Design and Development of High-Precision Scanning Flexural Mechanism Using PID

Shrishail Sollapur, Tarang Shinde, Satish Raut, Abhijit Atpadkar, Prashant Nimbalkar, and Mahesh Rathod

Abstract Rigid linkage mechanism has narrow accuracy and repeatability. The mechanism offers motion between the joints. A different approach has been made to develop S-type flexure mechanism for high-precision systems. This paper presents the flexural mechanism design with the building blocks. This S-shaped mechanism is developed using a numerical approach to get linear motion. The mechanism is incorporated with a voice coil motor (VCM), optical encoder, and dSPACE 1104 R&D microcontroller board. The S-shaped mechanism is integrated, designed, and developed with system integration and identification of the system. The proportional–internal–derivative (PID) controls the implementation of the mechanism. The system identification is done and performance is evaluated for the natural frequency, damping factor and also evaluated by experimentation for the same. The transfer function is used to build the control system and parameters are tuned with the help of PID. PID implementation in real time imparts the accuracy for positioning at a high scanning speed of 0.5 mm/s.

Keywords Flexure mechanism · PID control · DFM · VCM · dSPACE1104

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A. Sachdeva et al. (eds.), *Recent Advances in Operations Management and Optimization*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-99-7445-0_4

1 Introduction

The advances in the area of manufacturing, electronics, and materials have increased the precision technology in the present scenario [1, 3]. Precision manipulators with higher economic and performance features have enhanced small-scale technologies. In modern technology, nano- and micro-positioning stages are essential [1, 4]. Their usages are in applications like micromachining, confocal microscope, and scanning probe. A variety of XY mechanisms are developed in the wide area of the screw-type precision ball recirculation mechanisms. The previously developed XY mechanism has restrictions like limited range performance characteristics and accuracy. The control system is developed to obtain the required performance. A new method to build mechanisms such as flexural mechanisms with high-speed precision applications was developed [5–7]. Flexures are developed on elasticity of material for operation [8–10]. Motions are developed because of anamorphisms at the molecule level with two characteristics accuracy and high-speed applications. The advantage of the flexure mechanism is the smooth motion without friction and backlash. The flexure mechanisms are simple in construction (monolithic) and assembly. They have repeatability and also are predictable [11–13]. This work attempts to build and analyze motion with a large motion range. The degrees of freedom are obtained by the flexure mechanism. These are grouped into two types beams and hinges. The hinges are used for rotational motion and beams are used for planar motions.

2 Flexure Mechanism

Flexure mechanism provides mobility between the stage and fixed support. The motion is given by the interfacing element as explained in Fig. 1.

The DFM gives consideration merit over the conventional motion in characteristics as no friction loss and no lubrication is required. The interface element is replaced with beams eliminating friction, backlash, and high repeatability. The S-shaped flexure mechanism is shown in Fig. 2.

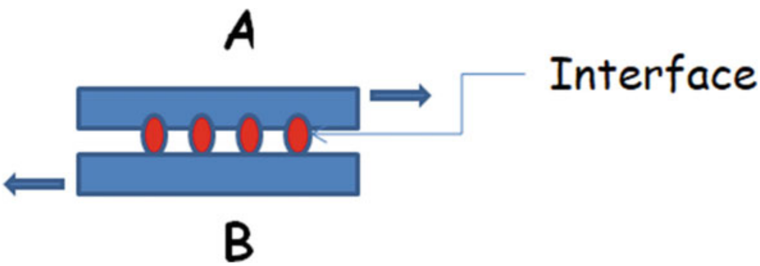


Fig. 1 Interfacing element [2]

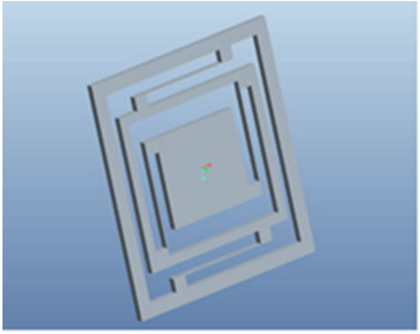


Fig. 2 S-shaped flexure mechanism

3 Analysis of Flexure Mechanism

The analysis of the flexure mechanism indicates that it proves null parasitic error and linear motion.

The deflection of S-shaped mechanism is given by Eq. 1.

$$\delta = \frac{\mathrm{F}L^3}{12\mathrm{EI}} \tag{1}$$

where

L = Flexure beam length in mm

F = Applied force in N

E = Beam material elastic modulus in N/mm^2

I = Mass moment of inertia mm^4

Rotation is given in Eq. 2,

$$\theta = t^2\left(\frac{1}{b1^2} + \frac{1}{b2^2}\right) \times \frac{\delta}{L} \tag{2}$$

where

t = Beam thickness in mm

b = Beam width in mm

Parasitic Error,

The load is applied to the mechanism of 1 N which produces a deflection of 0.4048 mm as shown in Fig. 3. The stresses are well within the range as shown in Fig. 4

The flexure mechanism is built and developed using S-shaped double flexure mechanism. The experimental setup is shown in Fig. 5.

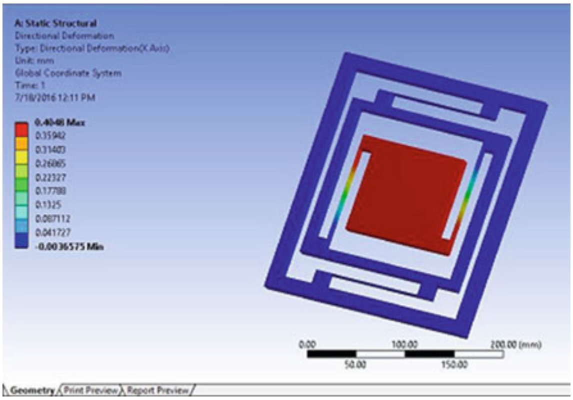


Fig. 3 Deflection of flexure mechanism

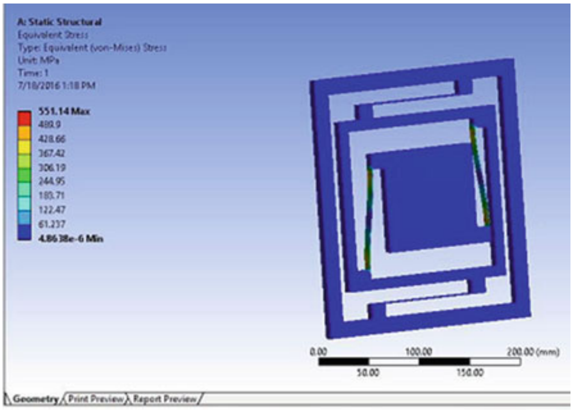


Fig. 4 Stress developed in flexure mechanism

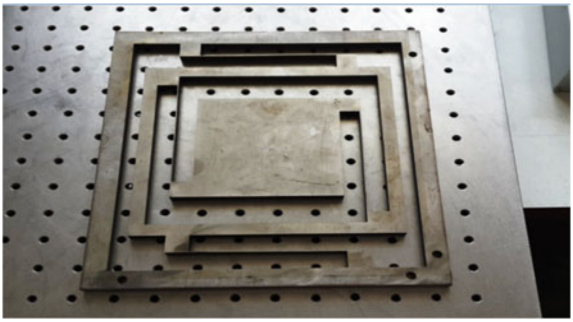


Fig. 5 Actual model of flexure mechanism

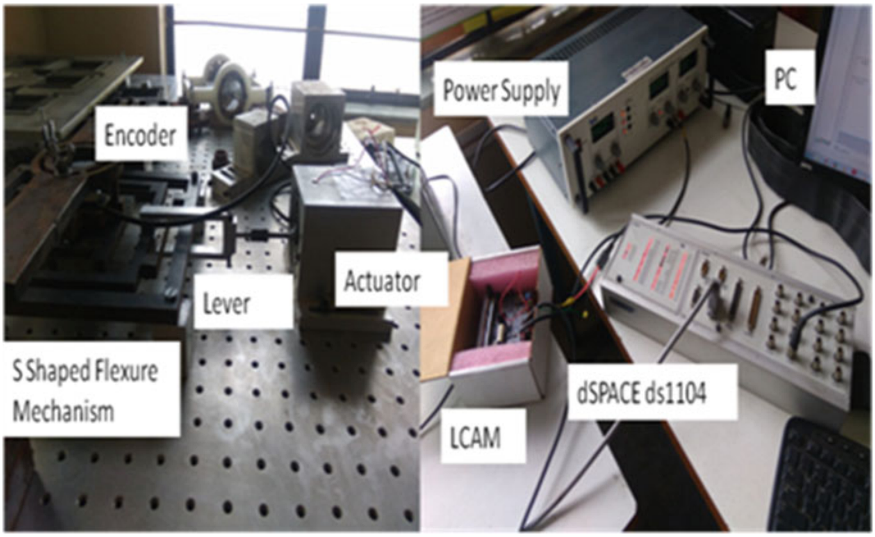


Fig. 6 Experimental setup

4 Mechatronics Integration of the System

The flexure mechanism is integrated with dSPACE DS 1104 microcontroller and actuator. The system is actuated by a voice coil motor (VCM) with applied force converting to current and voltage. The given current is low; therefore, it is amplified using LCAM. Simulink MATLAB file is prepared to compare the signal obtained from the encoder with a reference signal to evaluate the error signal. The motion head is moved by a given force. The encoder is mounted in the system and motion is detected. The values gained from the optical encoder are sent to dSPACE and saved in a mat file.

The overall mechatronics integration setup is shown in Fig. 6.

The different parameters like stiffness, damping factor are evaluated with dSPACE DS1104. The system natural is calculated from the setup.

5 Stiffness of the System

Stiffness is determined by the experimental force–deflection curve. The MATLAB code is built to control and actuate the voice coil motor. The position of the motion head is read by optical encode. The stiffness is evaluated for to and fro motion and obtained as shown in Fig. 7.

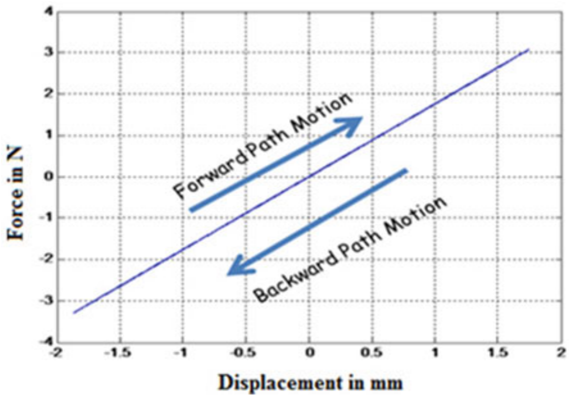


Fig. 7 Force–deflection curve

6 Damping Factor

As the initial state abruptly shifts from zero to one in relation to time, the system's temporal behaviour is defined. The amplitude value is set to zero to determine how the system responds to abrupt input for substantial deviations over a longer period of time. The output must stabilize at a steady state in order to get the steady state of the system's step response.

Experimental results are plotted on the graph (Fig. 8). From Fig. 8, both the damping factor and damped natural frequency are calculated. The motion head is given the free to and fro movement, finally coming to rest position.

The damping factor is evaluated from the logarithmic decrement and is given by

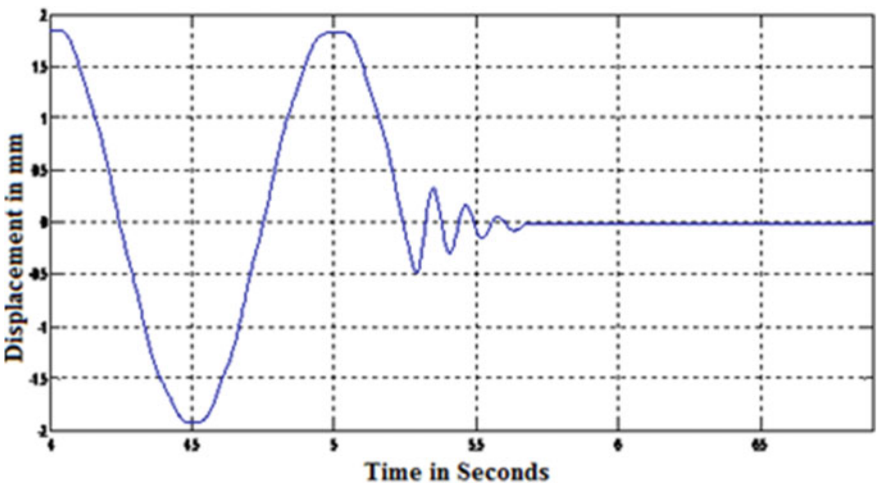


Fig. 8 The plot of displacement versus time

$$\delta = \frac{1}{n}\left[\log\left(\frac{X_0}{X_n}\right)\right]. \tag{3}$$

where

X_0 = First peak amplitude

X_n = Amplitude to peak at n periods

n = Successive number of peaks
Damping factor

$$\xi = \frac{\delta}{\sqrt{4\pi^2 - \delta^2}} \tag{4}$$

From the experimentation, the obtained values are

$$\delta = 1.1972, \xi = 0.19402$$

7 Identification of the System

An identification system is required to build the transfer function of the S-shaped flexure mechanism, to control the input signal to the actuator and positioning of the motion head. MATLAB code is built for the estimation of frequency response with an amplitude of 1 mm and is given a frequency response graph for the system to build. The peak frequency of 13.52 rad/s is obtained. The transfer function is developed using the experimental data of the system. The transfer function of the present model is

$$G(S) = \frac{1}{0.00963s^2 + 0.05055s + 1.762} \tag{5}$$

8 PID Implementation

The PID system feedback controller is adopted in industrial applications as shown in Fig. 9. The change between the variable being measured and the set point is evaluated by the PID controller using an error value. The PID controller uses influence variables to modify the process in an effort to decrease error. The PID controller is composed of three parameters the proportional, integral and derivatives values represented by P, I, D.

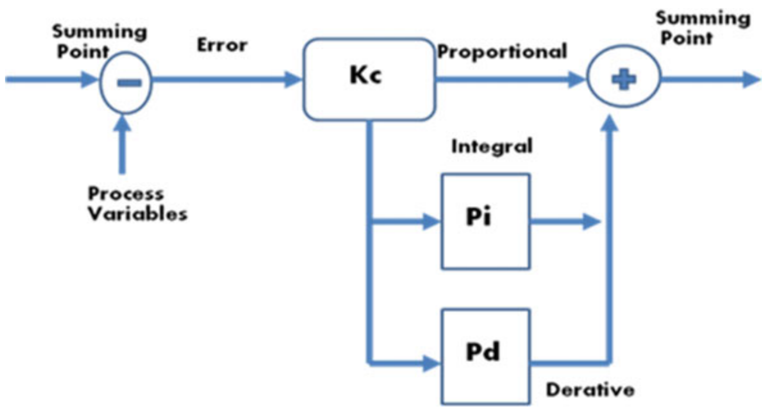
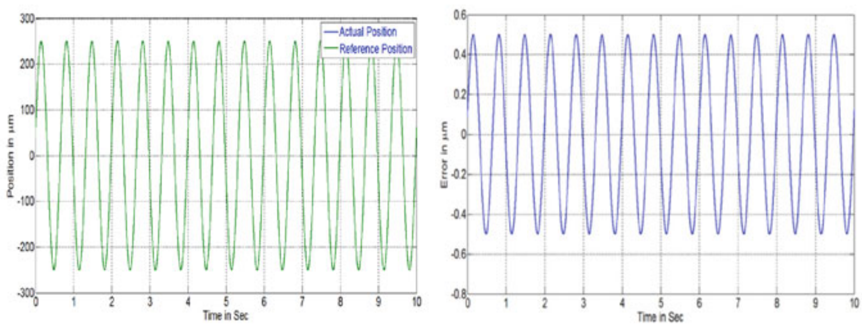


Fig. 9 PID controller

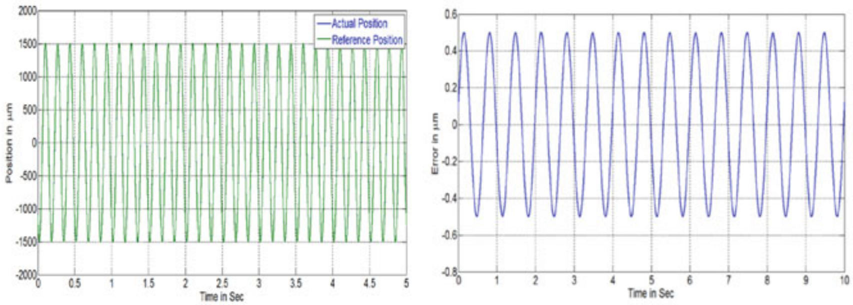
The proportional integral derivative controller is tuned using the Ziegler–Nichols approach. John G. Ziegler and Nathaniel B. Nichols constructed it. The system is implemented by setting the derivative (D) and integral (I) values to zero. The proportional increases as (P) from zero until it approaches the ultimate gain (‘U’) and oscillates with the same amplitude. The controller being utilized will determine the ultimate gain (U) and time cycle (T) values, which are used to construct the P, I, and D gains [7–9].

From Fig. 10, PID control result in real time on S-shaped flexure mechanism at lower velocity (0.5 Hz frequency with Speed = 300 μm/s) and lesser range of scan (Amplitude = 260 μm) for motion stage has been indicated. The accuracy of displacement is less than 0.5 μm.



(a): Comparing actual position with required reference (b): Real time positioning error positioning

Fig. 10 PID implementation on S-shaped flexure mechanism at 260 μm amplitude with 0.5 Hz frequency



(a): Comparing actual position with required reference (b): Real time positioning error

positioning

Fig. 11 PID implementation on S-shaped flexure mechanism at 1500 µm amplitude and 3 Hz frequency

PID control results in real time on S-Shaped flexure mechanism are comparatively higher speed (3 Hz frequency with speed = 1000 µm/s) and range of scan (Amplitude = 1500 µm) of motion stage (Fig. 11). The accuracy of deflection is less than 3 µm.

9 Conclusion

The S-shaped flexure mechanism is designed for precision applications. It is experimentally built and developed with dSPACE DS1104 microcontroller. Both static and dynamic parameters are characterized by experimental and theoretical agreed. PID control is implemented on S-shaped flexure mechanism using the dSPACE DS1104 Control desk environment. 0.5 µm of precision is reached at a slower scanning speed thanks to the Zeigler–Nicholas tuning algorithm being used to adjust the PID settings. The positioning accuracy of 3 µm is obtained at a higher speed of scanning. The least value of error and rejection is being obtained to track at various frequencies. For the regulation, LQR control can be used and LQI control accomplishes good distribution during rejection. The LQI method can adopt to track feed-forward control with other strategies on setup.

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