EXTRACTED CONTROL APPROACH FOR CNC NON-CIRCULAR TURNING

H. Zhou, B. Henson, and X. Wang

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ABSTRACT

Non-circular pistons are becoming increasingly popular in internal combustion engines as they facilitate the construction of a more efficient engine. However, at the moment, it is still a very expensive and time consuming procedure to cut non-circular pistons, owing to practical problems which have yet to be overcome. This paper will examine these problems and highlight an Extracted Computer Numerical Control (ECNC) solution which can be used on existing Computer Numerical Controlled (CNC) Lathes. A high speed linear servo unit is presented as an extracted part of the system. Repetitive control is also discussed in the paper.

KeyWords: CNC non-circular turning, elliptical piston, repetitive control, linear motor.

I. INTRODUCTION

Pistons [1] form an important part of the internal combustion engines [2] which operate under extremely tough conditions of high temperature, high pressure and dynamic force. Non-circular pistons, as opposed to circular ones, are becoming increasingly popular due to their resilience to deformation, a feature which allows the piston, and therefore the engine to run more smoothly. Furthermore, the use of non-circular pistons generally decrease the toxic emission of engine. In fact, certain regulatory bodies require all engines to incorporate elliptical shaped pistons.

However, cutting a non-circular piston is a challenging and difficult problem, based on the general Computer Numerical Control (CNC) machines available today [3]. One key problem arises from the need to precisely synchronize the tool position to the spindle rotation at high speeds which will, in turn, require a high bandwidth and sampling frequency on the part of the control electronics of the CNC machine. However, these requirements are typically beyond a general CNC machine. In addition, most CNC machines today have a closed-architecture [4-7] which makes it difficult to retrofit and modify them to enable high speed motion tracking for the cutting tool. Thus, it is very difficult to cut a non-circular piston using general CNC [8]. Rather, the common practice is to cut a master cam using a highly dedicated and elaborate machine, and then to duplicate the pistons from the master cam using a 3D copier-cutter. This practice usually results in poor duplication accuracy and slow cutting speed.

In this paper, we will present a new idea to incorporate additional functions to a general CNC which will facilitate the execution of non-circular turning, thus producing non-circular pistons based on only general CNC. The additional feature includes an extracted device which comprises a linear motor and a DSP-based controller. The linear motor will hold the cutter and execute the desired high frequency motion to synchronize with the spindle rotation. The paper is organized as follows. In Section 2, the conventional ways of cutting pistons with a CNC system are reviewed, and the difficulties faced when applied to non-circular pistons will be highlighted. The principles of the proposed ECNC system will be presented in Section 3, with details on...
the constituent components. Finally, experimental results will be provided in Section 4 to verify the applicability of the proposed approach.

II. PISTON CUTTING WITH CONVENTIONAL CNC

Conventional CNC machines [9] can be used to produce pistons. In this section, the use of these machines to produce circular and non-circular pistons will be reviewed, and the difficulties arising in the latter case will be highlighted.

2.1 Circular turning

Figure 1(a) shows the turning principle for circular pistons. The radius of the piston is \( R \). Thus to derive this circular cross-section, only one linear motion of the tool along the \( z \)-axis is needed. The tool will remain fixed in position along the \( x \)-axis direction, regardless of the angular position of the shaft (\( \alpha \)), to produce the circular cross-section on the piston. For such pistons, general CNC machines are adequate.

2.2 Non-circular turning

Non-circular turning is a more complicated process. The tool has to be moved along the \( x \)-axis according to the angular position of the spindle, as well as being positioned along the \( z \)-axis at the same time (Fig. 1(b)). In particular, the tool position along the \( x \)-axis direction has to be well synchronized with the spindle position, \( \alpha \), in order to realize the non-circular cross-section. This calls for precise and high frequency motion on the part of the tool along the \( x \)-axis. The non-circular cross-section for the piston can be exactly described, and translated to servo trajectories. For a general cross-section, the motion along \( x \) corresponds to both \( \alpha \) and \( z \), and it can be described as:

\[
 x = F(z, \alpha),
\]

where \( z \) and \( \alpha \) represent the tool position along the \( z \)-axis and spindle angular position respectively. For an elliptical cross-section, \( F \) will reduce to a sine function where the sinusoidal frequency is given by

\[
f = \frac{c_f n}{60} \text{ Hz},
\]

where \( n \) is the speed of spindle in rpm; \( c_f \) is a frequency coefficient to be specified according to the specific elliptical shape desired. The constant 60 in (2) is to normalize the frequency to the standard frequency unit.

2.3 Difficulties with non-circular turning

The main difficulty with using a conventional CNC to cut an elliptical (or non-circular) piston can now be illustrated. From (2), if \( n = 2400 \text{ rpm} \) and \( c_f = 2 \), then the tool is required to be moved at a high frequency of 80 Hz. It is very difficult for a general CNC lathe to be able to track such a high frequency sinusoid.

The difficulty may also be considered from a sampling viewpoint. If the number of samples required every spindle revolution is \( n_s \), then the sampling time (converted to \( \mu s \)) is

\[
t = \frac{60 \times 10^6}{c_f n_s} \mu s
\]

(3) follows directly from (2) by converting frequency into time period and splitting it into time samples based on the number of samples per period required.

If \( n_s = 1200 \), \( n = 2400 \text{rpm} \), then

\[
(t = \begin{cases} 
20.8 \mu s & c_f = 1 \\
10.4 \mu s & c_f = 2 
\end{cases})
\]

(4)

This short sampling time interval is yet another constraint which a general CNC system can rarely fulfill.

These tight requirements of high control bandwidth and sampling frequency are the key reasons why full function CNC machines for piston-cutting are fitted with dedicated control units which correspondingly command a far higher price compared to general CNC machines. To this end, full function dedicated CNC machines are commonly used instead to manufacture a master cam piston after which a mechanical copying-cutting machine will duplicate elliptical pistons based on the master cam. Figure 2 shows the principle of 3D
copying-cutting machine. The piston and master cam run at the same speed, while the tool and copy rod are moved in the direction of piston axis. The copy rod will be kept in contact with the surface of master cam by springs and the tool will be moved accordingly in the x-direction to replicate the shape of the master cam. While this method is widely used in the piston cutting industry, it incurs well-known problems in terms of inefficiency both in production cost and time, as well as a typical low level of accuracy achieved in duplication.

III. EXTRACTED CNC SYSTEM

A new CNC system configuration is proposed to be used for cutting pistons with very low cost and yet achieving high accuracy. In addition, it has an open-architecture and yet is able to use existing CNC functions. Such a system will be referred to as an Extracted CNC (ECNC) system henceforth. The main principles of an ECNC system are shown in the block diagram of Fig. 3.

The ECNC comprises of two core components. At the core of the ECNC is an existing and general CNC system called the Proprietary Architecture CNC (PACNC). Linked to the PACNC via a standard interface is an extracted device comprising of a linear motor and a DSP-based controller. In what follows, details of these core components will be furnished.

3.1 Proprietary architecture CNC (PACNC)

The kernel idea of the ECNC system is that the existing CNC system (PACNC) can be treated as a black box with known input and output signals. Thus, if an ECNC system is used for piston cutting, any commercial CNC system or general machine (if they meet the accuracy requirements) can be used as the basic functional unit. In this way, the cost of the new system can be much reduced, and yet the accuracy and speed can be kept high by using the extracted device. However, by itself, the PACNC will not be able to overcome the difficulties highlighted in the earlier section with respect to non-circular turning.

3.2 Extracted device — linear servo system

To meet the high frequency and high-speed requirements for the linear positioner for the cutting tool, a linear motor and a DSP-based control card can be used, which collectively form the extracted device. Figure 4 shows the physical structure of the linear motor and its servo system. This will be used as an extracted part of the ECNC elliptical piston cutting system. The accuracy and tracking performance achievable is determined entirely by this independent linear servo system. This device will execute any job related to the elliptical piston cutting. The data or instructions needed for the cutting operations will be transmitted from the PACNC to the DSP controller via a RS232 interface or M function interface. The linear motor can sustain a high tracking frequency, while the DSP controller will provide the control action within the short sampling interval to execute the desired motion for the cutting tool.

3.3 Benefits of ECNC

The advantages of the ECNC piston-cutting system proposed include the following features:

- Low cost and existing CNC can be retrofitted;
- High frequency and high accuracy cutting of elliptical and non-circular parts;
- Flexibility and short time to product.
IV. CONTROL FOR THE LINEAR SERVO SYSTEM

Another core part of the ECNC for non-circular turning is the control of the linear servo system. It is an independent unit from the original CNC system and only follows the path or instructions sent by a general CNC lathe. The tracking path could be any periodic analog or digital signal. Of course, from the view of mechanical metal cutting, the part shape must be smooth enough to use a lathe to turn it.

Figure 5 shows the tool and elliptical part of turning. The tool is directly mounted on the moving part of a linear servo motor. While the part is running, the tool must follow every point of the elliptical curve with high speed and high accuracy.

The signal or load on the tip of the tool is periodic. This will be the typical case to use a repetitive controller to control linear actuator to track reference command and reject disturbance.

From Fig. 6, the equation of a elliptical curve is

\[ r(\theta) = \sqrt{a^2 \cos^2 \theta + b^2 \sin^2 \theta} \]
\[ = \sqrt{(b+(a-b)\cos^2 \theta)^2 +((a-b)^2 \sin^2 \theta)/4} \quad (5) \]

For the elliptical section of a piston, usually \( a - b \) is 0.2-0.5 mm and \( a - b << b \) is hold. So the Eq. (5) can be simplified as

\[ r(\theta) = b + (a-b)\cos^2 \theta \]

Then, the movement in the 'X' direction while the tool tip tracks the elliptical curve is

\[ x(\theta) = a - b - (a-b)\cos^2 \theta \]
\[ = a - b \frac{1}{2} (1-\cos 2\theta) \quad (6) \]
\[ = a - b \frac{1}{2} (1-\sin \alpha) \]

where \( \alpha = 90 - 2\theta \).

Equation (6) shows that the tool tracking curve is similar to the curve of a sinus function. The linear motor is tested and its discrete-time transmission function is expressed as

\[ \frac{B(z^{-1})}{A(z^{-1})} = 4.9013 \times 10^{-3}, \quad \frac{z^{-1}(1+0.993z^{-1})}{1-1.9719z^{-1}+0.9775z^{-2}} \quad (7) \]

A digital repetitive controller [11] is designed and its output is

\[ u(k) = 0.25u_{k-1}(k+1) + 0.5u_{k-1}(k) + 0.25u_{k-1}(k-1) \]
\[ + k_s M(z^{-1}) o_{-1}(k)Q(z^{-1}) \quad (8) \]

where \( u(k), u(k+1) \) and \( u(k-1) \) are outputs of the controller; \( k \) is between 1 to \( N \), \( N \) is the sampling
number in one period; $e(k)$ is the tracking error. 

$$Q(z^{-1}) = 0.25 z + 0.5 + 0.25 z^{-1},$$  \hspace{1cm} (9)$$

$M(z^{-1})$ is

$$M(z^{-1}) = 1.541 z^3 (1 + 0.3947 z^{-1} - 0.5918 z^{2})$$ \hspace{1cm} (10)$$

Figure 7 shows the testing result. The linear motor is following a curve of $r(t) = 0.3 \sin(\omega t)$ (mm). After about 15 periods, the tracking error is decreased to be below 0.005 mm. Coefficient $K_r$ is an important parameter and must be carefully selected to keep the system stable.

V. ECNC EXPERIMENT

In this section, a laboratory test bed is setup for the test and verification of the proposed approach. A high-speed linear motor and a TMSC31-based DSP control card are used in the implementation of the extracted device for the CNC system. Two motors are used to emulate the spindle motor and the z-axis motor of the basic PACNC component.

Both the spindle motor and the z-axis motor yield 2000 pulse signals per revolution from their incremental encoders. These signals will give the positions of the spindle as well as the position of the cutter along the z-axis. To acquire these 2000 pulses over a revolution would require a sampling time of 30000/4 $\mu$s according to (3) with $c_f - 1$. If $n = 2400$ rpm, then the sampling time required would be 12.5 $\mu$s. This sample time is much shorter than that supported by a general CNC controller. For example, the update cycle for the high performance PMAC2 controller [10] is about 100 $\mu$s for one axis and 480 $\mu$s for 4 axes. The commercial FANUC CNC system has a sampling time of 125 $\mu$s for one axis.

However, the sampling interval can be accommodated by a C31 DSP-based controller. Around 8$\mu$s is needed for the A/D, D/A and encoder positions updating, leaving only about 4.5$\mu$s for execution of the control algorithms. During this period, the C31 DSP board can execute about 136 instructions and 450 instructions with a C67 DSP.

With a spindle speed of 2400 rpm, the linear motor has to execute a sinusoidal motion at a frequency of 40 Hz synchronized to a revolution of the spindle. Figure 8 shows the tracking results achieved. The lower part of the figure (B) shows that the sine waveform output of the linear motor synchronizes with the spindle motor index pulse signal (denoted by Index Pulse in the figure). Thus, an entire sinusoidal motion is executed between two consecutive index pulses which mark a complete spindle revolution.

The amplitude of the sine motion should also vary with the tool position along the z-axis, according to the desired elliptical variation along z-axis. In the experiment, the z-motor is set to move the tools along the z-direction. Wherever it is, the linear motor can track the section shape according to the index pulse of spindle. The top part of the figure (A) shows the sinusoidal motion of the linear motor in position A (z-direction). The bottom part of the figure (B) shows the sinusoidal motion of the linear motor in position B (z-direction). The amplitudes of the two figures are different, as a different position in z-direction has a different elliptical shape. But they all synchronize the spindle index signal. In fact, the shape of the section can change continually along the z-direction, but the linear motor can track the shape according to the index signal from the spindle along the z-direction and continue changing its tracking path.

![Fig. 7. Tracking error.](image1)

![Fig. 8. Tracking results.](image2)
In that way, we can produce any kind of non-circular shape of shaft using this method. The data of the non-circular shape will be put in the memory whether it is regular or irregular.

VI. CONCLUSION

The paper presents the configuration of an Extracted CNC (ECNC) system which uses a linear motor and a DSP-based controller to function as an extracted device for a general CNC machine. The extracted device will allow the execution of a high frequency trajectory to facilitate the execution of a non-circular turning process. This allows a low cost implementation on an existing CNC machine to perform highly accurate cutting of non-circular pistons.

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Huixing Zhou received the B.Eng. degree in the engineering from Dalian University of Technology, Dalian, China, and the Ph.D. degree in mechanical engineering from the Tsinghua University, Beijing, China, in 1983 and 1998, respectively. He is a Professor in the College of Mechanical Engineering, China Agricultural University, Beijing, China. His research interests include CNC system and motion control, linear actuators (piezo and VCM), and mechatronics. Professor Zhou is a senior member of CMES, member of IMechE and a Chartered Engineer.

Brian Henson is a Lecturer in Design and Manufacture in the School of Mechanical Engineering at the University of Leeds, UK. He joined the University of Leeds in 1992 as a Research Assistant and completed his Ph.D. in representations of assembled products in product data before becoming a Lecturer in 1996. His principal area of research is the product development process.

Xiankui Wang was born in Jiangsu Zhengjiang, in 1932. Professor and Doctoral supervisor, Department of Precision Instruments, Tsinghua University, Beijing, China. Research Fields: Precision and Ultraprecision Machining and Automation of Manufacturing System (NC, CAPP, CAM, CIMS). He is the Vice-Chairman of Precision Machining and Nanotechnology Institution of CMES and the Vice-Chairman of The Chinese Universities Society of Manufacturing Automation etc. 17 books and 285 papers have been published.