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A Review Paper on Compound Displacement Amplification Mechanism

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Abstract

This review article provides a survey of emerging technologies in displacement amplification of compliant mechanisms.The displacement amplification is possible with a compliant mechanism. The compliant mechanism isbeneficial and efficient because of simplicity in the design and where there is accuracy, compactness, and precision is needed.We can use various categories of displacement amplification of the compliant mechanism depending upon the application.In recent year'sbridge-type, lever-type and compound bridge-type compliant mechanism can be used for practical micro/nano manipulation tasks.The amplification ration can be improved by two L-shape lever mechanisms and one half-bridge type mechanism. Two L-shape lever mechanisms which are arranged in mirror symmetrical distribution can be used as the first stage to amplify the displacement of the PZT.

I. INTRODUCTION

Many studies have been conducted to design and investigate various displacements. Thecommonly used displacementamplifiers can be mainly divided into two types including lever-type and bridge-type. Lever-type flexure mechanism is the traditional displacement amplification mechanism. For instance, (Yong, Lu, and Handley 2008)used the amplification levers in the two axes of flexure-based XY Stage for fast Nano scale positioning,(Guo et al. 2016) presented a two stage displacement amplifier with symmetric structure. Kim et al. used a double amplification mechanism, which has two L-shape levers in a 3-DOFs flexure-based positioning system. Compared with the lever-type mechanism, bridge-type flexure mechanism has the advantages of large amplification ratio and compact size, which becomes more and more popular in modern industry(Lobontiu and Garcia 2003), formulated an analytical model for displacement and stiffness calculations of bridge-type flexure mechanism based on the Castigliano's second theorem.(Xu and Li 2011), designed a compound bridge-type amplifier, and established an analytical model for evaluation of its amplification ratio, input stiffness, and resonance frequency based on the Euler-Bernoulli beam bending theory. (Kim, Kim, and Kwaka 2003), developed a three dimensional bridge-type hinge mechanism and derived the equation of motionfor the hinge mechanism by using matrix methods. Although the bridge-type amplification mechanism is more widely used, in most cases, its input displacement still depends on the output displacement of the PZT itself. Therefore, it is necessary to amplify the input displacement of the bridge-type mechanism to obtain a higher amplification ratio. (Lai and Zhu 2017; Peroulis et al. 2012; Xianmin Zhang and Zhu 2018; Z. Zhu et al. 2018) firstly proposed a flexure-based vertical Nano-positioning stage using a hybrid displacement amplification mechanism which is composed of the lever-type and bridge-type mechanism to amplify the output displacement of the PZT.

However, the existence of the input decoupling mechanism results in the complex structure of the mechanism. The compression of the flexure hinge in the lever mechanism and the high input stiffness produced by the decoupling mechanism severely limit the amplification ratio of this kind of mechanism. (Han et al. 2017), proposed a novel symmetric two-stage lever-type amplifier called tensural displacement amplifier in which all the flexural hinges are loaded in tension and bending rather than compression and bending when deflected. The developed tensural lever-type mechanism can solve the problems of input decoupling and buckling, which gives a good idea for designing amplification mechanism. In this paper, a novel flexure-based displacement amplification mechanism is proposed. Two L-shape lever-type and one bridge-type mechanisms are combined to amplify the output displacement of the PZT with high amplification ratio. Similar with the amplifier in, the flexure hinges in the proposed mechanism are also loaded in tension and bending which can solve the potential buckling problems. The symmetrical distribution of L-shape lever mechanisms can avoid the bending moments and lateral forces applied to the PZT, which can effectively protect the PZT. An analytical model for the predictions of theoretical displacement amplification ratio, input stiffness and natural frequency of the mechanism is derived using the stiffness matrix method. Optimal design based on the analytical model is developed to ensure the large amplification ratio, high natural frequency and compact size. The finite element analysis (FEA) and the experimental tests are then conducted to validate the high accuracy of the analytical model and the good static and dynamic performances of the proposed mechanism.To achieve high-precision positioning performance, an appropriate actuation method plays a significant role. Lead Zirconium Titanate (PZT) based actuator, with the advantages of fast frequency response, Nano scale resolution, and high output force, are the most preferred actuators for the precision positioning stages. However, the precision positioning stages are usually required to achieve a stroke of several hundred microns, and PZT actuators with the output displacement stroke only 0.1%-0.2% of their own length are difficult to meet such requirements. In this case, it is necessary to amplify the output displacement of the PZT actuators by means of compliant amplification mechanism.

The lever amplification mechanism has a simple structure, but the amplification ratio is low in a limited space. The triangular amplification type mainly includes the Scott-Russell mechanism the bridge-type amplification mechanism and the rhombus amplification mechanism. The Scott-Russell mechanism is easily influenced by the angular deformation existed in the flexure hinges, and the reaction force generated in other parts making it difficult to get the desired amplification ratio. Therefore, a large number of scholars have focused on the study of the bridge-type amplification mechanism and the rhombus amplification mechanism in order to achieve the large amplification ratio in a compact space.(Wei et al. 2017),used the pseudo-rigid body approach to simplify the model of bridge-type amplification mechanism, and the geometric relationship was adopted to derive the ideal amplification ratio. Based on the Castigliano's second theorem,(Lobontiu and Garcia 2003),established an analytical model for stiffness analysis and displacement amplification ratio of the bridge-type amplification mechanism. (Ma et al. 2006),further simplified the ideal amplification ratio model of the bridge-type mechanism by introducing the instantaneous velocity analysis, and then the theory of elastic beam and the principle of virtual work were utilized to derive the theoretical amplification ratio through considering the torsional deformation and axial deformation of flexible hinges. (Xu and Li 2011), developed an analytical model of a composite bridge-type amplification mechanism using elastic beam theory. (Qi et al. 2015), combined the geometric relationship with the elastic beam theory and derived a novel amplification ratio model of the bridge-type amplification mechanism, which improved the accuracy of the original model. (Ye et al. 2010), abandoned the derivation method of the geometric approximation relationship, and theprinciple of the energy conservation and the elastic beam theory was employed. The deformation of the flexible hinges and connecting beams was considered in the model to further improve the accuracy of the theoretical amplification analysis.

II. LITURATURE SURVEY/BACKGROUND

Compliant mechanism based systems with precision motion are very much in demand in micro-precision industry because of which conventional rigid body mechanisms are becoming redundant due to less accuracy than compliant mechanism. In this paper author has attempted a novel approach to design a compliant mechanism with circular based contemporary flexure hinge(Aswin Srikanth and Bharanidaran 2017). A novel micro machined mechanical amplification unit for increasing the stroke of piezoelectric micro actuators up to high frequencies is presented in this paper. Frequencies from quasi-static up to 15 kHz & an amplification ratio of 5-13 is obtained when comparing displacements at the piezo element and at the lever tip. Results from finite element simulations were found to be in good agreement with experiments(Bolzmacher et al. 2010). In this paper Kinematic theory was used to analyse the ideal displacement amplification ratio of a bridge-type flexure hinge in this paper, and the flexure hinge was regarded as a pure multi-rigid body with ideal pivots. Elastic beam theory was used to analyse the theoretic displacement amplification ratio when considering the translational and rotational stiffness of the flexure pivots(Yang et al. 2017; Ye et al. 2010).

This paper presents the design theory and synthesis of compliant micro leverage mechanisms including single-stage and multistage micro levers. The analysis of a single-stage micro leverage mechanism is presented as the building block for the multistage micro leverage mechanisms. A resonant accelerometer with a two-stage micro leverage mechanism is designed and fabricated by a silicon-on-insulator MEMS process run(Su and Yang 2001). Specific analysis is presented in this paper to further understand the characteristics of displacement amplification of bridge-type mechanism. Kinematics theories are used to obtain the average ideal displacement amplification ratio during the deformation process. . Elastic beam theory is adopted to analyse the deformation of the hinges, and a novel formula of theoretical displacement amplification ratio is carried out(Kim, Kim, and Kwaka 2003). This paper presents the design methodology and dynamic modelling of a piezo-driven flexure-based Scott-Russell mechanism for Nano-manipulations. The transient responses of the flexure-based Scott-Russell mechanism to three typical signals are derived based on the Laplace transform method. It is noted that the cycloidal command signal can generate vibration-free motion, and thus improve the dynamic performance of the flexure-based mechanism(M. I. Frecker, Dziedzic, and Haluck 2002).

Compliant mechanism, a joint less mechanism is extensively being used for precision application such as biomedical, micro electro mechanical system (MEMS) and nanotechnology application due to absence of friction and hence, wears, lubrication, backlash issues. Compliant mechanisms are mainly used to enhance or lower the displacement of magnification ratios. In this work a compliant pantograph mechanism is designed and analysed for the linear displacement applications(Patil, Anerao, and Chinchanikar 2018). This paper presents the design, modelling, and experimental testing of a novel piezo-driven XY stage with parallel, decoupled, and compact kinematic structure. The experimental results show that the XY stage has a large amplification ratio of 7.48 and a large workspace range of 150.3 μm × 147.9 μm. In addition, the parasitic motion along the y-axis (x-axis) accounts for 0.94% (0.74%) of the x-axis (y-axis) motion, which indicates that the stage possesses excellent decoupling characteristics (Yang et al. 2017)**.** The present work approaches the experimental validation of compliant mechanism movements. It had studied the movements using four methods: photo capture method, video capture method, optical sensor method and palpation method. The presentation of the four methods, the experimental results and their interpretation are found in this study(Wilcox and Howell 2005)In this paper, a new topology that is a symmetric five bar profile for displacement amplification is proposed, and a compliant mechanical amplifier (CMA) based on the new topology is designed to amplify the stroke of a piezoelectric actuator. The designed CMA is clearly better than the CMA based on the topology of a double symmetric four bar profile. Finally, the design is fine-tuned by examining critical parameters for the proposed CMA in light of a large displacement amplification ratio (Ouyang, Zhang, and Gupta 2005)**.**

In this papertwo methods for handling the multiple output requirements are developed, a combined virtual load method and a weighted sum of objectives method. The problem formulations and numerical solution procedures are discussed and illustrated by design examples(M. Frecker, Kikuchi, and Kota 1999). The present work investigates the finite element analysis of compliant mechanism for plier type device using linear solver in Pre/Post tool available in Siemens NX 12. A computer aided design (CAD) model of the mechanism is recreated through approximate geometry tracing and the models are recorded for optimization. The model parameters are then imported into Pre/Post tool for simulation using the Linear Solver(Ibrahim, Warsame, and Pervaiz 2019). In the study, 'monolithic' compliant slider crank mechanism is proposed. A flexure based mechanism is developed for achieving geometric amplification of input motion. A Pseudo Rigid Body Model (PRBM) has been implemented to correlate the input force and corresponding displacement, for slider crank mechanism. The validation of the geometric model and PRBM has been carried out using finite element analysis (FEA) simulation and results are corroborated with experimental ones(Deshmukh et al. 2014). Analytical equations have previously been specifically developed for two configurations of bridge mechanisms: parallel and rhombic type. The formulations of the new analytical method are simplified and efficient, which help to achieve sufficient estimation and optimization of compliant bridge mechanisms for nano-positioning systems(Wei et al. 2017).

This paper presents the design, development, and testing of a novel three-degree-of- freedom compliant parallel-kinematic active constant-force stage. The active constant-force property enables a large travel and constant driving property, which is enabled by introducing symmetrical bistable flexure hinges (Xiaozhi Zhang and Xu 2019). In this paper, we focus on the continuum topology optimization methods and present a survey of the state-of-the-art design advances in this research area over the past 20 years. The presented overview can be helpful to those engaged in the topology optimization of compliant mechanisms who desire to be appraised of the field's recent state and research tendency (B. Zhu et al. 2020). This paper proposes a novel piezo-driven compliant stage for long travel range with Nano-motion. For long travel range, the piezo-driven compliant stage requires mechanical amplification mechanisms due to the short displacement of its stack-type piezoelectric element. The piezo-driven compliant stage consists of compliant mechanisms for motion guidance and displacement amplification, stack-type piezoelectric elements, and high-precision displacement sensors(Choi, Lee, and Hata 2010). This paper describes the development of a micro gripper mechanism capable of delivering high precision and fidelity manipulation of micro objects. The mechanism adopts a flexurebased concept on its joints to address the inherent nonlinearities associated with the application of conventional rigid hinges. A combination of two modelling techniques namely Pseudo Rigid Body Model (PRBM) and Finite Element Analysis (FEA) was implemented to expedite the prototyping procedure which leads to the establishment of high performance mechanism (Zubir, Shirinzadeh, and Tian 2009).

This paper explores the various advantages of the compliant mechanism and some of the difficulties in the design of the compliant mechanisms, and designing a compliant mechanism for displacement amplification of piezo-electric actuator is developed using a topological optimization approach(Arunkumar and Srinivasan 2006). This paper presents a precision compliant parallel-structure positioner, which is dually driven by six piezoelectric motors and six piezoelectric ceramics. This compliant system has a high load capacity of more than 2 kg because the parallel mechanism with high load capacity is the main architecture. This system can also provide relatively large workspace and high accuracy simultaneously compared with conventional compliant positioner systems because it perfectly integrates two kinds of piezoelectric actuators in one system (Dong, Sun, and Du 2007). The paper focuses on the development of design equations that can accurately predict the behaviour of such stages especially the "lost motion" due to hinge stretching. The development of these equations is based on a static analysis of a general configuration of a single-axis, translational, flexure-hinge type, piezo drivenmicro-positioning stage using amulti-lever structure. The displacement ratio between the input and output motions of one of the levers, plus the stiffness at either end of this lever are obtained based on the analysis(Jouaneh and Yang 2003).

The aim of this paper is to incorporate the flexure hinges that were introduced and modelled by means of their compliances within the previous chapter into various mechanisms, either planar or spatial, in order to derive static (quasi-static) models that can naturally include, develop, and take advantage of the compliance-defined flexures. Such mechanisms that are formed by connecting rigid links and flexure hinges will be called flexure based compliant mechanisms(Lobontiu and Garcia 2003). This paper describes an approach for synthesizing compliant mechanisms that uses topology optimization to meet particular functional needs. Topology optimization techniques are especially useful when the designer does not have a particular compliant mechanism already in mind. This approach can also be used to augment intuition based or experience-based compliant mechanism designs(M. I. Frecker, Dziedzic, and Haluck 2002). In this paper, a force estimation strategy is proposed by comparing the practically measured displacement with the estimated free one without external forces, when subjecting to any given actuation voltages. To have an accurate prediction of the free displacement relating to the actuation voltage, an improved fractional order model is proposed(Z. Zhu et al. 2018).

This paper presents the design theory and synthesis of compliant micro leverage mechanisms including single-stage and multistage micro levers. The analysis of a single-stage micro leverage mechanism is presented as the building block for the multistage micro leverage mechanisms(Su and Yang 2001). Commercial multilayer piezo actuators, in other words, piezo stacks have a limited deformation range of about 10mm per centimetre, and thus a flexure hinge is often used to amplify the small displacement of a piezo stack in many applications A flexure hinge has the strengths of no backlash, not requiring lubrication, and a compact structural design compared with other mechanical motion-transfer devices such as gears or pin joints(Kim, Kim, and Kwaka 2003). The paper formulates an analytical method for displacement and stiffness calculations of planar compliant mechanisms with single-axis flexure hinges. The procedure is based on the strain energy and Castigliano's displacement theorem and produces closed-form equations that incorporate the compliances characterizing any analytically-defined hinge, together with the other geometric and material properties of the compliant mechanism(Lobontiu and Garcia 2003).

This paper presents a precision compliant parallel-structure positioner, which is dually driven by six piezoelectric motors and six piezoelectric ceramics. This compliant system has a high load capacity of more than 2 kg because the parallel mechanism with high load capacity is the main architecture(Dong, Sun, and Du 2007). This paper describes the development of a micro gripper mechanism capable of delivering high precision and fidelity manipulation of micro objects. The mechanism adopts a flexurebased concept on its joints to address the inherent nonlinearities associated with the application of conventional rigid hinges(Zubir, Shirinzadeh, and Tian 2009).

III. RESEARCH GAP ANALYSIS

Although various amplification mechanisms have been used in the current flexure-based stages, limited investigations on the extension of double-rocker mechanisms to X-Y stage design have been implemented. Moreover, most of the reported piezo-driven X-Y stages have a small workspace range, which is not applicable for many multi-scale micro-manipulation tasks. Although a few X-Y stages have an amplification ratio larger than 7, the large cross-axis coupling ratio and huge structural parameters restrict their applications. In addition, for many manipulation tasks such as a scanning application using an atomic force microscope, a high-speed positioning is desirable. Hence, to guarantee an effective and reliable manipulation process,a high resonant frequency of the stage should also be concerned. To summarize, designing aX-Y stage with a large workspace, good decoupling performance, high resonant frequency, andcompact size remains essential but challenging.

A novel flexure-based displacement amplification mechanism is proposed with X-Y stages.Two L-shape lever-type and one bridge-type mechanisms are combined to amplify the outputdisplacement of the PZT with high amplification ratio. The flexure hinges in the proposedmechanism are also loaded in tension and bending which can solve the potential bucklingproblems. The symmetrical distribution of L-shape lever mechanisms can avoid the bendingmoments and lateral forces applied to the PZT, which can effectively protect the PZT.

IV. PROPOSED WORK/SYSTEM

The research work is focused on design and theoretical modelling totally decoupled X-Y stage with compound bridge mechanism for practical micro/nano manipulation tasks. Research work proposes a novel X-Y stage based on the compound bridge mechanism and the parallelogram mechanism is proposed to achieve a large workspace range and a totally decoupled motion of the output platform. The aim of work is to demonstrate theoretically and experimentally novel X-Y stage based on the compound bridge mechanism and the parallelogram mechanism for practical micro/nano manipulation tasks.
The X-Y compliant positioning stage with the Compound bridge-type mechanism has dimension of 150 mm x 150 mm x 12 mm as shown in figure 1. It consists of two Compound bridge-type amplification mechanisms, 16 leaf-type flexible beams and a working platform. In order to amplify the output displacement of the PZT actuators, two PZT actuators are bolted inside of the compound bridge-type amplification mechanism. The whole structure is arranged orthogonally which made the independent motions in X and Y directions achieved. The middle eight leaf-type flexible beams adopt a parallel and symmetrical arrangement to form two double parallelogram mechanisms which respectively connected to the working platform and the bridge-type amplification mechanism. In addition, two leaf-type flexible beams are also arranged in parallel between the output end of the Compound bridge- type amplification mechanism and the base.

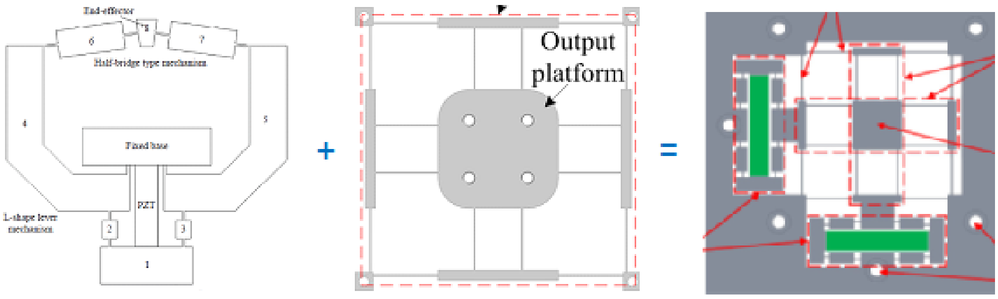


Figure1: A Proposed X-Y stage with Compound Bridge Mechanism

The detailed structural dimensions of X-Ystage is shown in Table 1. The schematic and working principle of flexure-based displacementamplification mechanism is depicted in Fig. 2. The amplification mechanism consistsof two L-shape lever mechanisms and one half-bridge type mechanism. Two L-shape levermechanisms which are arranged in mirror symmetrical distribution are used as the first stageto amplify the displacement of the PZT. The output displacements of the two L-shape levermechanisms are then input to the half-bridge type mechanism. The detailed design parameterof compound bridge type mechanism is shown in table 2.

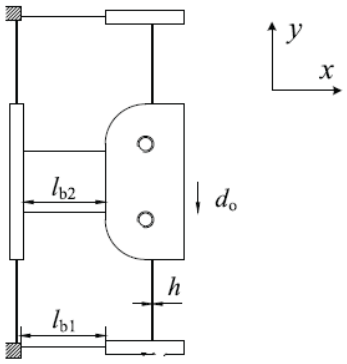


Figure 2: A Structural diagram of X-Y stage

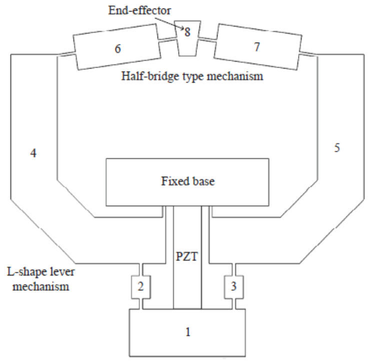


Figure 3: A Structural diagram of compound bridge type mechanism

Table 1: Structural parameters/ dimensions of the X-Y stage

Symbol	Value	Unit
l_{b1}	21.0	mm
l_{b2}	20.2	mm
h	0.4	mm

Table 2: Structural parameters/ dimensions of the Compound Bridge Type Mechanism

Symbol	Value	Unit	Symbol	Value	Unit
l_1	5	mm	l_6	36	mm
l_2	8	mm	b	10	mm
l_3	10	mm	t_1	1.4	mm
l_4	46	mm	t_2	1	mm
l_5	70	mm	α	8	o

The developed CATIA model of X-Y stage with the Compound bridge-type Mechanism isillustrated in figure 3.

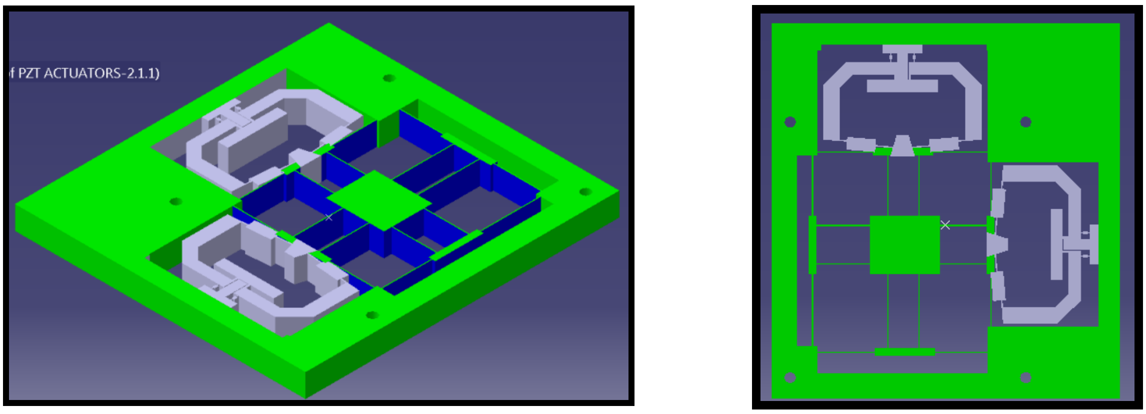


Figure 3: The developed CATIA model of X-Y stage with the Compound bridge-type Mechanism

The experimental configuration of the X-Y stage with the Compound bridge-type Mechanism is in Figure 4. The X-Y stage body the Compound bridge-type Mechanism will manufacture by wire EDM.

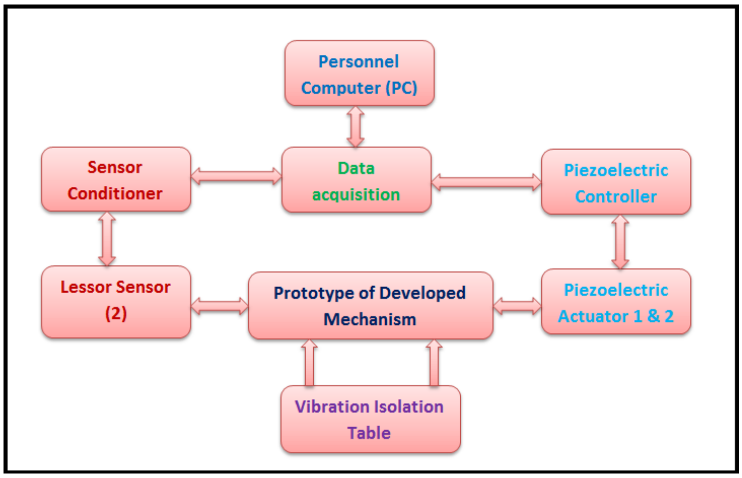
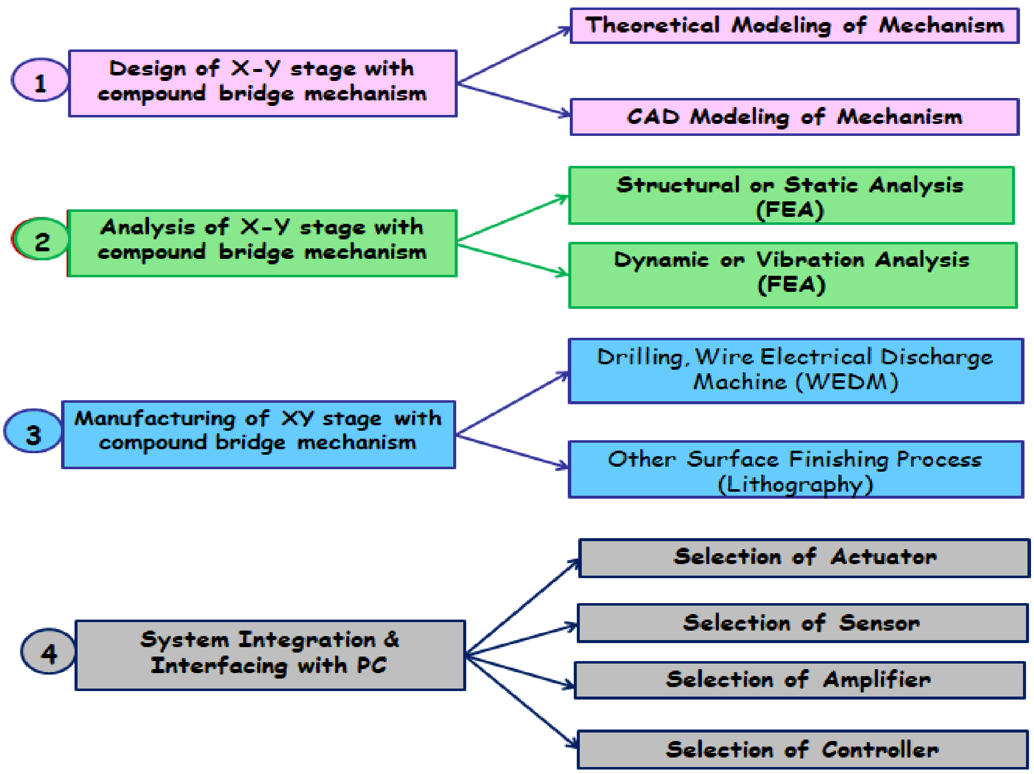


Figure 4: A Proposed Experimental Method for X-Y stage with Compound Bridge Mechanism

The input of Compound bridge-type Mechanism and output displacement of the X-Y stage was measured with a laser displacement sensor. (Model: LK-G30; Keyence Corporation). The laser displacement sensor had a resolution of 50 nm and a measuring range of ± 5 mmto providedrivingvoltage(0-120V)forthePZT,andthenominalstroke,stiffness,andblocking force oftheactuatorare 19± 2 mm (when drivingvoltageis150V), 89.5 N/μm, and 1700 N, respectively.Theclosed-loopcontrolofthePZTactuatorswouldrealizedthroughtheinside position sensor, and the influence of the hysteresis characteristics of the PZT actuator will almost eliminated. The data acquisition systems in combination with an analog output module and an analog input module will be used to provide four channel digital-to-analog (D/A) andanalog-todigital (A/D) modules for voltage output and data acquisition. Theexperimentalsystemwillperformed usingaPCwithLab-VIEWsoftware.

V. PROPOSED METHODOLOGY

The proposed, methodology for X-Y stage with compound bridge mechanism is as shown in figure 5. The methodology consist of six steps such as design of X-Y stage with compound bridge mechanism, analysis of X-Y stage with compound bridge mechanism, manufacturing of XY stage with compound bridge mechanism, system integration & interfacing with PC, system modeling, and performance analysis.



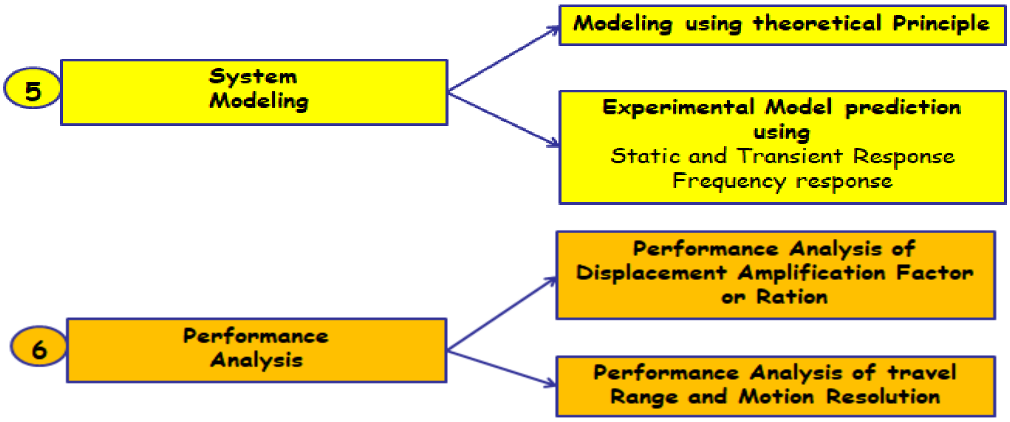


Figure 5: A Proposed Methodology for X-Y stage with Compound Bridge Mechanism

In design of X-Y stage with compound bridge mechanism, we will carry out theoretical modeling of mechanism and CAD modeling of mechanism. We will carry out Static Structural and dynamic analysis in analysis of X-Y stage with compound bridge mechanism. We will manufacture XY stage with compound bridge mechanism wire electric discharge machine, drilling machine and other surface finishing processes. We will select different sensors, actuator, amplifier and controller required for system integration and interfacing with PC systems. We will carry out system modeling based on theoretical principle and experimental model prediction. The performance analysis of different parameters like amplification ration, travel range and motion resolution will be carried out.

VI. CONCLUSION

The recent emerging trends in bridge-type, lever-type, and compound bridge-type displacement amplification of compliant mechanismshave reviewed in literature review.The gap analysis of different types of displacement amplification of compliant mechanismshas reviewed. We have proposed a design and theoretical modeling totally decoupled X-Y stage with compound bridge mechanism for practical micro/nano manipulation tasks. We have proposed methodology and experimental method for X-Y stage with compound bridge mechanism.The amplification ration can be improved by two L-shape lever mechanisms and one half-bridge type mechanism. Two L-shape lever mechanisms which are arranged in mirror symmetrical distributioncan be used as the first stage to amplify the displacement of the PZT.

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