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Ball Screw Preload Retention with Compliant Spacer Split Nut

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Abstract

This disclosure describes a ball screw preload retention mechanism employing a split nut assembly with an interposed compliant spacer. The arrangement addresses the issue of preload degradation in ball screw systems due to wear, which typically results in increasing backlash and subsequent positional inaccuracy long before the ball screw itself reaches its mechanical wear limit. By dynamically maintaining a consistent preload force, the system extends the useful service life of linear motion actuators. The compliant spacer continuously exerts an axial force on the split nut halves, compensating for material loss and preventing the premature onset of significant backlash, thereby preserving accuracy and operational efficiency.

1. Technical Field

[0001] The technical field relates to linear motion systems, particularly those employing ball screws for precise and efficient translation of rotary motion into linear motion. More specifically, it concerns mechanisms designed to maintain preload in ball screw assemblies over extended operational periods, thereby preserving positional accuracy and extending the system's useful service life.

2. Technical Context

[0002] Ball screw assemblies are widely utilized in applications requiring high precision, high efficiency, and significant load capacity for linear positioning. A critical aspect of their performance is the presence of a preload, typically achieved by axially offsetting two nut halves or by using oversized balls. This preload eliminates axial backlash, increases stiffness, and improves accuracy. However, during operation, wear occurs on the ball screw (10) raceways and the balls within the nut assembly. This wear, which is generally concentrated in the frequently used portions of the travel, results in a gradual reduction of the preload force. As the preload diminishes, axial play, or backlash, begins to develop. This backlash manifests as positional errors, where the actual position of the driven load deviates from the commanded position, especially during reversals of direction. The onset of significant backlash often renders the ball screw system unsuitable for its intended purpose, even though the structural integrity of the ball screw (10) and nut components may still be adequate for load bearing. Replacing such a system prematurely incurs considerable cost and downtime. The problem addressed is the premature reduction of system utility due to preload loss resulting from wear-induced backlash, rather than catastrophic failure or complete material exhaustion.

3. System Overview

[0003] The disclosed system for ball screw preload retention integrates a specialized split nut assembly (12) with a compliant spacer (14) to dynamically maintain axial preload on a ball screw (10). As depicted in FIG. 1, the ball screw (10) is driven by a drive motor (20) and its linear position is monitored by a position sensor (16). A controller (18) receives feedback from the position sensor (16) and manages the drive motor (20). The core of the preload retention mechanism is the split nut assembly (12), which comprises two nut halves (22, 24) separated by a compliant spacer (14). The compliant spacer (14) exerts a continuous axial force against the two nut halves (22, 24), causing them to engage the ball screw (10) in opposing directions and thereby establish a predetermined preload. This arrangement allows the compliant spacer (14) to expand as wear occurs within the ball screw (10) and nut raceways, automatically compensating for material loss and sustaining the preload force. The system aims to extend the duration over which the ball screw (10) operates within acceptable backlash limits, deferring the point at which positional inaccuracy renders it functionally obsolete.

4. Components

[0004] The primary components of the system are:

[0005]

- **Ball Screw (10):** A precision-machined threaded shaft with helical grooves, or raceways, designed to accommodate recirculating balls. It converts the rotary motion of the drive motor (20) into linear motion.
- **Split Nut Assembly (12):** This assembly consists of two individual nut halves, a first nut half (22) and a second nut half (24), which thread onto the ball screw (10). Each nut half contains internal helical raceways corresponding to those on the ball screw (10), along with ball recirculation paths. The nut halves are designed to be axially separated by the compliant spacer (14).
- **Compliant Spacer (14):** Positioned between the first nut half (22) and the second nut half (24), as illustrated in FIG. 2, the compliant spacer (14) is a resilient element. It is pre-compressed during assembly to exert a continuous axial force that pushes the nut halves apart. This force creates the desired preload on the ball screw (10). The spacer (14) can be a spring washer, a coil spring assembly, or an elastomeric element. Its characteristic defines how its resistive force changes with deformation.
- **Drive Motor (20):** A rotary actuator, typically an electric servo motor or stepper motor, responsible for rotating the ball screw (10) to generate linear motion.
- **Position Sensor (16):** A device, such as a linear encoder or a rotary encoder on the motor shaft, that measures the absolute or incremental linear position of the nut assembly (12) or the angular position of the ball screw (10).
- **Controller (18):** An electronic unit that interprets commands, processes position feedback from the sensor (16), and issues control signals to the drive motor (20) to achieve desired linear movements.
- **Bearing Supports (26):** Bearings that axially and radially support the ball screw (10) at its ends, allowing smooth rotation while resisting axial and radial loads.
- **Mounting Flange (28):** A structural component on the split nut assembly (12) that facilitates attachment to the driven load.

5. Operation

[0006] The operation of the ball screw preload retention system involves initial setup, steady-state running, and responses to wear and fault conditions.

[0007] **Start-up and Initial Preload:** During assembly, the two nut halves (22, 24) are placed onto the ball screw (10) with the compliant spacer (14) inserted between them. The compliant spacer (14) is compressed to a predetermined axial displacement, generating an initial preload force (F_p) that axially offsets the nut halves relative to the ball screw's (10) lead. This preload ensures that all balls are engaged in the raceways without any clearance, eliminating backlash. The initial compression of the spacer (14) is set to achieve a design preload, for example, 5% to 10% of the dynamic load rating of the ball screw.

[0008] **Steady Running:** During normal operation, the drive motor (20) rotates the ball screw (10). The ball screw (10) engages the balls within the split nut assembly (12), converting rotary motion into linear motion of the nut and its attached load. The compliant spacer (14) continuously exerts its axial force, maintaining the preload. As the ball screw (10) and nut raceways experience wear, material is gradually removed from the load-bearing surfaces. This wear would typically lead to an increase in internal clearance and a reduction in preload in a fixed-preload system. However, in this system, the compliant spacer (14) is designed to expand axially as wear occurs, taking up the increased clearance. This expansion causes the nut halves (22, 24) to spread slightly further apart along the ball screw (10), continuously pushing them into opposing engagement and thereby largely preserving the preload force. The amount of preload loss is significantly reduced compared to fixed-preload designs. The position sensor (16) provides feedback to the controller (18), which adjusts the drive motor (20) to achieve accurate positioning.

[0009] **Preload Loss Measurement in Service:** Preload loss can be monitored in service by observing the magnitude of positional error during reversal of motion. A common method involves commanding the system to move a small, repeatable distance, for example, 0.1 mm, then reversing direction and commanding it to move the same distance back. The actual distance traveled in the reverse direction before the load begins to move can indicate backlash. Alternatively, the drive torque required to maintain constant velocity can be monitored. As preload decreases, the drag torque typically decreases. An increase in positional error during reversals beyond a specified threshold, or a reduction in measured drag torque below a lower limit, indicates significant preload degradation. The controller (18) can log these parameters over time.

[0010] **Trade-off against Drag Torque and Heat:** A higher initial preload results in increased stiffness and reduced backlash, but it also leads to greater frictional drag torque within the nut assembly (12). This elevated drag torque consumes more power from the drive motor (20) and generates additional heat. Excessive heat can degrade lubricant properties and potentially cause thermal expansion, leading to further positional errors. The compliant spacer (14) characteristic is critical here. A spacer with a flat force-displacement curve (low spring rate) maintains a more consistent preload force over a wider range of wear, but requires a larger initial compression to achieve the desired preload, potentially increasing initial drag. A spacer with a steeper force-displacement curve (high spring rate) is more sensitive to wear, meaning preload will decrease more rapidly with material loss, but might allow for a lower initial compression for the same preload. The design aims to balance the need for sustained preload with acceptable levels of drag torque and thermal generation. Typical design considerations target a preload force that results in a drag torque between

0.5% and 2% of the motor's rated torque. The operating temperature rise of the nut assembly should remain below 15 K to 20 K above ambient.

[0011] **End of Life Criterion:** The end of life for the ball screw system is primarily determined by the point at which positional accuracy degrades beyond acceptable limits, rather than outright mechanical failure. With this system, the end-of-life criterion is typically reached when the compliant spacer (14) has expanded to its maximum design limit, or when the preload force, despite the spacer's compensation, has diminished to a point where the backlash exceeds a specified threshold, for example, 0.025 mm to 0.050 mm. This indicates that the wear has progressed to a degree that the spacer can no longer effectively maintain the required preload. Another criterion could be an increase in operational noise or vibration, or an observed increase in the peak torque required to overcome static friction after periods of rest, even if dynamic drag torque remains acceptable. Once this criterion is met, the ball screw assembly (12) requires replacement or refurbishment to restore positional accuracy.

6. Example Embodiments

[0012] **Embodiment 1** This embodiment utilizes a stack of Belleville washers as the compliant spacer (14). The washers are arranged in series, parallel, or series-parallel combinations to achieve the desired force-displacement characteristic. For instance, a series arrangement provides a softer spring rate, maintaining a more consistent preload force over a larger wear-induced expansion, which is beneficial for systems with high expected wear. The preload can be adjusted during assembly by varying the number of washers or the degree of initial compression. The Belleville washers are housed within a recess machined into one of the nut halves (22) and abut against the opposing nut half (24).

[0013] **Embodiment 2** In this embodiment, the compliant spacer (14) consists of a compression coil spring. A single coil spring or multiple coil springs arranged circumferentially between the nut halves (22, 24) provide the axial preload. The spring constant of the coil spring is selected such that the change in preload force over the expected wear range remains within an acceptable percentage, for example, a 10% to 20% reduction from the initial preload. This configuration is mechanically simpler than a Belleville washer stack and can be suitable for applications where the wear compensation range is relatively small or where cost is a significant factor. A guide rod or sleeve can be used to prevent buckling of the coil spring.

[0014] **Embodiment 3** This embodiment employs an elastomeric ring or disc as the compliant spacer (14). Materials such as polyurethane or specialized rubber compounds can be formulated to provide specific force-deflection properties. The elastomeric spacer (14) has the advantage of inherent damping characteristics, which can reduce vibration within the nut assembly (12). The geometry of the elastomeric component, such as its thickness and cross-sectional profile, dictates its spring rate and maximum allowable deflection. This approach can be particularly effective in environments subject to shock or vibration, providing both preload and some level of vibration isolation.

7. Alternative Configurations

[0015] Instead of a single compliant spacer (14) between two distinct nut halves (22, 24), the compliant element could be integrated directly into one or both nut halves. For example, one nut half could be designed with an integral spring feature, such as flexural arms or a diaphragm, that provides the compliant axial force. Another configuration might involve a resilient coating applied to the ball raceways of one nut half, effectively making the raceway itself compliant. The nut halves (22, 24) could also be pre-tensioned by an external mechanism, such as a set of adjustable bolts acting against a rigid housing, with the compliant spacer (14) then regulating the preload rather than directly generating it. The preload force could also be applied from outside the nut assembly, through a spring-loaded yoke or similar structure that pushes one nut half axially relative to the other.

8. Parameter Variations

Parameter	Range	Effect of Increasing Value	Effect of Decreasing Value
Initial Preload Force	50 N to 500 N	Higher stiffness, lower backlash, increased drag torque, increased heat generation, reduced overall efficiency.	Lower stiffness, earlier onset of backlash, reduced drag torque, reduced heat generation, higher overall efficiency.
Spacer Spring Rate	10 N/mm to 100 N/mm	Preload force decreases more rapidly with wear, less overall expansion required for compensation.	Preload force remains more constant with wear, larger expansion required for compensation, can accommodate more wear.
Spacer Material Stiffness	50 Shore A to 90 Shore D	Higher initial stiffness, less deformation for a given force, potentially higher dynamic damping.	Lower initial stiffness, more deformation for a given force, potentially lower dynamic damping.
Nut Lead Accuracy	Grade C7 to Grade C3	Higher positional accuracy, lower friction, higher manufacturing cost.	Lower positional accuracy, higher friction, lower manufacturing cost.
Ball Diameter Tolerance	Grade 10 to Grade 5	More consistent load distribution, reduced noise, higher cost.	Less consistent load distribution, increased noise, lower cost.
Lubricant Viscosity	ISO VG 32 to ISO VG 220	Increased film strength, higher drag, better wear protection.	Reduced film strength, lower drag, lower wear protection.

9. Additional Implementations

[0017] The concept of a compliant spacer (14) for preload retention can be extended to other types of linear motion guides where preload is critical for accuracy and stiffness. For instance, linear guideways employing recirculating rolling elements, such as linear bearings with ball or roller cages, could benefit from a similar compliant element within the bearing block. This would dynamically compensate for wear in the raceways of the linear guide, maintaining constant contact and stiffness. In rack and pinion systems, a compliant element could be used to continuously bias the pinion into engagement with the rack, compensating for wear on the tooth flanks and reducing backlash. Furthermore, the compliant spacer (14) could be made from a magnetorheological or electrorheological material, allowing its stiffness and damping properties to be actively adjusted by an external magnetic or electric field. This would enable dynamic tuning of the preload and drag torque characteristics in real-time, optimizing performance for varying load conditions or operational phases. The preload could also be supplemented or controlled by a hydraulic or pneumatic cylinder acting on one of the nut halves (22, 24), with the compliant spacer (14) providing a baseline or emergency preload.

10. Figures

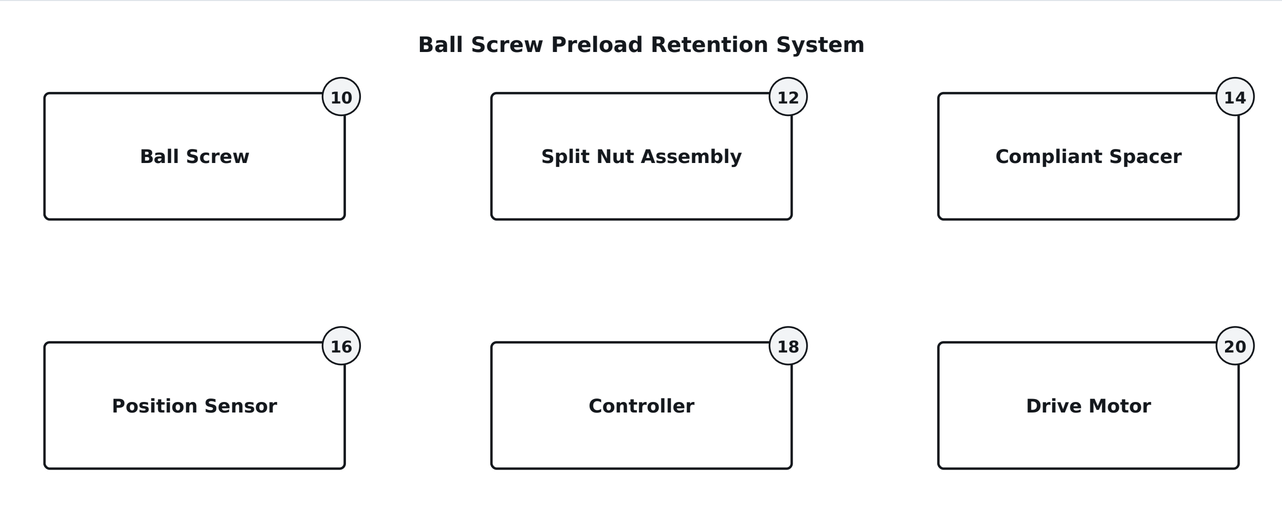

FIG. 1 A block diagram illustrating the primary functional components of the ball screw preload retention system. PNG

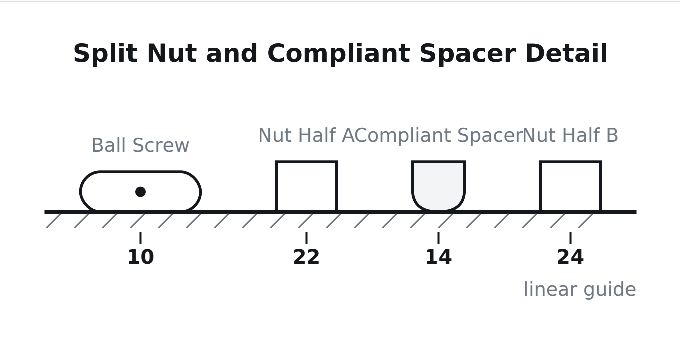

FIG. 2 An elevation view showing the arrangement of the split nut halves and the compliant spacer on the ball screw. PNG

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