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Design and control of a fast tool servo used in noncircular piston turning process

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ABSTRACT

Noncircular pistons are becoming more and more popular in the automotive industry. The challenge of machining this kind of pistons (e.g., middle-convex and varying ellipse piston (MCVEP)), lies in the rigorous demand of the cutting feed mechanism for large force generation, high stiffness, fast response, long stroke and high accuracy. The conventional processing methods cannot meet the challenge so a new piezoelectric actuator (PEA) based fast tool servo (FTS) mechanism was developed to incorporate additional functions to a general CNC system that will facilitate the execution of MCVEP turning. Since the desired tool trajectories are approximately periodic signals in MCVEP turning, and the repetitive control can achieve asymptotic tracking and disturbance rejection of periodic signals, a plug-in repetitive control is designed to be added on the conventional PID controller. In the experiments, the designed prototype was used to machine a MCVEP for the gasoline engine, which was equipped with the PEA-based FTS system, as well as the plug-in repetitive controller. The machining test validated the effective of the designed noncircular turning system.

1. Introduction

Piston is one of the key parts of internal combustion engines, operating under harsh conditions of high temperature, high pressure and heavy mechanical load. To ensure the favorable strained condition and guidance quality, the middle-convex and varying ellipse pistons (MCVEPs), instead of perfect circular ones, are becoming more and more popular. As shown in Fig. 1, MCVEP has the following features [1–3]: (1) the axial profile of MCVEP is a cam shape (middle-convex); (2) the cross-section curve of piston skirt is ellipse; (3) the ellipticity of each section is variable and (4) the long axis of each ellipse is in the same angle as that of the cross-section.

Although the noncircular pistons can improve performance of engines, and the general Computer Numerical Control (CNC) machines are available today, manufacturing of these kinds of pistons is still a challenging and difficult problem [4,5]. The primary difficulty lies in the high-frequency synchronization of radial reciprocating movement of turning tool with the rotation of main spindle, as demands the cutting feed mechanism to be of large force generation, high stiffness, fast response, long stroke and high accuracy. And yet, these requirements are typically beyond a general CNC servo mechanism. As a result, the usual practice is to cut a master cam using a highly dedicated and elaborate machine, and then

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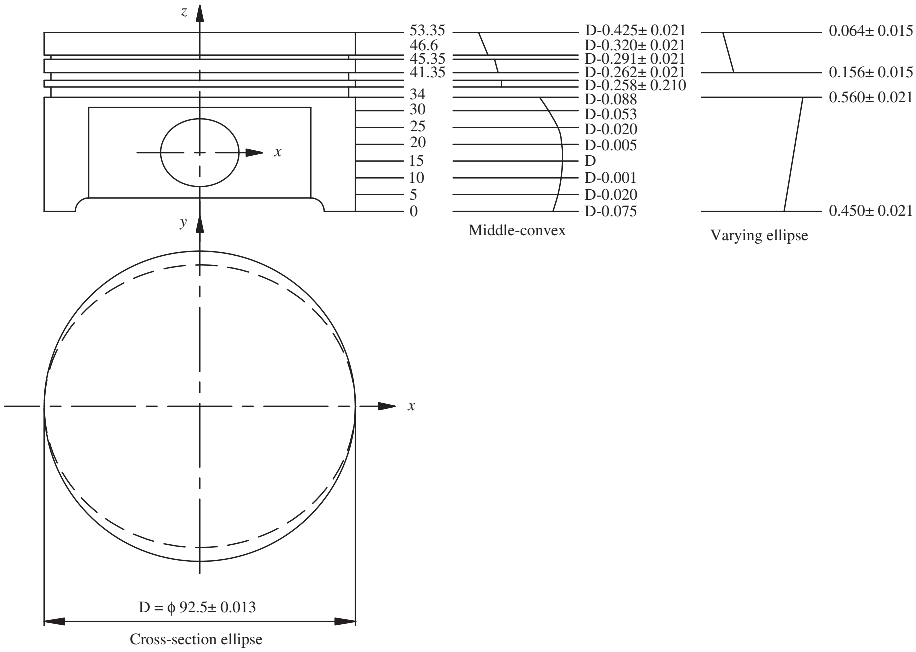

Fig. 1. Profile of a middle-convex and varying ellipse piston.

to duplicate the pistons from the master cam using a 3D copier-cutter [5]. The major problems of this approach are the poor duplication accuracy and slow cutting speed.

In recent years, researches on a special servo tool stage called fast tool servo (FTS) spring up. FTS refers to servo controlled fast acting tool holder capable of generating fast but small range tool motion for precision machining [6], and has been widely used in active vibration abatement, chatter suppression, and dynamic machine error compensation. There are several drivers available for FTS systems, such as linear motor [1,5], voice coil motor [7,8], giant magnetostrictive actuator (GMA) [3], piezoelectric actuator (PEA) [9,10], hydraulic actuator[11] and electromagnetic actuator [12]. Recent advancement in the manufacturing of PEA-based FTS makes the out-of-round turning of pistons more possible [13,14].

The inherent nonlinearity in PEA causes large tracking error. Traditional techniques involving feedback and feedforward control have been applied to reduce the tracking error to 2–3% of the displacement range [15,16]. Although relatively precise positioning is achieved, residual tracking errors may still be large due to long travel range. For instance, the travel range of FTS is 300 μm in a gasoline engine MCVEP turning process, and 2% leaves tracking error of 6 μm, which is certainly larger than the required precision (≤ 5 μm). Since both the reference profile and the disturbing force are repeated in the process, repetitive control meets the requirement [17,18], which is based on learning from previous trials to update the input profile such that the error in the next trial decreases.

In this paper, a PEA-based FTS will be presented to incorporate additional functions to a general CNC system that will facilitate the execution of MCVEP turning. The remainder of this paper is organized as follows. In Section 2, the principle of noncircular turning is introduced. In accordance to the features of MCVEP turning, a PEA-based FTS is designed and modeled in the following sections. Since the desired tool trajectories are approximately periodic signals in MCVEP turning, and the repetitive control can achieve asymptotic tracking and disturbance rejection of periodic signals, a plug-in repetitive control is designed to be added on the conventional PID controller in Section 5. The hardware structure of MCVEP turning system is illustrated in Section 6. In the experiments, the dynamic model of the FTS system was identified firstly. Then, the proposed plug-in repetitive control was validated. Finally, a MCVEP was machined in the designed prototype.

2. Principle of noncircular turning

Noncircular turning is such a complicated process that the tool has to be moved along the X-axis according to the angular position of the spindle, as well as positioned along the Z-axis at the same time. In particular, the tool position along the X-direction has to be well synchronized with the spindle position, θ, in order to realize the noncircular cross section. This calls for precise and high frequency motion on part of the tool along the X-axis. The noncircular cross section for the piston can be exactly described, and translated to servo trajectories [5]. For a general cross section, the motion along X corresponds to both Z and θ, and it can be described as follows:

$$X = F(Z, \theta) \tag{1}$$