



Design and Analysis of Compliant motion amplifier based XYZ precise positioning Stage -A Short Review

Mr.Santosh.B.Jadhav¹, Dr.Suhas.P.Deshmukh²

¹Ph.D., Research Scholar, Rajarshi Shahu College of Engineering, Tathwade, Pune, Maharashtra (INDIA)

²Ph.D., Research Guide, Rajarshi Shahu College of Engineering, Tathwade, Pune, Maharashtra (INDIA)

Abstract: The compliant positioning stage with high precision is the popular area of research due to demand of high resolution motion in many applications. XYZ positioning stage is an ideal choice for the many applications where 3D translational motion is sufficient eg. atomic force microscope (AFM). PZT actuators are most promising alternative among the actuators available due to its advantages such as high displacement resolution, ability to produce large blocking force etc. However due to its small motion range i.e. 15-20 microns, the use of PZT becomes infeasible for the many applications. To overcome the drawback, it is integrated with compliant motion amplifier (CMA). Since CMA offers many benefits with the use of flexure hinge in the structural design of the CMA. Therefore the primary goal of CMA is to amplify the motion in the desired direction for the given limited input displacement of the PZT actuator and maintain the high resolution at the same time. The use of CMA for the XYZ stage to produce perfectly decoupled motion with desired amplification & high natural frequency can be achieved. The paper provides the brief review of the compliant motion amplifier used in the single direction amplification, planar motion, and XYZ positioning mechanism.

Keywords: Compliant motion amplifier, precision, decoupled motion, displacement resolution, large blocking force, flexure hinge etc.

I. Introduction

Micro/nano positioning stages are widely used in modern high technology eg. atomic force microscopy, micro/nano assembly [1-2], manipulation [3]. X-Ray lithography and microscanning [4-5] biomedicine and biocell surgery [6-7] and so on. Due to demand of higher accuracy and natural frequency rises. More attention has been attracted on the research of the nanopositioning stage. Piezoelectric actuators are the micro motion generators which are capable to produce the high displacement resolution, high force output with low strain etc. Due to its small motion range i.e. 15-20 microns, the use of PZT actuators becomes limited or infeasible for many of the above mentioned applications. One technique to overcome this drawback is to integrate the PZT actuator with compliant motion amplifier (CMA) which offers many benefits with the use of flexure hinge in the design of CMA. Therefore the main goal of the CMA is to achieve the amplification in the desired direction for a given input motion of PZT actuator and to obtain the high positioning resolution at the same time. Level principle [8] and bridge principle [9] are the fundamental methodologies to enlarge the output displacement. The lever principle amplifier shows its power of large amplifier ratio but linearity is not good as compared with bridge principle amplifier in the range of high amplified ratio [10]. Recent research towards the mechanical design optimization of flexure based mechanisms for nanopositioning stage can be divided into serial kinematic mechanisms and parallel kinematic mechanisms [11] uses serial kinematic mechanisms while reference [12] adopts parallel kinematic mechanisms. The motion along each direction can be independently measured and controlled in serial kinematic mechanisms. On the other hand, the parallel kinematic mechanism has many advantages including structural compactness, high stiffness and high accuracy. But the coupling of the cross axis motion, complex kinematic equation and small workspace limits the wide application of this mechanism. So it is necessary to design the flexure mechanism to decouple the motion of parallel nanopositioning stage. The objective of this work is to devise a new decoupled XYZ compliant parallel stage with decoupled flexure joint. The flexure joint has many advantages such as no backlash, no wear, smooth and continuous displacements and almost linear displacement relationship between the input and output. The flexure joints are classified into single axis flexure hinges, two axis flexure hinges and multi-axis flexure hinges. The analysis of right circular notch flexure hinge which is the single axis flexure hinges is conducted by Paros and Weisbord in reference [14]. This right circular flexure hinge has been widely used in science and engineering applications like atomic force microscopy scanner [15], parallel micro manipulator [16]. In addition parallel flexure stages with multiple degrees of freedom are widely used in micro/nano positioning. It provides efficient

tool in precision engineering applications such as micro scanning [21], X-ray lithography [22], micro/nano assembly [23]. A 5 DOF Flexure stage with module of 2xT-R, 1-T and the interface of 3XT-R-RT is produced in [20]. a compact 3-PPRR XYZ CPMs without overlapping SCs [24].

II. Literature review

Organization: Section A, summarizes the most common topologies of compliant mechanism for displacement amplification purposes. In this section flexure hinge design designs, within the compliant mechanisms are also reviewed. Section B, Summarizes the different applications in single direction, planar, spatial motion mechanisms (XYZ stages). Section C, Synthesis and analysis methods are reviewed.

A. Review of the most common topologies of Compliant Motion Amplifiers (CMA):

Ouyang et.al 2008, presented and compared the most popular topologies of Compliant motion amplifiers used in integration with PZT actuators for micro motion applications [35]. Different topologies such as buckling beam topology, lever arm topology, double lever arm topology, parallel four bar topology, double symmetric four bar topology, symmetric five bar topology are discussed. Buckling beam topology consists of long slender beam that buckles due to axial compressive force when the force exceeds a critical value. Bharti S. et.al 2003, proposed several amplifier designs based on the buckling principle. However two drawbacks are associated with an amplifier based on buckling beam topology are overall large dimensions as compared to others and the driving force should be large enough for buckling to be produced [38]. Rue et.al 1997, proposed the topology of parallel four bar structure to improve the stiffness and its natural frequency of the mechanical amplifiers and deals with lateral displacement problem of lever arm structure. This problem can be resolved by implementation of double symmetric four bar structures. The double symmetric four bar topology is used to amplify the input displacement generated by the PZT actuators. The drawback of it is relatively low stiffness and low NF which may limit their industrial application. Ouyang et.al 2008 developed the new symmetric five bar topology in which combination of symmetric four bar topology and a lever arm topology. It can significantly increase the system stiffness hence the structure's natural frequency with large amplification ratio [35]. Xu et.al 1996, have presented the application of some fundamental compound bridge amplifier topologies which utilizes the three basic amplifying elements of simple lever, bridge and four bar linkage amplifiers eg. symmetric structure of a bridge displacement amplifier provides with a higher gain and linear output motion for precision oriented applications. Alternatively the four bar linkage flexure hinged amplifier is capable of producing the large output displacements for both precision and high displacement oriented applications. The simple lever flexure hinge based displacement amplifier is able to produce the large output displacement and having highest efficiency due to less hinges than the other two topologies. Also effect of geometric profiles of the flexure hinges on the performance of the flexure hinged displacement amplifiers. Different hinge profiles such as elliptical and corner filled, circular hinge designs are analysed and compared [37].

B. Design and analysis of one direction motion amplifiers, compliant XY stage and compliant XYZ stage:

Xu et.al 2011, investigated the compact size flexure based compound bridge type (CBT) displacement amplifier for piezoelectric drives. The CBT design is having large amplification ratio and large lateral stiffness which makes it suitable for actuator isolation and protection than the ordinary bridge type amplifiers. The CBT amplifier is optimized for a large resonance frequency subject to other performance constraints. Since the developed CBT model is capable of generating the output displacement over 1mm which is suitable for development of micro/nano positioning stages with a cubic millimeter sized workspace. It utilizes the right circular flexure hinge however, for this model it is also suggested that other hinge geometries can be implemented [31]. Polit et.al 2011 presented a high bandwidth (i.e. NF) X Y nanopositioning system. The developed system is designed to achieve a high NF with minimizing the parasitic motion. The structure of the device is based on the parallel kinematic mechanism, which features two parallel independent kinematic chains. Each kinematic chain consisted of a prismatic joint connected to PZT actuator and a parallelogram hybrid flexure mechanism connected to the end effector of the device. Kinematic and dynamic analysis of the mechanism shows that the compliant structure of the stage possessed a high NF and decoupled motion in XY directions. The proposed mechanism can be employed the applications in high throughput nanoscale metrology, imaging and manufacturing [32]. A. Eskandari & P. R. Ouyang et.al 2013, proposed XY planar motion compliant mechanical amplifier based on the symmetric five bar topology. Detailed FEA of static and dynamic characteristics of the proposed XY CMDA design is provided and the optimization is carried out to increase the amplification ratio with the minimum compromise in the natural frequency are discussed. Xu et.al 2012 designed and developed a new flexure based dual stage system which features a new decoupling design to minimize the interference behavior between the coarse motion generator and the fine motion generator stages of the device. The output displacement of the mechanism is guided by the compliant mechanism which consists of eight right circular hinges [16]. Ouyang et.al 2011 presented a spatial hybrid motion compliant mechanism based on symmetric five bar topology. In this study, a spatial hybrid motion mechanism with the 3 DOF is developed which is capable of combining the macro and micro motions through only one compliant mechanism. The integral compliant structure of the proposed mechanism helped to eliminate the coupling interaction between the macro motion and

the micro motion [34]. Li and Xu et.al 2011 designed and developed a totally decoupled Piezo driven XYZ flexure parallel micro positioning stage (TDPS) for micro/nano manipulation. In the research XYZ TDPS with displacement amplifier and simple architecture for the ease of the manufacturing. The proposed design of an XYZ stage with decoupled output motion by eliminating the cross axis coupling errors between the X,Y and Z directional translational and parasitic rotation errors around the axes .the right circular hinges were employed for the design. It is suggested that the other hinge geometries compatible to the mechanism can be implemented [30].Shorya Awtar et.al 2014 proposed novel parallel kinematic flexure mechanism which provides highly decoupled motions along the three translational directions X,Y and Z and have high stiffness along three rotational directions. Geometric decoupling ensures large motion range along each translational direction and enables integration with large stroke ground mounted linear actuators [46].X.Zhang,Qingsong Xu, presented the design of new compact parallel flexure stage with three DOFs.Bridge-principle is proposed by a serial connection of two fundamental bridge amplifiers and then analytical study of amplifiers in terms of two stage amplifiers is conducted by performing the Finite element analysis simulations . PPR flexure joint is demonstrated to reduce the cross axes error. Due to large amplification ratio and flexures, two stage amplifiers is then employed to devise an XYZ parallel stage with decoupled motion. Driven by three low voltage piezoelectric stacks, the XYZ stage provides larger decoupled motions by using the two stacked amplifiers which connects the actuators and output platform with PPR joint [47].

C. Synthesis and Analysis methods:

Howell et.al 2001, presented rigid body kinematic synthesis approach which is useful when a compliant mechanism is to be used to perform a traditional rigid body mechanism task, such as path or motion generation, without concern for the energy storage in the flexible members Howell & Midha et.al, 2001 presented the pseudo-rigid body model (PRBM) approach to model the deflection of flexible members using rigid body components which has equivalent force-deflection characteristics. Different types of compliant segments require different pseudo-rigid models that predict the deflection path and force-deflection relationship of a flexible segment. Howell et.al.2001 discussed synthesis with compliance approach which accounts for energy storage. With this type of synthesis, the unique characteristics inherent in compliant mechanisms may be used to design mechanisms with specified energy storage characteristics. The synthesis equations include not only the rigid body loop closure equations from the pseudo-rigid body model, but also include equations dealing with the desired energy storage relationships [39].Jensen and Howell et.al.1999, discussed the kinematic geometry of the mechanism is determined, the structural properties of the flexible members may be chosen as per the allowable stresses and input requirements. The synthesis problems in which rigid-body are applied directly to the pseudo-rigid body model will hereafter be referred to as rigid-body replacement synthesis. If only the kinematics of the mechanism is an issue, it may be called kinematic synthesis. The topological design of compliant mechanism is then solved as a problem of material distribution using the Optimality Criteria method as discussed by Lau &Du 2001, Lin and Shih 2002.Unlike traditional optimization, and topological optimization does not require the explicit definition of optimization parameters [19].There are different emerging approaches to design compliant mechanisms such as pseudo-rigid-body-model (PRBM) approach, innovative design approaches such as the constraint-based design (CBD) approach,the screw theory based (STB) approach, the freedom and constraint topology (FACT) approach and the building-block synthesis (BBS) approach. Compliant mechanisms obtained using different design approaches can be classified into three categories: lumped-compliance mechanisms such as that in Li's work ,distributed-compliance mechanisms such as that in Awtar's work .If lumped compliance is adopted in the PRBM approach, a limited motion range is produced, but if distributed compliance is used, a relatively large motion range can be generated [40].M.jia,R.P.Jia et.al 2015,presented an based on parameterized compliance for type synthesis of flexure mechanism with serial, parallel or hybrid topologies .The parameterized compliance matrices are derived for commonly used flexure elements which are significantly influenced by flexure parameters including material and geometric properties. Different parameters of flexure elements generate different degrees of freedom (DOF) characteristics of types. Enlightened by the compliance analysis of flexure elements, parameterization approach help to analyse and synthesize flexure mechanisms with case study as serial chains, parallel chains and combination of hybrid chains [48]. Alejandro E.Albanesi et.al 2010,presented brief overview and comparisons of methods applied in the design of compliant mechanisms.Several methods have being conceived to analyse and design the mechanisms which gain part of their motion from the deflection of flexible members rather than from movable joints only. The most widely used tool are pseudo rigid model based methods, optimization based methods and a novel inverse design method. The pseudo rigid body model is used to model the deflection of flexible members using rigid body components which has equivalent force –deflection characteristics .The rigid link mechanism theory may be used to analyze the compliant mechanism .Different compliant segments require different pseudo rigid models that predicts the deflection path and force –deflection relationship of a flexible segment. [49].

III. Conclusion

Compliant motion amplifier offers the ideal choice to overcome the drawback of PZT actuators in precise positioning applications. In the present study, use of various topologies for the displacement amplification purpose along with the effect of various hinge profiles on the static and dynamic performances of Compliant motion amplifier (CMA) i.e. amplification ratio, natural frequency etc. are reviewed. The static and dynamic performance of CMA in case of planar & spatial motion mechanisms i.e. XYZ precise positioning stages are studied in detail. The future work aimed to design and develop compliant motion amplifier (CMA) based XYZ positioning stage with desired amplification and achieving perfectly decoupled motion while maintaining the high natural frequency of the mechanism.

References

- [1] E.S. Ferguson, Kinematics of Mechanisms from the Times of Watt .Washington, DC (USA): The museum of History and technology, paper No. 27, pp. 185-230, 1962.
- [2] B.A. Gozen and O.B. Ozdoganlar, "Design and evaluations of mechanical nanomanufacturing system for nano milling," *Precis. Eng.*, Vol. No 36.1, pp 19-30, 2012.
- [3] Y. Tian, B. Shirinzadeh, and D. Zhang, "Design and dynamics of a 3-DOF flexure-based parallel mechanism for micro/nano manipulation," *Microelectronic Engineering*, vol. 87, pp. 230-241, 2010.
- [4] P. F. Indermuehle, C. Linder, J. Brugger, V.P. Jaecklin, and N.F. de Rooij, "Design and fabrication of an overhanging xy-microactuator with integrated tip for scanning surface profiling," *Sensors and Actuators A: Physical*, vol. 43, no. 1-3, pp. 346-350, 1994.
- [5] H. T. H. Chen, W. Ng, and R. L. Engelstad, "Finite element analysis of a scanning X-ray microscope micro positioning stage," *Review of Scientific Instruments*, vol. 63, no. 1, pp. 591-594, 1992.
- [6] F. Beyeler, A. Neild, S. Oberti, D. J. Bell, Y. Sun, J. Dual, and B. J. Nelson, "Monolithically fabricated microgripper with integrated force sensor for manipulating microobjects and biological cells aligned in an ultrasonic field," *J. Microelectromech. Syst.*, vol. 16, pp. 7-15, 2007.
- [7] S. Thalhammer, "Laser micro-tools in cell biology and molecular medicine," *Laser Phys.*, vol. 13, no. 5, pp. 681-91, 2003.
- [8] Y. Qin, Y. Tian, and D. Zhang, "Experimental Investigation of Robust Motion Tracking Control for a 2-DOF Flexure-Based Mechanism," *IEEE/ASME Transactions on Mechatronics*, vol. 19, no. 6, pp. 1737-1745, 2014.
- [9] K. B. Choi, H. J. Lim, G. H. Kim, and J. J. Lee, "A flexure-based scanner for a fully bidirectional operation driven by a differential piezo force," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 228, no. 17, pp. 3186-3199, 2014.
- [10] Bhagat, B. Shirinzadeh, L. Clark, P. Chea, Y. Qin, Y. Tian, et al., "Design and analysis of a novel flexure-based 3-DOF mechanism," *Mechanism and Machine Theory*, vol. 74, pp. 173-187, 2014.
- [11] B. J. Kenton and K. K. Leang, "Design and control of a three-axis serial-kinematic high-bandwidth nanopositioner," *Mechatronics, IEEE/ASME Transactions on*, vol. 17, pp. 356-369, 2012.
- [12] Q. Xu and Y. Li, "Design and analysis of a new singularity-free three prismatic revolute-cylindrical translational parallel manipulator," *Proceedings of the Institution of Mechanical Engineers. Part C, Journal of Mechanical Engineering Science*, vol. 221, no. 5, pp. 565-576, 2007.
- [13] D. Kang and D. Gweon, "Analysis and design of a cartwheel-type flexure hinge," *Precision Engineering*, vol. 37, pp. 33-43, 2013.
- [14] J.M. Paros, and L. Weisbord, "How to design flexure hinges," *Machine Design*, vol. 37, pp. 151-156, 1965.
- [15] D. Kim, D. Kang, J. Shim, I. Song, and D. Gweon, "Optimal design of a flexure hinge-based XYZ atomic force microscopy scanner for minimizing Abbe errors," *Review of Scientific Instruments*, vol. 76, p. 073706, 2005.
- [16] Q. Xu, "New Flexure Parallel-Kinematic Micro positioning System with Large Workspace," *IEEE Transactions on Robotics*, vol. 28, no. 2, pp. 478-491, 2012.
- [17] S.T. Smith, V.G. Badami, J.S. Dale, Y. Xu, "Elliptical flexure hinges," *Review of Scientific Instruments* vol. 68, pp. 1474-1483, 1997.
- [18] N. Lobontiu, J.S.N. Paine, E. Garcia, and M. Goldfarb, "Cornerfilleted flexure hinges," *ASME Journal of Mechanical Design*, vol. 123, pp. 346-352, 2001.
- [19] K.-B. Choi, H. Lee, and K. Min Young, "Cartwheel flexure-based compliant stage for large displacement driven by a stack-type piezoelectric element," in *Proc. of International Conference on, Control, Automation and Systems (ICCAS'07)*, 2007, pp. 2754-2758.
- [20] R. Murielle and C. Reymond, "A new concept of modular kinematics to design ultra-high precision flexure-based robots," *Proc. 41st Int. Symp. of Robotics and 6th German Conf. on Robotics*.
- [21] H. T. H. Chen, W. Ng, and R. L. Engelstad, "Finite element analysis of a scanning X-ray microscope micropositioning stage," *Review of Scientific Instruments*, vol. 63, no. 1, pp. 591-594, 1992.
- [22] B.A. Gozen, and O.B. Ozdoganlar, "Design and evaluation of a mechanical nanomanufacturing system for nanomilling," *Precis. Eng.*, vol. 36, no. 1, pp. 19-30, 2012.
- [23] G. Hao and H. Li, "Design of 3-Legged XYZ Compliant Parallel Manipulators with Minimised Parasitic Rotations," *Robotica*, vol. 33, no. 4, pp. 787-806, 2015.
- [24] P. F. Indermuehle, C. Linder, J. Brugger, V.P. Jaecklin, and N.F. de Rooij, "Design and fabrication of an overhanging xy-Microactuator with integrated tip for scanning surface profiling," *Sensors and Actuators A: Physical*, vol. 43, pp. 346-350, 1994.
- [25] Lobontiu, E. Garcia, "Analytical model of displacement amplification and stiffness optimization for a class of flexure-based compliant mechanisms," *Comput. Struct.*, vol. 81, pp. 2797-2810, 2003.
- [26] H.-W. Ma, S.-M. Yao, Li-Q. Wang, Z. Zhong, "Analysis of the displacement amplification ratio of a bridge-type flexure hinge," *Sensors Actuators A*, vol. 132, pp. 730-736, 2006.
- [27] G. Ye, W. Li, Y.-Q. Wang, X.-F. Yang, L. Yu, "Kinematics analysis of bridge-type micro-displacement mechanism based on flexure hinge," *Proceedings of the 2010 IEEE International Conference on Information and Automation*, 2010, pp. 66-100.
- [28] K.q. Qi, Y. Xiang, C. Fang, Y. Zhang, and C.-s. Yu, "Analysis of the displacement amplification ratio of bridge-type mechanism," *Mechanism and Machine Theory*, vol. 87, pp. 45-56, 2015.
- [29] S. Awatar and A. H. Slocum, "Constraint-based design of parallel kinematic XY flexure mechanisms," *J. Mech. Des.*, vol. 129, no. 8, pp. 816-830, 2007.
- [30] Y. Li and Q. Xu, "A Totally Decoupled Piezo-Driven XYZ Flexure Parallel Micropositioning Stage for Micro/Nanomanipulation," *IEEE Transactions on Automation Science and Engineering*, vol. 8, pp. 265-279, 2011.

- [31] X. Zhang and Qingsong Xu, Design of a New Flexure-Based XYZ Parallel Nanopositioning Stage, Proceedings of 2015 IEEE Conference on robotics and biomimetics, Zuhai china, December 6-9, 2015.
- [32] Polit, S., & Dong, J. 2011. Development of a High-Bandwidth XY Nanopositioning Stage for High-Rate Micro-/Nanomanufacturing. *IEEE/ASME transactions on mechatronics*, 16 (4), 724-733.
- [33] Li Y.&Xu Q. 2011. A Totally Decoupled Piezo-Driven XYZ Flexure Parallel Micro positioning Stage for Micro/Nano manipulation. *IEEE transactions on automation science and engineering*, 8 (2), 265-279
- [34] Ouyang P. R. 2011. A Spatial Hybrid Motion Mechanism: Design and Optimization. *Mechatronics*, 21 (3), 479-489.
- [35] Ouyang P. R., Zhang W. J., & Yang, G. S. 2008. Micro-motion devices technology: The state of arts review. *Int J Adv Manuf Technol*, 463– 478
- [36] Ouyang P.R., Zhang W.J., Gupta, M. M. 2008. A New Compliant Mechanical Amplifier Based on a Symmetric Five-Bar Topology. *Journal of Mechanical Design*, 130 (10).
- [37] Xu W& King T. 1996, Piezoactuator displacement amplifiers: flexibility, accuracy, and Stress considerations, *Journal of precision Engineering*, 19 (2), pp. 4-10.
- [38] Bharti S, Frecker M. 2003. Compliant mechanical amplifier design using multiple optimally placed actuators. 2003, ASME International Mechanical Engineering Congress, pp. 1-8. Washington, D.C.
- [39] Howell, L. L. 2001. *Compliant Mechanisms*. New York: Wiley and Sons.
- [40] Kim, C.J., Moon, Y. M., Kota, S., 2008, “A Building Block Approach to the Conceptual Synthesis of Compliant Mechanisms Utilizing Compliance and Stiffness Ellipsoids”, *Journal of Mechanical Design*, 130(2): 022308
- [41] Kim, C., 2009, “Design Strategies for the Topology Synthesis of Dual Input-Single Output Compliant Mechanisms”, *Journal of Mechanisms and Robotics*, 1(4): 041002.
- [42] Park, S. R., & Yang, S. H. (2005). A mathematical approach for analyzing ultra precision Positioning system with compliant mechanism. *Journal of Materials Processing technology*, 164-165, 1584 - 1589.
- [43] Yong Y. K., & Lu, T.-F. 2009. Kinetostatic modeling of 3-RRR compliant micro-motion stages with flexure hinges. *Mechanism and Machine Theory*, 38 (6), 1156–1175.
- [44] Kim, C.J., Moon, Y. M., Kota, S., 2008, “A Building Block Approach to the Conceptual Synthesis of Compliant Mechanisms Utilizing Compliance and Stiffness Ellipsoids”, *Journal of Mechanical Design*, 130(2): 022308.
- [45] Kim, C., 2009, “Design Strategies for the Topology Synthesis of Dual Input-Single Output Compliant Mechanisms”, *Journal of Mechanisms and Robotics*, 1(4): 041002.
- [46] Shorya Awtar 2013, An XYZ Parallel-Kinematic Flexure Mechanism With Geometrically Decoupled Degrees of Freedom, *Journal of mechanisms and robotics*, Vol.No-5, pp.10-17.
- [47] Xiaohi Zhang, Q. Xu 2015, Design of a new flexurebased XYZ parallel nanopositioning stage, proceedings of 2015 IEEE conference on robotics and Biomimetics Zhuhai, china December 6-9, 2015.
- [48] M.jia, R.P.Jia et.al, 2015, A compliance based parametrization approach for type synthesis of flexure mechanisms 2015, Vol.no 7
- [49] Alejandro E.Albanesi et.al 2010, A review on design methods for compliant mechanisms ,Argentinia 15-18, Nov.2010 Mecca computational Vol XXIX, pp 59-72.

III. Acknowledgments

I would like to thank many people who have helped me directly, indirectly along this journey. First to my guide Dr.S.P.Deshmukh for their continous support as well as providing valuable guidance in the research direction.