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Machine tool feed drives

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ABSTRACT

This paper reviews the design and control of feed drive systems used in machine tools. Machine tool guides designed using friction, rolling element, hydrostatic and magnetic levitation principles are reviewed. Mechanical drives based on ball-screw and linear motors are presented along with their compliance models. The electrical motors and sensors used in powering and measuring the motion are discussed. The control of both rigid and flexible drive systems is presented along with active damping strategies. Virtual modeling of feed drives is discussed. The paper presents the engineering principles and current challenges in the design, analysis and control of feed drives.

1. Introduction

Feed drives are used to position the machine tool components carrying the cutting tool and workpiece to the desired location; hence their positioning accuracy and speed determine the quality and productivity of machine tools. A general architecture of feed drive hardware and its computer control structure are shown in Fig. 1. Feed drives are either powered by linear motors directly, or by rotary motors via ball screw and nut assembly as shown in Fig. 2. The drive train consists of a machine tool table resting on the guide, and moved linearly either by a ball screw drive-nut or by a linear motor system. The ball screw may be connected to the rotary servo motor directly or via gear reduction for large machines. The motor is powered by amplifier electronics connected to a Computer Numerical Control (CNC) system as shown in Fig. 1a. The table is positioned by the servo drives by following a trajectory generation and control algorithm as shown in Fig. 1b. An NC program generated in CAD/CAM system is loaded to the CNC unit of the machine tool. CNC parses the NC program into tool path segments which may consist of linear, circular, spline or other geometric motions. The feedrate entered in the NC program is combined with the acceleration and jerk limits of the feed drives, and time stamped discrete position commands are sent to each drive servo by the real time trajectory generation algorithm. The trajectory generation algorithm considers the kinematics of the machine in decoupling the spatial tool motion into each feed drive. Modern CNC units use jerk continuous, i.e. fifth order polynomials, to generate position commands at each discrete time interval [3]. The discrete position commands are processed by real time control laws of each servo drive, and the corresponding digital velocity commands are converted into electrical signals which are fed to the amplifier and motor of the drive. The speed and accuracy of positioning the machine tool are affected by the trajectory generation and control algorithms, mechanical drives and guides, amplifiers, motors and sensors used in each feed drive.

By considering the importance of the topic, CIRP published two key note articles on feed drive systems. Koren et al. presented a survey of feedback, feedforward, and cross-coupled controllers applied on feed drives [62,63]. Pritschow et al. compared the performance of linear drives against the conventional electro-mechanical ball screw drives Electromechanical Drives [83]. The latest CNC design architecture has also been surveyed by Pritschow et al. [84]. This keynote paper presents a review of recent technological developments and academic advances achieved in feed drive systems. Ongoing research challenges are also discussed in order to push the feed drive accuracy and performance to higher levels.

The paper is organized as follows. The machine tool guides based on friction, roller bearing, hydrostatic and levitation principles are presented in Section 2. The rack-pinion, ball screw and linear drive structures are given in Section 3, followed by their structural dynamic models in Section 4. Electric motors and sensors used in feed drives are discussed in Sections 5 and 6, respectively. The control of rigid and flexible feed drives is presented in Section 7. The paper is concluded by highlighting the current research challenges in feed drive design and control.

2. Machine tool guides

The roller-based guides have gained popularity due to their high performance and modular integration to machine tools. On the other hand, hydrostatic guides are preferred in the applications where higher accuracy, stiffness and damping are required. Aerostatic, magnetic or vacuum guides are used in the precision positioning applications where the external load is small.

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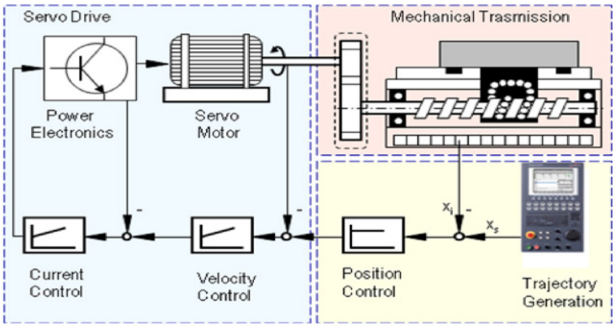
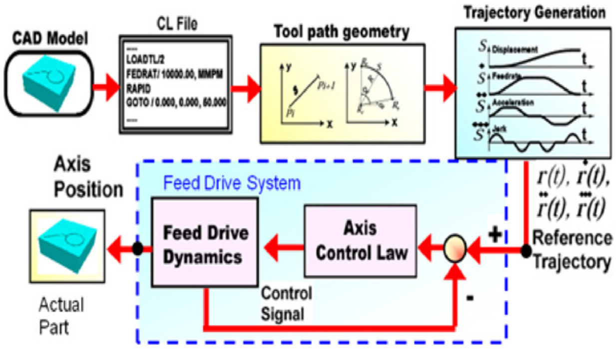


a. Physical components of a feed drive (WZL)



b. Feed drive control algorithms (UBC).

Fig. 1. Architecture of a feed drive control system. (a) Physical components of a feed drive (WZL). (b) Feed drive control algorithms (UBC).

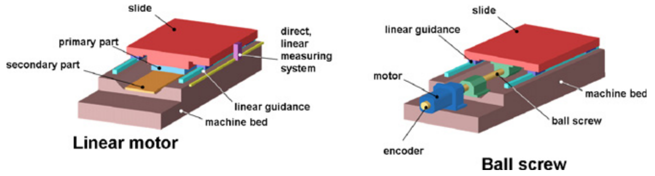


Fig. 2. Linear and ball-screw drive mechanisms.

The required functional r for the longitudinal guides are the following:

- Geometric accuracy since it is translated to the part directly.
- Stiffness to withstand the machining process and the inertial forces with minimum deformation.
- Wear resistance and low friction to avoid gripping, stick–slip phenomena and aging of the surfaces.
- Toughness to withstand impacts from the machining process.

2.1. Friction guides

Friction guides have good damping, strength against impact loads and high load capacity with up to 140 MPa. They are primarily used in speeds under 0.5 m/s. Uniform contact with minimum adhesion between the bed and slide is obtained by scraping and leaving uniform marks on the contact surfaces. The slide-ways are lubricated by 1 mm deep lubrication slots opened on the moving part of the guides. The guides can also be coated with few mm thick polymers in order to reduce the friction. Various configurations of friction guides are shown in Fig. 3.

Different pairs of materials are used to manufacture friction guides. Casting, steel, bronze and certain polymers are used as sliding materials. A key factor to ensure the controllability and smooth operation of the guide is to avoid the stick–slip phenomenon which appears when the static friction coefficient is higher than the dynamic friction coefficient. The development of polymer based materials with additives which favour lubrication, for example, Turcite™, SKC® or Moglice®, has allowed to a great extent the reduction of the stick–slip phenomenon (see Figs. 4 and 5).

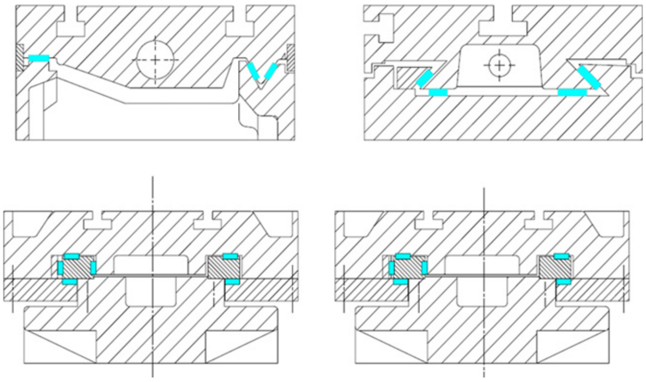


Fig. 3. Configurations of friction guides (by Busak Shamban®).

2.2. Rolling guides

Recirculating and stationary roller-based guides are most widely used in present machine tool applications (see Fig. 6). The stationary rolling bearings tend to be used when the stroke of the slide is relatively short. The rolling elements can be steel balls, rollers or needles, which are preloaded between two cages attached to stationary and moving parts of the guides. They have

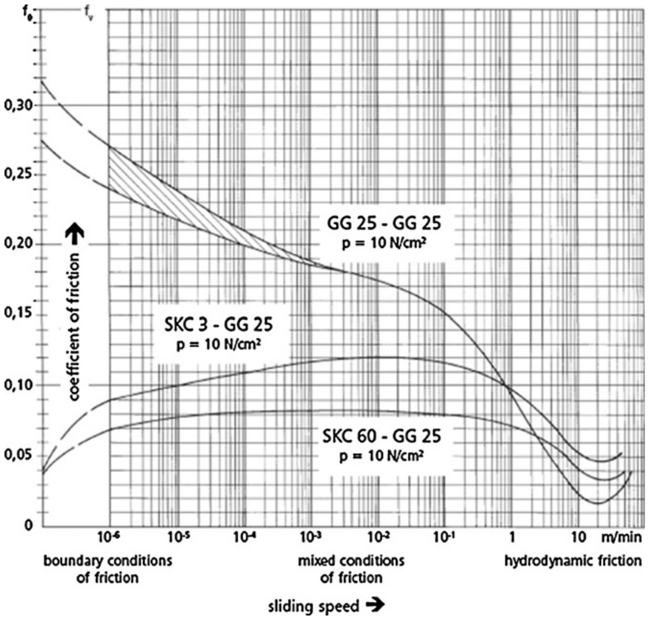


Fig. 4. Comparative diagram of frictional behaviour (SKC®).

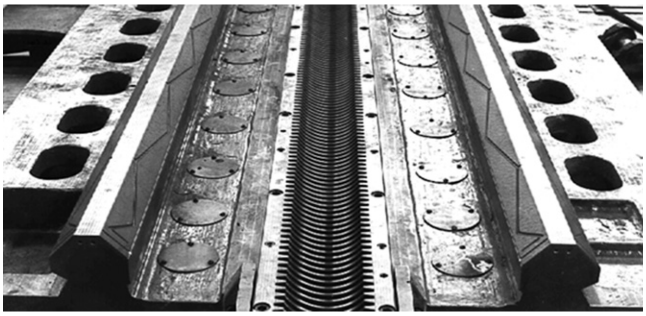


Fig. 5. Coated slideways in a table of a gantry milling machine (by SKC®).