro and nano grippers offer a promising method of grabbing and manipulating objects on a micro and nanoscale in three dimensions. Researchers have increasingly turned to boron nitride Nanotubes for applications due to their unique physicochemical properties, such as hydrophobicity, heat and electrical insulation, resistance to oxidation, and ability to store hydrogen. Hence an endeavor is made to use boron nitride nanotubes (BNNTs) at the tip of a microgripper with a Piezoelectric (PZT) actuator and a two-stage flexure-based amplification to manipulate nanowires and nanotubes with jaw displacements in the sub-100 nm range. The vibration response analysis of single walled boron nitride nanotubes is indispensable to achieve precise and well-controlled motion of the end effector. A free vibration analysis of Single walled boron nitride nanotubes (SWBNNT) based on Euler-Bernoulli beam theory is performed and is compared with results from the finite element method. The displacement analysis of piezoelectric driven ceramic plate in micro gripper is carried out in at different driving voltages and the result shown that the displacement increases linearly with the driving voltage. The modal vibration analysis of micro grippers with tip material single walled boron nitride nanotubes (SWBNNT) is performed in FEM software to determine and compare the dominant mode of vibration for grabbing and releasing the nano objects. SWBNNT is considered to be transversely isotropic material and have a cantilevered configuration in micro grippers.

***Index Terms* – BNNT, Euler-Bernoulli Micro gripper, FEM, Vibration.**

I. INTRODUCTION

Micro objects are invisible to the naked eye and behave in different ways, making them difficult to handle. Handling micro objects precisely in micro assembly requires micromanipulation. Hence a rigorous research effort is being devoted to the development of ultra-precision positioning stages, nano-measuring technologies, and grasping methodologies in order to achieve successful micro assembly operations [1]-[5]. As an alternative to optical, electrostatic, Bernoulli, ultrasonic and magnetic micro-nano manipulation, microgrippers are preferred because they can handle different-shaped objects with high accuracy and low cost. Actuation principles and displacement transmission mechanisms (DTMs) play crucial roles in the development of different types of micro grippers [6]. Micro grasping operations typically use four major actuation techniques: electrostatic micro grippers, electro thermal micro grippers, piezoelectric (PZT) actuators and Shaped memory alloy actuators [7]. piezoelectric (PZT) actuators have been widely used in precision positioning system and micro grippers due to high force output to weight ratio, fast response and zero backlash [8]-[10]. Assuring the operation and manipulation of micro grippers demands a large opening displacement. The output displacement of the actuator is usually amplified by DTMs [11].Several compliant mechanisms with Single-axis flexure hinges, right circular flexure hinges and leaf-type flexure hinges are proposed to act as the micro displacement in microgrippers [12]. A larger displacement amplification ratio was achieved with PZT-actuated microgripper with a three-stage flexure-based amplification [7]. A double-arm microgripper with a flexible mechanism is used in wire-bonding to achieve a reasonable level of displacement [13]. Red ruby was used at the tip of the arms to clamp and release the microwire. Micro grippers should have the right shape and material at the tips to effectively handle fragile micro-objects and deliver them at their destination [4]. The material superiorities have inspired more and more investigations on boron nitride nanotubes (BNNTs)[14]-[17]. Studies indicate that BNNTs are more suitable for development as sensors and transducers because of their chemical inertness and structural stability. A systematic study on dynamic characteristics of BNNT based micro grippers has been analyzed in the present work and compares the results of simulations based on FEM to those from continuum mechanics..

II. MECHANISM OF THE MICROGRIPPER

The design specifications of these microgrippers generally emphasize the requirement for wide opening displacement capabilities, fine structural rigidity and ease of manufacture or compatibility with well-developed microelectronic fabrication techniques. The basic function of the micro grippers is to clamp and release the objects by closing and opening its arms. The designed micro gripper consists of a piezoelectric ceramic stack, flexible mechanism, double parallel arms, BNNT, and fixing hole. In the tip of the micro gripper, the BNNTs are castoff for more precise clamping and longer service life. A total of 96 tubes are arranged vertically in the tip of the nanogripper, with 48 tubes in each arm. The output displacement of the actuator is small, it is usually amplified by multigrade leverage. The motion transmission is realized through the two-stage amplification. The Displacement Amplification Factor (DAF) is the ratio between output displacement and input displacement applied from the nanoactuator to the gripper mechanism. The ceramic stack moves with a given voltage due to the inverse piezoelectric effect (PZT). The flexible mechanism amplifies the displacement of the ceramics stack, providing sufficient displacement at the tip of the arms. The double arms return to their original position after turning off the electric signal, clamping the nanotubes and nanowires. A continuous electric signal will cause the double arms to repeatedly open and close. Table 1 shows the Dimensions of micro gripper and piezoelectric stack. The PZT stack comprises three PZT ceramic plates. Figure 1and 2 displays the front and isometric view of the micro gripper.

Dimensions of Micro gripper(μm)	
Length, L_1	3
length of the first Lever L_2	6
Length, L_3	1
length of the second Lever L_4	16
Thickness of arms	0.3
Length of PZT stack	7.5
Width of PZT stack	3
Thickness of PZT stack	0.3

Table 1: Dimensions of Micro gripper

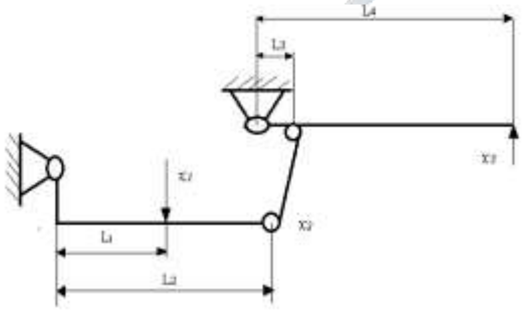

Figure 1: Dimension of micro gripper

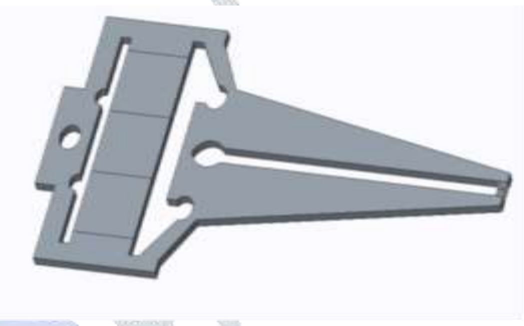

Figure 2: Model of Micro gripper

III. BORON NITRIDE NANOTUBE (BNNT)

Micro grippers can generate motion through deforming compliant structures, so choosing the right material is one of the most crucial aspects. Compatibility between gripper jaws and the gripped objects in the contact area is the other important factor. Choosing suitable material also depends on special working conditions like biological or electrolyte environments. BNNTs have piezoelectric properties that can be used in high resolution precise piezoelectric devices for measuring force or applying force. In the tip of the Micro gripper, the boron nitride nanotube (BNNTs) are used for more precise clamping and longer service life. They are hollow cylinders formed by boron (B) and nitrogen (N) atoms, covalently bonded together in hexagonal shapes. BNNTs have higher elastic modulus and tensile strength, high thermal conductivity rate, good chemical inertness and high temperature resistant properties. BNNTs have been modelled as thin-walled tubes of outer diameter 50 nm, thickness 1.32 nm, and length 300 nm for the purpose of determining their suitability as the tip of the Micro gripper. Dynamic responses of BNNTs with cantilevered configurations were analysed successfully by continuum mechanics and FEM simulations. Based on the assumption that linear binding forces act along a single walled nanotube, the stress-strain relationship, stiffness coefficients, elastic modulus, transverse modulus, and Poisson's ratio have been evaluated.

The equation of motion of free vibration based on the Euler–Bernoulli beam theory can be expressed as

$$EI\frac{\partial^2 y}{\partial x^2} + \rho A\frac{\partial^2 y}{\partial t^2} = 0 \qquad (3.1)$$

where E is Young’s modulus, I the second moment of the cross sectional area A, and ρ the density of the material.

$$f_n = \frac{\beta_i^2}{2\pi l^2}\sqrt{\frac{EI}{\rho A}} \qquad (3.2)$$

Where β1 = 1.875, β2 = 4.694, β3 = 7.854 and β4 = 10.995 for the first, second, third and fourth harmonics, respectively. The vibration modes of the proposed BNNT at the tip of Micro gripper are conducted using FEM software. A system's Natural frequency is its frequency of oscillation if it is not driven or dampened. A plot of two mode shapes and natural frequencies of BNNT are shown in figures 3 and 4.

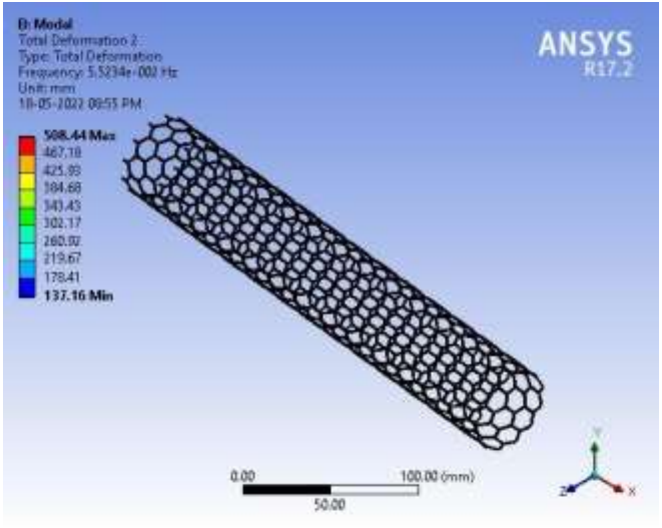

Figure 3: Natural Frequency of BNNT - Mode Shape I

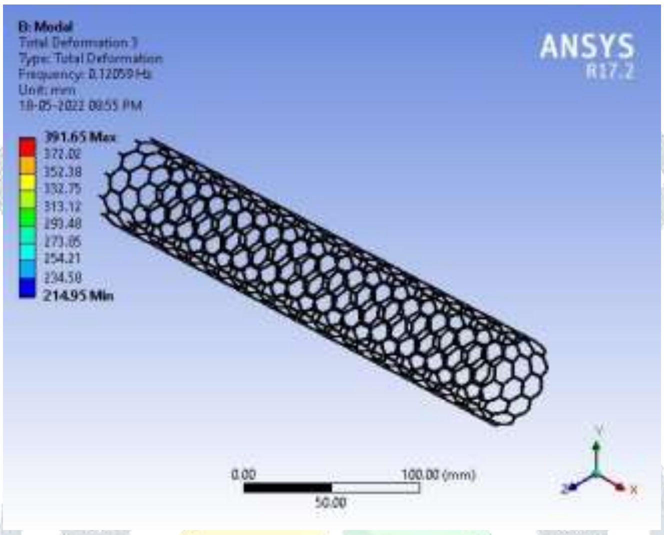

Figure 4: Natural Frequency of BNNT - Mode Shape II

Natural Frequency	**Analytical Solution Frequency (Hz)**	**FEA Solution Frequency (Hz)**
First mode	5.4×10^{-2}	5.52×10^{-2}
Second Mode	0.1093	0.1205

Table 2: Comparison of FEM and Analytical results

The FEM simulation results listed in table 2 are found to be in good agreement with present analytical method that confirms the validity of the current FE model and indicates its suitability for use SWBNNT in micro grippers.

IV. CHARACTERISTIC ANALYSIS

Based on finite element analysis (FEA), the characteristics of the Micro gripper are investigated using ANSYS software. Piezoelectric ceramics can be defined with the help of piezoelectric element solid5 in order to accurately study the dynamic characteristics of the micro gripper. The piezoelectric property of piezoelectric ceramics could be defined through its Young’s modulus, possion’s ratio and density.

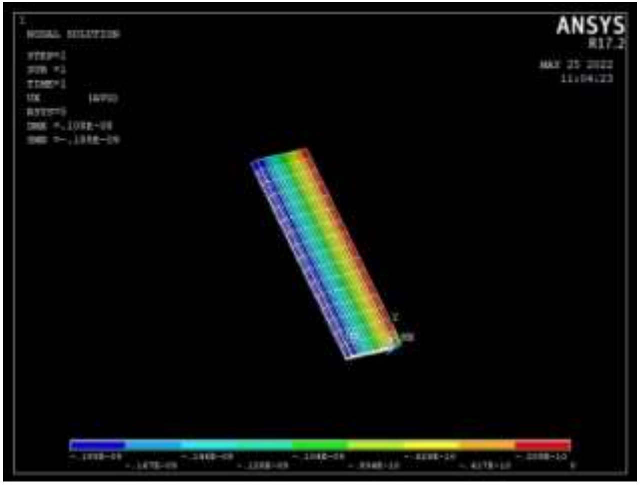

Figure 5: Piezoelectric Stack Displacement for 2V

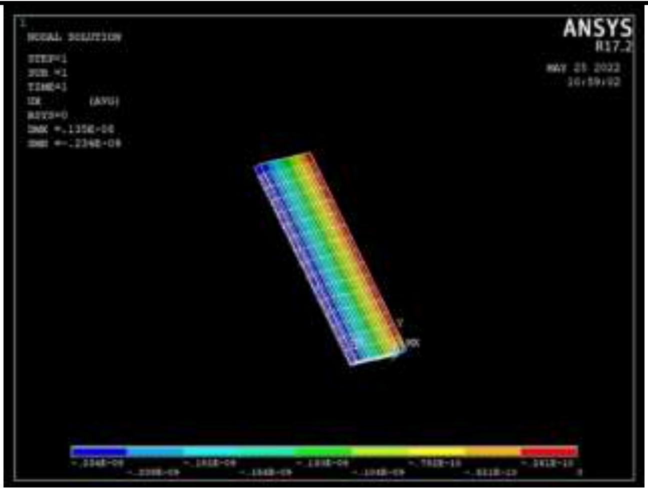

Figure 6: Piezoelectric Stack Displacement for 2.5V

Figure 5 and 6 spectacles the displacement contour of a single PZT ceramic plate when the driven voltage is 2V and 2.5 V, respectively. Displacement of PZT ceramic stack is enumerated in Table 3 based on the displacement contour of a single PZT ceramic plate.

S.No	**Voltage (volt)**	**Displacement of a single PZT ceramic plate (nm)**	**Displacement of Three PZT ceramic plates (nm)**
1	2	1.08	3.24
2	2.5	1.35	4.05

Table 3: Displacement of PZT ceramic plate

A compliant structure with multigrade leverage is used to achieve a reasonable level of displacement. Nano actuators, like piezoelectric actuators, often have a low actuation range. An amplification mechanism with a high displacement factor is needed to increase the gripping range so that the gripper can manipulate higher dimensions nano objects. The input displacement generated from the PZT stack is amplified as the first displacement by the first lever. Then, the first displacement is further amplified by the second lever. The total amplification of the gripper is a product of these two magnifications. Table 4 reveals the displacement of flexible mechanism to grasp nano objects.

Output displacement of the first leverage $$x_2 = x_1 \times \frac{L_2}{L_1} \tag{4.1}$$

Amplification Factor: $$K = \frac{L_2 \times L_4}{L_1 \times L_3} \tag{4.2}$$

$$K = \frac{6\times16}{3\times1} = 32$$

Output displacement of the second leverage= $K \times x_1$ (4.3)

S.No	**Voltage (volt)**	**Input displacement of the PZT stack (x_1) (nm)**	**Output displacement of the first leverage (x_2) (nm)**	**Amplification Factor K**	**Output displacement of the second leverage (x_3) (nm)**
1	1	1.6	3.2	32	51.2
2	1.5	2.4	4.8		76.8
3	2	3.24	6.5		103.7
4	2.5	4.05	8.1		129.6

Table 4: Displacement of flexible mechanism

When the voltage is more than 2 V, the displacement of the gripper is over 100 nm, connotation that the PZT gripper achieves appropriate displacement from this compliant mechanical structure. Optimal voltage of the gripper operation was estimated to be as small as ~2V to grasp 100nm sized wires or tubes. Figure 7 reveals that the displacement contour of the PZT stack is shown to be symmetrical, and the displacement varies linearly with the voltage.

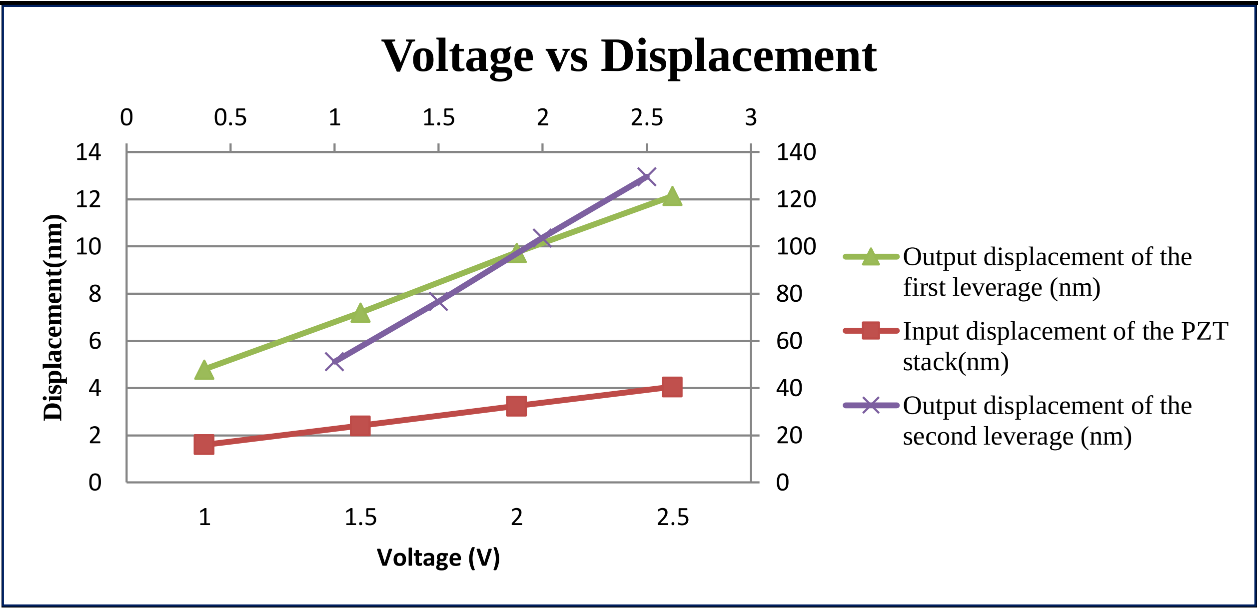

Figure 7 : Voltage vs Displacement of flexible mechanism

Natural frequency is important for the micro gripper to run at high speed. Therefore, the initial dynamic analysis is done to look at the vibration modes and characteristics of the micro gripper. Modal shapes reflect the deflection capabilities of structures. The shape of the modal curve for lowest frequency indicates a state of lower energy. As input increases, it will deflect into two, three, or the next modal shape depending on the energy. Higher modal shapes require a very high energy state that a structure or system never encounters throughout its lifetime. It is sufficient to have the first few modes of a system.

. The first three orders of natural frequencies of micro gripper are 459 Hz ,1300 Hz and 2482 Hz. The modal vibration analysis in the FEM shows that three vibration modes have frequencies below 2600 Hz .If driven by inappropriate frequencies, these vibration modes may be excited and cause undesirable vibration resonance.

Figure 8 and 9 discloses that first mode shape of gripper in xyz view and $x-z$ plane respectively. It can be found that the first-order natural frequency is comparatively small, and it is mainly featured by the longitudinal vibration of the lever. Observations on x–z plane indicate that the modal shape of the first-order natural frequency is the translation of the lever along the y axis.

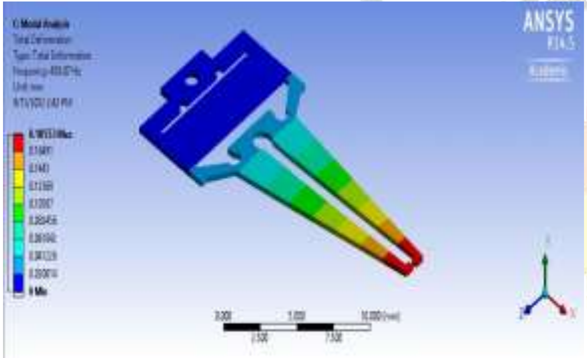

Figure 8: Mode shape-First Natural Frequency

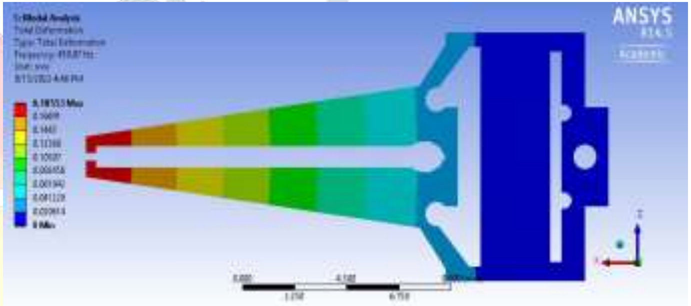

Figure 9: Mode shape-First Natural Frequency -xz Plane

The mode shape of the second natural frequency in xyz view shown in the figure 10 represent the translation of the arm along the x axis accompanied with the out of plane movement of the arm in opposite direction in the $x-z$ plane .

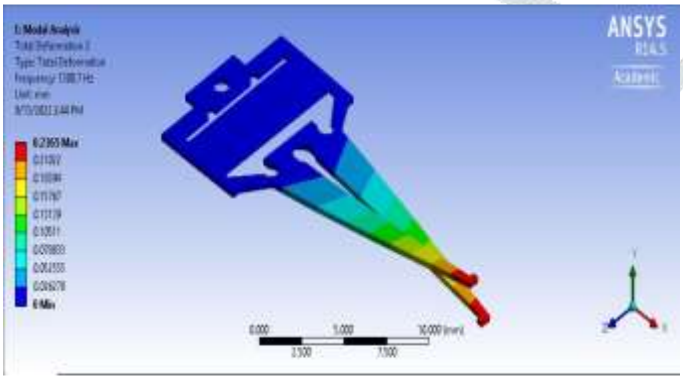

Figure 10: Mode shape-Second Natural Frequency

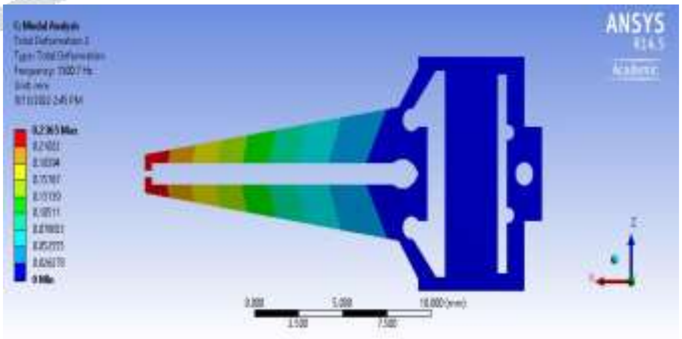

Figure 11: Mode shape-Second Natural Frequency-xz Plane

The dominant modal shape of the third-order natural frequency is the bending vibration of double arms as represented in the figure 12.

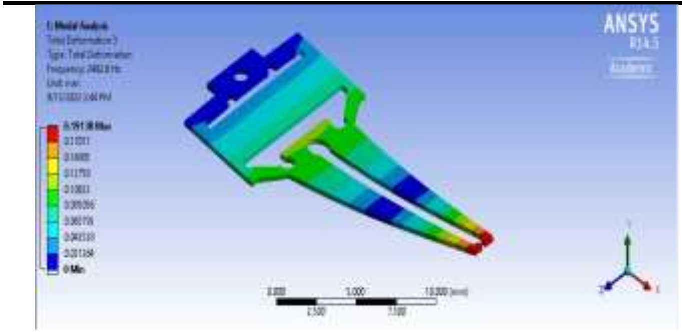

Figure 12: Mode shape-Third Natural Frequency

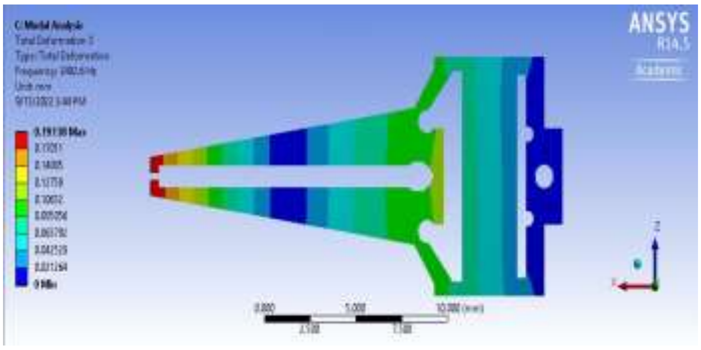

Figure 13: Mode shape-Third Natural Frequency-xz Plane

Through modal analysis, the First three orders of natural frequencies and their mode shape was obtained and arms were open and close in opposite directions. Even though the density of the Boron nitride is less, the frequency of BNNT is considerably high. The gripping of the nano scaled objects can be controlled more effectively as the displacement of the arms is very minimal when the arms of micro gripper with BNNT is oriented in First and third mode of frequency maneuvering, The second mode shape indicate translation and rotation of double arms with a maximum amplitude of 0.2365mm and third mode shape displays that though the middle portion of the arm had minimal deformation when vibrating at the natural frequency of 2482Hz,double arms be likely to bend about x . Hence the first mode is the working mode frequency which ensures a more secure grasp of nano objects. Due to the high stiffness and light density of BNNT [16], there is intrinsic elastic compliance in the double arms, which makes grasping safer than with a dense tip.

V. CONCLUSION

In the present study, a micro gripper featuring PZT stack, flexible mechanism and BNNT is investigated and the following conclusions are drawn.

The FEM simulation of the Boron nitride nanotube is found to be in good agreement with the existing analytical method and demonstrates its potential for use in future research on the SWBNNT in micro grippers. The Natural frequencies of micro gripper are obtained in ANSYS workbench to investigate vibrational characteristics. The lever's longitudinal vibration primarily exhibits first-order natural frequency. Second- and third-order natural frequencies, respectively, are displayed in arm shearing and bending. The natural frequency of micro gripper is very high despite the fact that Boron Nitride has a lower density. Hence the micro gripper with BNNT is preferred to reduce vibrations and more securely grab nano objects. The amplification of the micro gripper is calculated according to the leverage relationship and the amplification ratio is found to be 32 and the displacement of the double arm can reach over 150 nm. From the Displacement-Voltage graph, the displacement increases linearly with the driving voltage and the sufficient displacement of 100nm is achieved at 2V. When the arms of Nano gripper with BNNT is oriented in the first mode of frequency manoeuvring, the gripping of the nano scaled objects can be controlled more effectively as the displacement of the arms is very minimal. Hence, First mode frequency is selected as the working and dominant vibration mode for clamping and releasing the nano objects.

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