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Double nut ball screw with improved operating characteristics

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ABSTRACT

The performance and availability of production machines is strongly affected by the operating characteristics of the installed ball screws. In this context, the value of preloading is an important property greatly influencing the quality of the feed motion as well as the expected service life. Dynamic applications often require ball screws with high preloading values. As a result, such systems typically suffer from high friction values with the involved wear and heat generation. This paper presents a novel design principle for ball screws, allowing for a considerable reduction of the preloading and hence an overall improvement of the operating characteristics.

1. Introduction

Ball screws are the components most frequently used for transforming rotational into linear motion. The operating characteristics and the availability of this component thereby have a decisive impact on the productivity of modern production machines.

The term operating characteristics in this case refers to all properties affecting the motion quality and the efficiency of a ball screw. Next to accuracy and uniformity of the feed motion, issues such as wear, heat generation and thermal stability have a dominant impact on the quality of the feed motion and the attainable service life accordingly.

One fundamental parameter in this context is the value of preloading [1]. In order to eliminate backlash and provide the required rigidity for dynamic processes, most applications in the field of production technology use preloaded ball screws. For high demanding applications, such as in feed drives for machine tools, typically ball screws with 2-point-contact are being used [2].

While the induced pretension eliminates backlash and increases the rigidity of the component, the friction characteristics change significantly with the value of preloading: bore and sliding friction accumulate, the uniformity of the motion diminishes, and wear and heat generation increase, compromising the quality of the feed motion as well as the attainable service life.

In order to overcome this inherent trade-off between rigidity and friction characteristics, numerous approaches have been presented in literature. Amongst others, new design principles with improved lead geometry and increased contact angles [3] have been proposed. Others have used ceramic balls or PVD coatings [4] to reduce friction and improve the operating characteristics of ball screws. In addition to that, most ball screw manufacturers provide forced cooling options for the shaft and/or the ball screw nut in order to cope with thermal issues as discussed in [5].

Next to these, numerous adaptronic approaches have been presented in literature [6–8], in which additional actuator-sensor-systems allow for an acquisition and adjustment of the preloading according to the actual requirements. Most of the solutions developed, however, are still quite cost-intensive and with certain restrictions for the application. On this account, adaptronic ball screw systems are not used in industrial applications up until today.

Within this paper, a novel design principle for high performance ball screws is presented. By means of an appropriate ball screw nut design and the use of additional spring elements, the value of preloading can be reduced for a large number of applications, leading to an overall improvement of the operating characteristics.

1.1. Preloading value

A graphical tool that gives insight into the conditions of a double nut system at different load conditions is the force-displacement diagram depicted in Fig. 1 [9]. The two curves represent the prevailing load on each half of the double nut plotted against the axial displacement of the flange.

In a first instance, the preload value is mechanically set as part of the assembling process. For a double nut system, this is usually achieved by inserting a spacer between the two halves of the nut or by simply tightening the nuts against each other. In this manner, the clearance between balls and tracks is eliminated and a 2-point-contact is established. The actual value of preloading determines the axial stiffness of the ball screw: the higher the value of preloading, the greater the stiffness of the component. According to the theory of Hertzian contact stress, the relationship between internal preloading force F_P and the resulting stiffness of the ball screw nut C_N can be described as follows:

$$C_N \approx \frac{1}{3} F_P^2. \qquad (1)$$

The total stiffness of a ball screw assembly, however, does not exclusively depend on the rigidity of the ball screw nut. Instead, it

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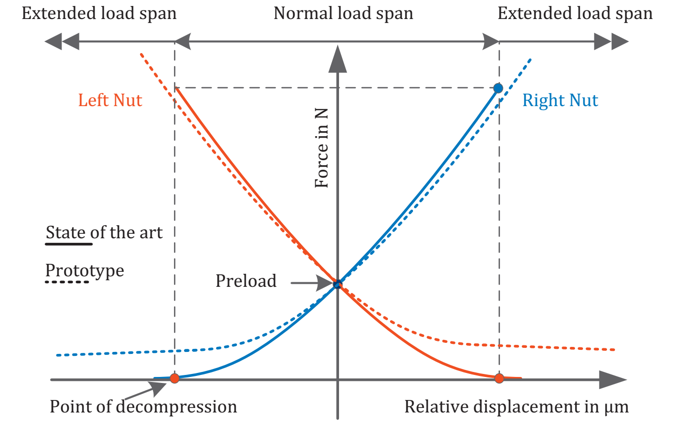

Fig. 1. Force-displacement of left and right nut within a preloaded double nut system.

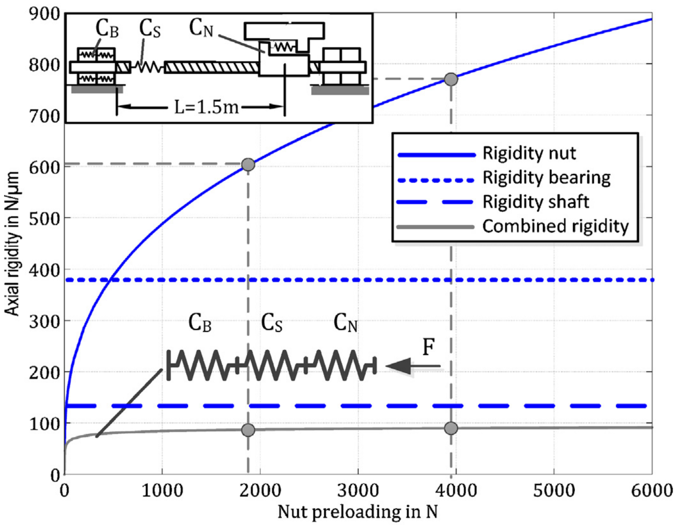

Fig. 2. Single and combined rigidity of a ball screw in axial direction.

is defined by the serial combination of the individual components: stiffness of the nut C_N, stiffness of the shaft C_S and stiffness of the supporting bearing C_B (see Fig. 2). The data plotted in Fig. 2 corresponds to the actual values of a mid-sized feed drive for machine tools, also used for further examinations.

As illustrated in Fig. 2, increasing the value of preloading above a certain level has little impact on the overall effective stiffness. The axial stiffness of a typical ball screw assembly is primarily defined by the geometry of the ball screw shaft [10]. Hence, for most applications, the rigidity of the ball screw nut is of secondary importance when choosing the value of preloading.

For a large number of applications, the relevant boundary condition is maintaining a certain contact pressure between the balls and the tracks throughout all operating states. If an axial load is applied to the ball screw, the load distribution within the nut changes. Considering the force-displacement diagram in Fig. 1, the contact pressure between balls and tracks on the one side of the nut increases, while on the other side the contact pressure is reduced. If the axial load reaches the level of approximately 2.83 times the preloading value, one side of the nut passes the point of decompression [11]. In this state, the preloading is fully ceased and the balls roll in an undefined manner. This is an undesirable mode of operation, which causes a sudden change in the contact conditions, possible disruptions of the oil film and an excessive increase in wear. In order to avoid such a mode of operation, the preloading value is usually set to a level which can cope with the axial loads while still maintaining a certain contact pressure on the balls.

In particular dynamic applications with large acceleration forces often require high preloading values. As a result, the ball screw is operated at high preloading throughout the entire operation, even though this additional tension is only needed for a short period of time, e.g. during acceleration. The high preloading values commonly used in the field of production machines, cause a significant additional stress to the component, greatly affecting the efficiency and the quality of the feed motion.

2. Functional principle and prototype

The driving question of the presented design optimization was how to bypass axial load peaks into a mechanism that enables the system to run with moderate preloading values, hence avoiding excessive contact stress and thereby improving the operating characteristics. The idea lead to a system which remains unchanged to the state of the art double nut design, however, with an additional mechanism to prevent from overload. Fig. 3 shows the functional principal of the designed double nut for different load conditions: under moderate load conditions, e.g. during the machining process, the system behaves like a standard double nut with the known contact properties, operation characteristics and rigidity values.

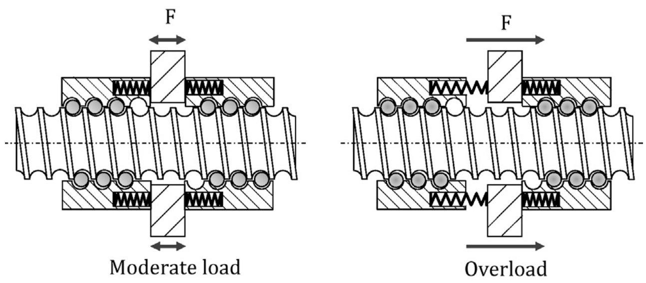

Fig. 3. Novel double-nut design under moderate and extensive axial load.

In case of an extensive axial load, the decompressed part of the double nut goes into a free-floating state in which an additional spring mechanism sustains the load compression required for a proper rolling condition. This guarantees a defined contact between the balls and the track, independent of the applied axial load. Note that the actual load is constantly supported by the opposing and preloaded part of the ball screw nut. This guarantees high rigidity values in both directions and a constant symmetrical behaviour throughout the entire mode of operation. The corresponding characteristic of the new double nut design is also illustrated in Fig. 1.

Based on the basic functional principle [12] a proper design for an actual prototype has been developed and realized. Fig. 4 shows the assembled prototype already installed on a feed drive test bench.

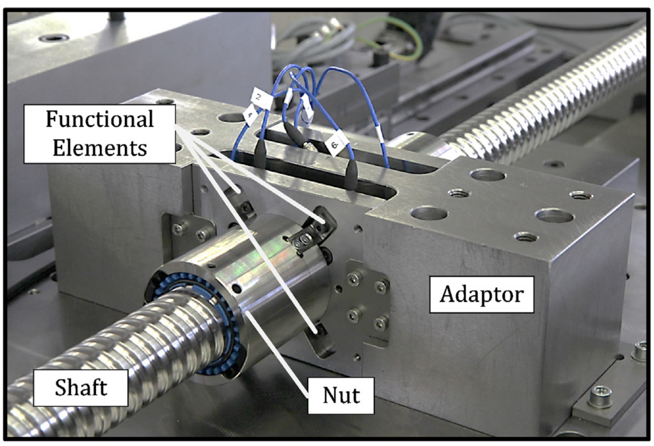

Fig. 4. Prototype of a double nut ball screw with improved operating characteristics.