Design and Experimental Testing of a Bellows-Based Pneumatic Force Actuator Postprint

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Date: 2018-05-15T15:59:19+00:00

Abstract

In response to the design requirements and specifications for the axial support of the primary mirror of the 2m ring solar telescope, a pneumatic force actuator based on a bellows was developed and comprehensive experimental testing was conducted. This pneumatic force actuator employs a retractable high-strength high-elasticity metal bellows as its core component, uses linear bearings as the guiding mechanism, and integrates a unidirectional pressure sensor as the force feedback element, while also considering the convenience of installation and adjustment processes in the design. Testing shows that the unidirectional output force of this pneumatic force actuator reaches 200N, the linearity error between input air pressure and output force is less than 2%, force resolution is less than 0.23N, and closed-loop force accuracy is better than $±$0.3N. Test results verify that this pneumatic force actuator has a simple principle and structure, good installation and maintenance processes, meets the design specifications, and can satisfy the requirements for axial support of the primary mirror of the 2m ring solar telescope. The development work lays a foundation for improving design details of pneumatic force actuators and optimizing processes for primary mirror support systems, and can provide a reference for engineering applications in other precision optical mirror support systems.

Full Text

Design and Test of a Bellows-Based Pneumatic Force Actuator

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Abstract

To meet the design requirements and specifications for the axial support of the primary mirror of the 2-meter Ring Solar Telescope (RST), a bellows-based pneumatic force actuator (BPFA) was developed and comprehensively tested. The actuator employs a high-strength, high-elasticity metal bellows as its core component, utilizes a linear bearing as the guiding mechanism, and integrates a unidirectional pressure sensor for force feedback. The design also considers the convenience of installation and adjustment processes. Testing demonstrates that the BPFA achieves a unidirectional output force of 200 N with a linearity error between input pressure and output force of less than 2%, a force resolution below 0.23 N, and a closed-loop force accuracy better than $±$0.3 N. The results verify that the pneumatic force actuator features a simple principle and structure, good installation and maintenance procedures, and meets the design specifications for the axial support of the 2-meter RST primary mirror. This development establishes a foundation for improving the detailed design of pneumatic force actuators and optimizing the manufacturing processes of primary mirror support systems, providing a valuable reference for engineering applications in other precision optical mirror support systems.

Keywords: solar telescope; axial support; bellows; force actuator; pneumatic force actuator

Introduction

The 2-meter Ring Solar Telescope at Yunnan Observatories features a primary mirror with an outer diameter of 2020 mm, edge thickness of 150 mm, and central aperture diameter of 1300 mm [1-4]. The axial support system adopts a semi-active configuration [5], employing 36 pneumatic force actuators as the main axial support mechanism, supplemented by three displacement actuators for adjusting and positioning the axial location and tilt orientation of the primary mirror [6-7] without providing support force. Preliminary optimization of the 2-meter ring primary mirror support system revealed that when the mirror is in a horizontal orientation, each axial support point bears a maximum load of 161.86 N, achieving a reflective surface accuracy of 3 nm RMS. To ensure mirror surface accuracy of 10 nm RMS, the uniform random error in axial support force must remain within (-0.5, +0.5) N [8].

These optimization results provided specific design criteria for the axial support force actuators. Following actuator scheme analysis, a pneumatic force actuator was selected as the core component for primary mirror axial support [9]. A detailed design was developed using a bellows as the key functional element, comprehensive testing was completed, and a simplified 9-point primary mirror axial support prototype system was constructed using this pneumatic force actuator. Test results demonstrate that the actuator achieves the design specifications for closed-loop output force accuracy, features a simple structure with excellent manufacturability, and allows for convenient installation and removal from the back of the mirror cell with easy height adjustment, exhibiting good installation and maintenance characteristics.

1. Force Actuator Scheme Analysis

Currently, commonly used force actuators for astronomical telescope mirrors and other precision optical mirrors include electromechanical, piezoelectric, hydraulic, and pneumatic types. Electromechanical actuators employ stepper motors combined with lead screws to achieve precise linear displacement output, offering simple structure and high precision but requiring high lubrication standards for mechanical components and incurring substantial maintenance costs. Piezoelectric actuators utilize the inverse piezoelectric effect of smart ceramic materials for precise displacement output, converting displacement to force through spring elements, and feature high precision and high frequency response, but are relatively expensive. Hydraulic actuators are also costly, with complex leak-proofing processes, and leakage can cause difficult-to-remediate contamination of instruments and the environment. Pneumatic force actuators offer simple principles and structure, stable performance, low cost, and system cleanliness, along with excellent reliability and maintainability. Given the extremely slow support state changes and minimal dynamic performance requirements of the 2-meter ring solar telescope primary mirror support system, a pneumatic force actuator was selected as the core unit for primary mirror axial support.

2. Design and Implementation

2.1 Design Specifications and Process Requirements

The 2-meter ring mirror presents different support performance requirements compared to traditional full-aperture mirrors or mirrors with relatively small central apertures, demanding greater flexibility and sensitivity from the support system. Preliminary design and analysis of the primary mirror support system indicated a maximum theoretical support force of 161.86 N per axial support point; therefore, the actuator maximum output force was specified as no less than 200 N. To achieve 10 nm RMS mirror surface accuracy, axial support force uniform random error must remain within (-0.5, +0.5) N, requiring actuator output force error not exceeding $±$0.5 N. The output force resolution should be no greater than one-third of this error, establishing a design requirement of no more than 0.3 N. The design must also accommodate good installation procedures and convenient height adjustment, requiring that actuators be installable and removable from the back of the mirror cell. Due to variations in mirror cell mounting surface heights and actuator length tolerances, an adjustable height range of $±$2 mm is required.

2.2 Design Configuration

Based on the technical requirements of the 2-meter Ring Solar Telescope, a pneumatic force actuator with integrated pressure feedback was designed. As shown in Figure 1: see original paper, to overcome the inherent friction and hysteresis limitations of traditional cylinder-piston structures, a high-strength, high-elasticity metal bellows was adopted as the core expandable pressure-sealed output device (referred to as an elastic cylinder), with a linear bearing serving as the axial guiding mechanism. To minimize overall actuator height and achieve a compact design, the linear guide bearing is fixed to the lower side of the upper end cap from below. Since the 2-meter RST primary mirror uses only pneumatic force actuators for axial support operating exclusively in compression, a unidirectional pressure sensor was employed as the force feedback element. The design also considers convenience in manufacturing, installation, and maintenance—the pneumatic force actuator passes through corresponding mounting holes from below the mirror cell plate and is secured to the bottom surface of the mirror cell plate with screws. The actuator can be slightly rotated to adjust height consistency, with axial installation position adjustability of no less than 4 mm, locked in place with a locknut. Compressed air from the electromagnetic proportional valve is supplied through the bottom air inlet. Figure 1: see original paper shows the three-dimensional design of the pneumatic force actuator.

Figure 1. (a) Structural design of the pneumatic force actuator; (b) 3D illustration of the pneumatic force actuator.
1. Mirror, 2. Invar pad, 3. Unidirectional pressure sensor, 4. Guide rod, 5. Outer cylinder, 6. Linear bearing, 7. Upper end cap, 8. Upper seal cap, 9. Metal bellows, 10. Mirror cell, 11. Flange, 12. Height adjustment and locknut, 13. Lower seal cap, 14. Air inlet

Based on the maximum output force requirements and force sensitivity specifications, and considering the extremely low dynamic performance characteristics of the ring astronomical primary mirror support system, a strain-gauge load cell with a 0-200 N range was selected. This force sensor provides sensitivity of 1.0-1.5$±$0.05 mV/V and full-scale linearity error of $±$0.3% FS, yielding maximum error better than 0.6 N. According to the output force amplitude requirements, the elastic cylinder internal pressure range was designed for 1-3 bar. [Figure 2: see original paper] shows a photograph of the pneumatic force actuator.

Figure 2. Photograph of the pneumatic force actuator.

3. Test Methods and Content

To verify whether the pneumatic force actuator meets design specifications and engineering application performance requirements, a comprehensive test platform was established. Performance testing primarily includes open-loop output force range measurement, full-scale linearity testing, resolution testing, and static stiffness characteristics testing under both vertical and horizontal operating conditions at various internal pressures.

The specific approach combines displacement input and pressure loading to examine relationships between bellows axial compression displacement and output force, internal pressure and output force, and response time versus output force under closed-loop control. [Figure 3: see original paper] shows the experimental test platform, which comprises the pneumatic force actuator, micro-displacement actuator, micro-displacement actuator driver, laser displacement sensor, unidirectional pressure sensor, USB data acquisition card, voltage-type electromagnetic proportional valve, and air supply. The micro-displacement actuator applies axial compression to the pneumatic force actuator, with displacement measured by a Keyence H050 laser displacement sensor. Simultaneously, the USB data acquisition card collects output force feedback from the pressure sensor. The micro-displacement actuator provides nominal displacement resolution of 40 nm/step with 6 mm travel. The laser displacement sensor offers a 0-10 mm measurement range, full-scale linearity of \$±\$0.02% FS, and repeatability of 25 nm. The voltage-type electromagnetic proportional valve supplies pressure from 0.01-5 bar with maximum flow of 6 L/min, sensitivity of 0.01 bar, and full-scale linearity error of \$±\$1% FS.

Due to disturbances, friction, and other nonlinear factors in open-loop primary mirror axial support systems, actual output force exhibits uncertain errors relative to ideal values. Closed-loop control tests were conducted on the pneumatic force actuator to address this limitation.

Figure 3. Experimental test platform for the pneumatic force actuator. (a) Vertical installation; (b) Horizontal installation.

4. Test Results and Analysis

4.1 Output Force Range and Linearity Test

To characterize the relationship between internal pressure and output force across the bellows' operating range, tests were conducted at three axial compression displacement levels: 0.5 mm, 1.0 mm, and 1.5 mm. The electromagnetic proportional valve pressurized the bellows chamber from 0 bar (relative to ambient atmospheric pressure) to 1.5 bar, then depressurized back to 0 bar. Due to gas compressibility and slower response of pneumatic systems, the pressure was changed in 0.1 bar increments with 10-second stabilization periods before recording data.

The relationship curves between bellows internal pressure and output force, along with error fitting curves, are shown in [Figure 4: see original paper] and [Figure 5: see original paper]. Analysis of these curves reveals good linearity between internal pressure and output force across different compression states. However, at the same axial compression displacement, output force measured during depressurization is approximately 1.5 N higher than during pressurization, exceeding design requirements. This hysteresis results from directional changes in friction forces from the guide linear bearing and potential friction between the bellows outer surface and inner cylinder wall.

The linearity error curves in [Figure 5: see original paper] indicate maximum nonlinearity error of output force does not exceed 2% across different axial compression displacements. The effective output force range is 0-200 N with good system linearity throughout the operating range.

Figure 4. Curves of input pressure versus output force at different compressed displacements.

Figure 5. Full-range linearity error curves. (a) Pressurization; (b) Depressurization.

4.2 Output Force Resolution Test

Output force resolution is directly related to electromagnetic proportional valve resolution. Under stable operating conditions, the minimum change in output force resulting from incremental pressure adjustments defines the resolution. Testing progressively reduced input pressure increments until no discernible output force change was observed.

Table 1 lists the maximum, minimum, and average output force changes corresponding to various input pressure increments. The data shows that as input pressure increment decreases, output force change decreases linearly. When the input pressure increment is 0.0015 bar, the mean output force change is 0.23 N; at 0.001 bar, no significant change is observed. Therefore, the output force resolution is determined to be 0.23 N, meeting the design requirement.

Table 1. Output force resolution.

4.3 Static Stiffness Characteristics Test

Stiffness represents the bellows' resistance to elastic deformation—the force required to produce unit displacement. With the bellows chamber pressurized to different levels, the micro-displacement actuator applies axial compression while the laser displacement sensor measures displacement across a full range of at least 3 mm. The unidirectional pressure sensor simultaneously provides output force feedback to analyze the relationship between bellows axial compression and output force. Tests were conducted at seven pressure levels from 0-1.5 bar in 0.25 bar increments, recording data at 0.2 mm compression intervals.

[Figure 6: see original paper] and [Figure 7: see original paper] present static stiffness characteristic curves and linear fitting error curves for the pneumatic force actuator in two extreme operating conditions: vertical and horizontal orientations.

Figure 6. Full-range static stiffness test in vertical orientation. (a) Input displacement versus output force; (b) Fitting error curve.

Figure 7. Full-range static stiffness test in horizontal orientation. (a) Input displacement versus output force; (b) Fitting error curve.

Analysis of Figure 6: see original paper and Figure 7: see original paper shows that with identical internal pressure, output force variation across the full displacement range is 3.5-7.6 N. The fitting error curves in Figure 6: see original paper and Figure 7: see original paper reveal maximum static stiffness nonlinearity errors reaching 17% in both orientations, indicating suboptimal linear static stiffness characteristics. This is also attributed to friction from the guide linear bearing and potential contact between the bellows outer surface and cylinder inner wall, which prevents open-loop force accuracy from meeting design requirements and necessitates closed-loop testing.

4.4 Closed-Loop Output Force Accuracy Test

Open-loop operation exhibits output errors exceeding the $±$0.5 N accuracy requirement, demonstrating that open-loop control cannot satisfy the 2-meter ring mirror surface accuracy specifications. Therefore, closed-loop control tests were performed.

[Figure 8: see original paper] shows the control structure diagram, which incorporates two feedback control loops. During operation, according to primary mirror position and orientation requirements, the bellows compression state is established. To achieve precise force output, the actual output force measured by the unidirectional pressure sensor is fed back to the computer control system for comparison with the target force, and the electromagnetic proportional valve compensates pressure until specifications are met.

Closed-loop control tests were conducted across the full 0-200 N output force range. Based on open-loop control, the electromagnetic proportional valve pressurizes or depressurizes the actuator according to input pressure, while the system recursively compensates using force feedback from the pressure sensor until output force error falls within $±$0.3 N. [Figure 9: see original paper] shows the closed-loop control test results.

Figure 8. Block diagram of closed-loop control system for pneumatic force actuator.

Figure 9. Closed-loop feedback system correction curves. (a) Pressurization; (b) Depressurization.

Test results are summarized in **Table 2** . The data demonstrates that the closed-loop control system combining the pneumatic force actuator with unidirectional pressure sensor feedback achieves the required output force accuracy of $±$0.3 N, with simple control, stable and reliable operation.

Table 2. Test results.

Conclusion

Based on the technical requirements and design specifications for the 2-meter Ring Solar Telescope, a pneumatic force actuator was developed using a metal bellows as the core pressure-sealed element. The actuator features simple structure and convenient installation and maintenance. Comprehensive testing reveals good output force linearity, though static stiffness linearity under varying pressures is suboptimal. This indicates that friction from the guiding mechanism and potential contact between the bellows and housing prevents open-loop operation from meeting the 2-meter ring primary mirror surface accuracy and support force precision requirements. However, closed-loop control test results demonstrate that the pneumatic force actuator achieves the required control accuracy with a simple, stable, and reliable system suitable for engineering applications. A 9-point axial support prototype platform has been constructed based on this actuator. Future work will involve small-system-level closed-loop debugging on this prototype platform and optimization of the pneumatic force actuator's structural design and manufacturing details.

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Note: Figure translations are in progress. See original paper for figures.