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Precision polishing platform based on a flexure-based constant force mechanism

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Abstract

This work presents a precision polishing platform inspired by constant force mechanisms, aimed at enhancing precision and stability in polishing processes. Traditional platforms often struggle with maintaining consistent force application, leading to variations in surface finish and dimensional accuracy. Our solution addresses this challenge by providing a constant reaction force, ensuring constant polishing force distribution even amidst external force fluctuations on the workpiece. Notably, the platform's constant force region exhibits significant large deformation relative to its own geometric size, amplifying its ability to sustain consistent pressure across the polishing surface. Additionally, the platform offers simplicity in structure and ease of manufacture, facilitating cost-effective production and widespread adoption. Its adaptability enables accommodation of diverse workpiece types under specific conditions, adding versatility and flexibility to various polishing applications. Leveraging an energy method based on the smooth curvature model, the constant force mechanism ensures reliable and efficient operation. The optimal inclined angle is 58.7550 degrees with a beam length of 100 mm. The constant force region extends up to 28.8% of the beam's length (28.8 mm). With potential applications in optics, semiconductors, and medical devices, this platform provides an alternative solution for industries requiring precise surface finishing.

Keywords: Manufacturing, Polishing, Precision

1. Introduction

Precision polishing platforms hold a pivotal position across various industries, particularly in fields like optics and semiconductors, where they wield a direct influence on the ultimate quality of end products. Previous research has emphasized the significance of delving into polishing technologies [1-4]. The innovative concept of flexural constant force mechanisms emerges as an alternative approach to enhance the performance of these precision polishing platforms.

Flexural mechanisms offer unique advantages in precision engineering due to their ability to transmit precise motion and force through the predictable deformation of flexural elements, such as beams or flexures [5]. A novel large XY parallel manipulator based on flexural beams was proposed in [6], which is utilized for high-precision motion stages. The application of flexural beams eliminates the need for complex assembly mechanisms, reduces lubrication requirements, and minimizes wear. By leveraging flexural mechanisms, researchers aim to streamline the design and manufacturing process of vibration isolators while maintaining or improving performance. Prior research has convincingly showcased the successful implementation and efficacy of constant force mechanisms within precision polishing platforms. A polishing force control system is developed in [7] to improve the polishing stability, which achieved constant-force polishing through dynamically control the load. Besides, a polishing end-effector is proposed in [8], which achieves regulating the contact force passively. In addition, a parallel polishing machine is proposed in [9], which achieves higher polishing precision. Another polishing platform based on constant-force mechanism is introduced in [10], which addressed the challenge of controlling constant force in industrial deburring operations. The previous mentioned polishing platforms enable the attainment of precise control over the applied force during the polishing process, culminating in elevated surface quality and heightened processing accuracy.

The precision polishing platform delineated in this study possesses several notable advantages: Firstly, it exhibits a considerable deformation range relative to its geometric dimensions. Secondly, the consistent application of force to the workpiece ensures the maintenance of high precision during the polishing process. Thirdly, its structural simplicity facilitates ease of manufacture. Lastly, the platform's adaptability and passive provision of constant force support obviate the reliance for force sensors or closed-loop control systems.

Flexural constant force mechanisms showcase ongoing technological advancements and hold potential for optimizing precision polishing platforms. As technology evolves, these platforms are set to play a more indispensable role, offering new opportunities and challenges in related fields. The synergy between technological innovation and platform adaptability creates a landscape, promising novel opportunities for advancement.

The structure of this paper is as follows: In Section 2, the design of the constant force polishing platform is presented. Section 3 discusses the energy method utilized for modeling large deformation flexural beams, along with the optimization objective. The final section provides a summary of the content.

2. Design of a constant force polishing platform

Our constant force polishing platform, inspired by constant force mechanisms, provides an innovative solution to challenges posed by traditional fixed or spring-supported platforms. Unlike conventional approaches requiring meticulous force control during polishing, our design ensures precision by delivering a consistent reaction force within the constant force realm. This stability allows our platform to maintain a reliable polishing force, even amidst external force fluctuations on the workpiece, enhancing polishing effectiveness for consistent and precise workpiece processing.

Moreover, the structure of our platform is simple and easy to manufacture, allowing for cost-effective production and widespread adoption. Its adaptive nature enables it to accommodate different types of workpieces under certain conditions, providing versatility and flexibility in various polishing applications. This adaptability not only enhances the platform's usability but also increases its value proposition for industries seeking tailored solutions for precise surface polishing.

The working principle of proposed precision polishing platform can be found in Figure 1.

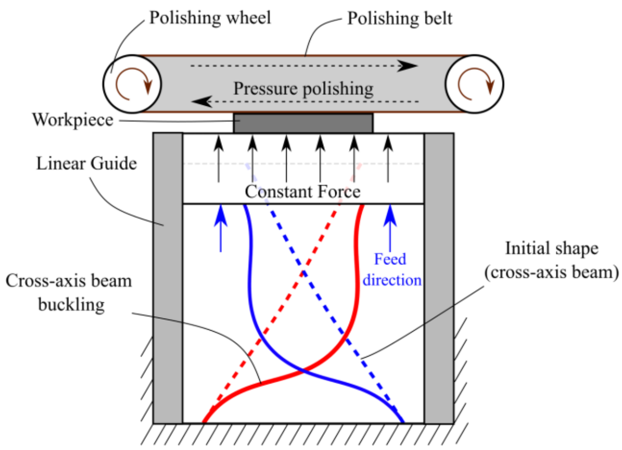

Figure 1. Working principle of precision polishing platform

The precision polishing platform can be used to polish the surfaces of a variety of materials, including metal, plastic, and glass. The proposed precision polishing platform operates by moving the polishing belt past the surface of the workpiece. The polishing wheel rotates and the polishing belt abrades the surface of the workpiece. The constant-force support platform ensures that the workpiece remains in constant-force contact with the polishing wheel at all times and thus ensures high polishing precision. The polishing platform consists of a constant-force support platform and a pressure polishing system.

Constant-force support platform: The constant force mechanism is a single-degree-of-freedom (DOF) mechanism that moves vertically. This mechanism is composed of a pair of cross-axis inclined compliant beams. The flexural beam with initial shape and buckling shape can be seen in Fig.1. Besides, a linear guide is fixed to the ground to ensure the platform moves along vertical direction as a single DOF mechanism. The platform is compact due to the cross-axis design based on the position-space method. By utilizing this flexural mechanism as the support of the polishing platform, the platform can achieve constant-force support within a specific range of movement.

Pressure polishing system: The pressure polishing system relies on removing materials from the surface using abrasives, resulting in a smooth, polished surface. A polishing belt is affixed to the polishing wheel. As the polishing wheel rotates, the rotational movement is converted to linear movement by the polishing belt. Through the relative motion between the workpiece's surface and the polishing belt, the workpiece is polished as required.

The polishing process primarily relies on pressure polishing, where pressure is applied to the polishing surface to enhance abrasion and eliminate surface defects. A polishing belt is mounted on two rotating wheels, allowing it to glide over the polishing surface. By utilizing four flexural beams on the moving platform, a constant force is exerted on the workpiece, ensuring consistent pressure on the polishing surface. This results in a uniform distribution of force within the constant force region, maintaining its stability throughout the process.

For the proposed precision polishing platform, any workpiece with a thickness smaller than that of the constant force region can undergo polishing. This constraint ensures adequate contact between the polishing belt and the workpiece. The polishing process necessitates no fixture adjustments and can passively provide constant force support. Consequently, it is also deemed adaptable to workpieces of various heights.

The inspiration for constant force polishing platform stems from the need for enhanced precision and stability in polishing processes, particularly in industries where surface quality is paramount. Traditional polishing methods often struggle to maintain consistent force application, leading to variations in surface finish and dimensional accuracy. With our platform, we aim to overcome these limitations by ensuring a constant polishing force throughout the process. This not only improves the overall quality of the polished surfaces but also enhances the efficiency and reliability of the polishing operation, leading to reduced scrap rates and increased productivity.

In addition to its immediate applications in precision polishing, our constant force polishing platform holds promise for advancements in various fields requiring controlled material removal and surface refinement. By providing a stable and predictable polishing force, our platform opens doors for new possibilities in manufacturing processes, such as optics, semiconductors, and medical devices. Furthermore, the adaptability of our platform allows for customization to suit specific industry requirements, offering a versatile solution for a wide range of polishing applications.

3. Flexural constant force mechanism

This section introduces the modelling process of the constant force mechanism, highlighting the advantageous features of our modelling approach. Our method brings notable benefits, particularly in the modelling of large deformation flexural beams. It demonstrates a high level of efficacy in accurately capturing the intricate nonlinear behaviour of such beams.

3.1. Modelling methodology: SCME method

Our previous work introduces the energy method based on the smooth curvature model (SCME method), which aims to effectively model the complex nonlinear post-buckling behavior of inclined flexural beams. This method is grounded in the principle of minimum strain energy, implying that the equilibrium configuration corresponds to the minimum total strain energy. To accurately capture the bending strain energy of large deformation beams, the high-order smooth curvature model is adopted. The Lagrange multiplier method is then utilized to determine the minimum strain energy and corresponding tip loads simultaneously. Additionally, the SCME method allows for determining the deformation shape and maximum stress using the smooth curvature model. Notably, the proposed SCME method is capable of modelling flexural beams with inclined angles ranging from 0 to 90 degrees. The accuracy of the SCME method has been validated through finite element analysis and experimental tests. In the SCME method, the approximated curvature of deflected beam is expressed in Eq. (1):

$$\omega(\boldsymbol{\alpha}, s) \approx \frac{1}{L} \sum_{n=0}^{N} \alpha_n \varphi_n(s) \tag{1}$$

where $\boldsymbol{\alpha} = (\alpha_0, \alpha_1, \alpha_2, \cdots, \alpha_N)^T$ is a vector that contains the generalized coefficients an $\varphi_n(s)$ represent the shifted Legendre polynomials. Based on the equation (3.1), the expression of bending strain energy can be formulated using Eq. (2):

$$U_b = \frac{1}{2} \int_0^L EI\omega(\alpha, s)^2\, ds \tag{2}$$

Simultaneously, the beam tip position and orientation can be determined through integration from $s = 0$ to $s = L$. The expressions for the beam tip position and orientation are provided in equations (3-5):

$$\varphi_{tip}(\boldsymbol{\alpha}) = \varphi(\boldsymbol{\alpha}, L) = \alpha_0 \tag{3}$$

$$x_{tip}(\alpha) = \int_0^L \cos(\varphi(\boldsymbol{\alpha}, s)) \tag{4}$$

$$y_{tip}(\alpha) = \int_0^L \sin(\varphi(\boldsymbol{\alpha}, s)) \tag{5}$$

To determine the minimum bending strain energy, the Lagrange multiplier method is applied to minimize the strain energy under the equation constraint, as expressed in Eq.(6):

$$\mathcal{L}(\boldsymbol{\alpha}, \boldsymbol{\lambda}) = U_b(\boldsymbol{\alpha}) + [\lambda_1 \quad \lambda_2 \quad \lambda_3] \begin{bmatrix} x_g - x_{tip} \\ y_g - y_{tip} \\ \varphi_g - \varphi_{tip} \end{bmatrix} \tag{6}$$

Where the x_g, y_g and φ_g are given trajectory points. By utilizing the SCME method, we can derive the corresponding force at beam tip as:

$$F_x = -\lambda_1 \cos\theta + \lambda_2 \sin\theta \tag{7}$$

$$F_y = -\lambda_1 \sin\theta - \lambda_2 \cos\theta \tag{8}$$

Where θ is the inclined angle of complaint beam. In addition, the SCME method can also derive the maximum stress during the deformation process. The stress evaluation considers the axial stress since the axial stress contribute additionally and is not negligible. Hence the stress is evaluated as:

$$\sigma_{\max} = \sigma_{\text{bending}} + \sigma_{\text{axial}}$$

$$= \frac{Et\omega(s)}{2} + \frac{\sqrt{F_x^2 + F_y^2} \cos\left(\varphi_{\text{tip}}(\alpha) - \varphi_s(\alpha)\right)}{Wt} \tag{9}$$

The above process briefly reviews the modeling process of the constant force mechanism, and we intend to incorporate the SCME method into the optimization algorithm.

3.2. Optimization strategy

Optimization strategies can be applied to determine the constant force mechanism with the longest constant force region, denoted as Ω. This could help to optimize the performance of the precision polishing platform. This region Ω is defined as follows: the forces within Ω fluctuate above and below the buckling force by no more than a specific percentage ξ of the buckling force. Once the force exceeds the predefined constant force range, it marks the end of the constant force region. Therefore, all the forces within the constant force region can be expressed as:

$$\left|F_y^{\Omega} - F_{bl}\right| \leq \xi \cdot F_{bl} \tag{10}$$

where F_y^{Ω} represents the force in the constant force region, F_{bl} is the buckling force, ξ is the tolerance coefficient. The optimization objective is:

$$Maxmize: \ \Omega(\theta)$$

$$\text{Subject to: } \sigma_{max} \leq \sigma_{yield}$$
$$50° \leq \theta \leq 80°$$

The optimization process can be implemented in MATLAB. The suggested optimization algorithm is the genetic algorithm. Genetic algorithms are heuristic global optimization techniques inspired by the principles of natural selection and genetics. They involve evolving solutions to complex problems over successive generations, utilizing techniques such as selection, crossover, and mutation to search for optimal or near-optimal solutions.

3.3. Case study

In this section, we will undertake a case study utilizing the proposed modeling and optimization method. The case study will focus on examining a small-scale constant force mechanism. Details regarding the mechanical properties and determined geometric dimensions can be referenced in Table 1 and Table 2.

Table 1. Mechanical properties of flexural beams.

Material	Tough PLA
Young's Modulus	2800 MPa
Yield Strength	45 MPa
Poisson Ratio	0.35

Table 2. Determined geometric dimensions.

Beam length	100 mm
Beam Thickness	0.5 mm

The optimization process has been conducted. The tolerance coefficient ξ is selected to be 2%. The optimal result obtained is:

$$\theta = 58.7550°$$

$$\sigma_{\max} = 44.9470\ MPa \ \leq \ \sigma_{yield}$$

$$\Omega = [0\, , 28.8mm]$$

According to the optimal outcome, the proposed constant force mechanism has a total height of 51.87 mm, with the constant force region measuring 28.8 mm. This optimal constant force region occupies 55.5% of the structure's height, highlighting its characteristic of being a large constant force region. The force-displacement relationship based on the optimal result can be referred to Figure 2.

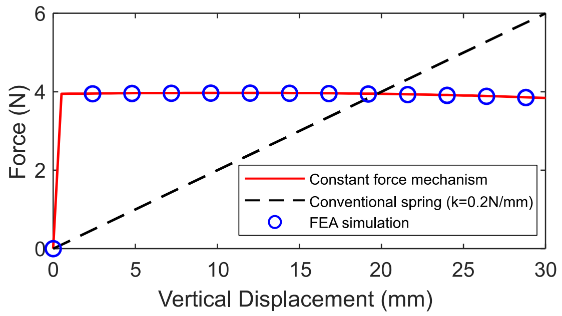

Figure 2. The force-displacement relationship of constant force mechanism and spring. The modeling result is verified using FEA simulation, which is conducted in Strand7.

In Figure 2, a comparison is presented between the force-displacement relationships of a constant force mechanism and a conventional spring with a stiffness of 0.2 N/mm. It is evident that as the vertical displacement increases, the reaction force applied to the workpiece surface increases linearly when a spring is utilized as a feed mechanism. Conversely, with the implementation of the proposed constant force mechanism, the force remains consistently around a specific value. This stability enhances the polishing process by mitigating the impact of fluctuations in force.

4. Conclusion

In conclusion, this study introduces a precision polishing platform with a flexural constant force mechanism, ensuring a constant polishing force for improved precision. The modelling process, utilizing the SCME method, effectively captures the nonlinear behaviour of large deformation flexural beams. Future research could involve exploring the modelling and analysis of shear forces on the platform and conducting experimental validations to assess its stability. These efforts would contribute to advancing our understanding and optimizing the design of precision polishing platforms.

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