Design of a Precision, Agile Line Boring Station

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Abstract

This paper describes a new agile line boring station for machining of long bores in automotive applications, e.g. crank and camshaft bores in engine blocks. The machine includes a "smart" line boring tool with an on-line compensation mechanism, relying on sensing and intelligence built into the tool itself, for real-time correction of the boring process. To supplement the advantages provided by the "smart" tool, a prototype agile line boring machine was developed as a joint effort between the University of Michigan and Lamb Technicon, a machine tool builder. The design integrates multiple new concepts of mechanical structure of the machine with an intelligent controller.

Keywords: Machine Tool, Cutting, Control

1 INTRODUCTION

Recent changes in the automotive market (competitive global market, customer-driven environment, fuel economy and emission regulations) drive an urgent need for new powertrain machining technologies that provide flexibility at an affordable cost. Although FMS technology has been introduced some 20 years ago [1], only in the last few years CNC and FMS were started to be utilized in automotive applications. Introduction of CNC machines into powertrain machining systems increased the level of flexibility in engine production (see Figure 1). But machining of long bores as needed in cam and crank shafts of engine blocks (see Figure 2) still remains an exception, requiring use of dedicated equipment, and hence impeding achievement of full system agility.

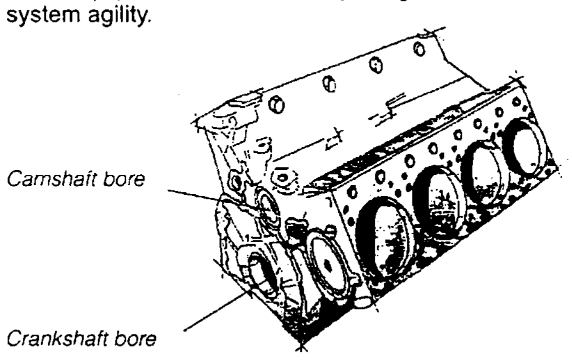

Figure 1: View of a car engine block.

Precision line boring is a very demanding application in terms of both quality and production rate requirements. Increasing flexibility without compromising quality or production rate (in a station that operates at least 16 hours a day) is difficult and challenging, and requires a systems approach integrating advanced control with precise machine hardware. To achieve this goal, leading edge technologies in machine design, sensing, tooling, and advanced control were applied in this project in a coordinated systems approach.

The goal of this project was to enable the implementation of fully agile machining systems for engine blocks, by designing an agile precision line boring station to machine the bores for crankshafts and camshafts. Major challenges of agility in production systems are product variety and time constraints: (1) the ability to produce a *variety* of product models on the same production system, under a *variety* of conditions (e.g., different materials, different cooling methods); and (2) the ability to reduce production time for unpredictable orders by decreasing the system changeover time between product models, and reducing its downtime.

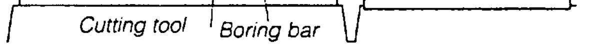

Figure 2: Line boring with guided tooling.

However, there are trade-offs between agility and machining precision. The process requires usage of a very long (e.g., 80 cm) and heavy tool. Flexibility requires elimination of support bushings for the tool, thus the tool may become a subject to vibrations and deflections preventing achievement of the required precision of 10 μm.

2 STATE-OF-THE-ART

In powertrain components where bearing support is necessary for cam and crank shafts, a number of precision bearing nests are located in-line. When the distance between two such bores is not too large (less than 5-10 bore diameters), line boring is used. Line boring ensures that the holes are of the same diameter and concentricity error is minimized. In typical automotive applications the range of machined bore diameters is D = 30 - 75 mm; the required cylindricity of the bore lies within 10 - 25 μm, and the surface finish is R_a = 2 - 50 µm. In extreme cases boring bars can be as long as 1350 mm and weigh up to 120 kg.

The state-of-the-art in flexible line boring technology has been assessed in a recent benchmarking study [2]. Results of the searches turned out to be relatively limited, most likely because proprietary information is not released by manufacturers, and academic research is almost non-existent in this area. Reviews of the recent developments in the general-purpose boring technology [3][4][5] reveal new trends in the area of traditional boring applications. The most prominent trend observed is an increased presence of instrumentation and control in the boring tools in response to increasing precision demands.

Since requirements for precision and accuracy are critical for manufacturing, machine tool error analysis have been a very important research area. Machine tool error analysis and compensation is heavily based on the Abbe Principle [6][7][8]. Error induced by the machining process are usually classified into quasistatic errors (e.g., geometric, thermal, and alignment errors), and non-quasistatic (e.g., tool deflection [9] and vibrations, workpiece deflections, controller tracking errors) [10]. Quasistatic errors usually account for more than 70 percent of total error budget.

Error modeling has become an important part of machine tool error compensation procedures. Initial methods originated first from the error modeling of CMMs [11]. In most models a method relying on homogenous transformation was used to describe the quasistatic error [12][13]. Drawbacks of most of these models are due to the fact that many characteristics of machine tools were ignored (e.g., error behavior under cutting load, part accuracy issues, thermal effects).

3 SENSORIZED TOOL

The boring tool itself is recognized as a major bottleneck in increasing flexibility and precision of the line boring processes. This section describes the development of a new concept of the line boring tool, supporting agility at the boring station level. This task is accomplished by the following means: (1) enabling automated tool change of the long boring bars by elimination of support bushings, (2) an on-line compensation mechanism relying on sensing and intelligence built into the tool itself to compensate for the increased compliance of the tool without supports. This sensorized tool we call "smart tool."

The boring bar is located in the motorized, high-precision spindle (rotational speed up to 6,000 rpm) and is connected with it through the standard taper mechanism enhanced with additional electrical connectors. The tool body (see Figure 3) contains a number of sensors and the actuation mechanism. The necessary instrumentation supporting the sensors and the actuation mechanism is located in the package attached to the rear end of the spindle and rotating with it. The instrumentation package (including on-board computer) and the piezoelectric actuator are receiving power from an external source via an inductive device. The housing for the instrumentation can work with multiple boring bars thus eliminating the need for frequent disconnections.

The inner details of the boring bar are shown in Figure 3. Functionally, the bar contains three subsystems: a) sensors, b) actuation mechanism, and c) cutting inserts. Details of the Smart Tool design, sensing, and control are elaborated on in [14].

For the purpose of tracking the reference signal, a digital linear quadratic optimal control law has been designed and implemented on a single-board PC/104 computer running at 5kHz sampling frequency. A full feedback control law was designed to create a stiff tool tip with ability to reject the dynamic cutting forces. Such control law requires knowledge of all the current states of the system. A state space realization was chosen in such a way that the first state is

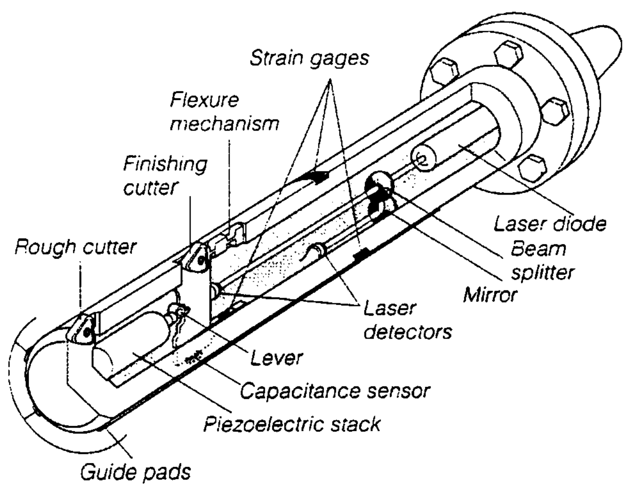

Figure 3: The "smart" boring tool.

current tool tip position. A Kalman filter observer has been designed to estimate the states in real-time for the full state feedback.

4 BORING STATION DESIGN

Our Agile Line Boring Station is a flexible high-speed machine. There is no intermediate support for the boring tool. The deflections at the tool tip due to machine inaccuracies and vibrations are compensated in real time with the help of the laser based measurement system and a piezoelectric actuator. The Agile Line Boring Station has the following specifications:

1. Spindle: a conventional, motorized spindle with modified arbor, 7.5 hp, 0-6000 rpm. Rotary inductive power and data transfer system mounted around the arbor.
2. Motion ranges: 500 mm x-axis, 800 mm y-axis (including tool change), 800 mm z-axis
3. Tool changer: holds six tools.
4. Positioning: accuracy ± 2 µm; repeatability ± 1 µm.

Multiple different concepts were studied during the design process, and the one described below was selected.

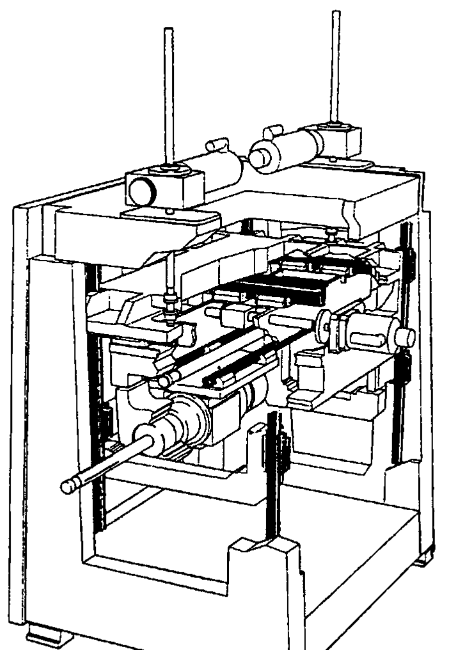

Figure 4: Line boring machine tool design.

The design concept of our machine is radical compared with traditional designs - the spindle was inverted and mounted to the underside of a cross-slide and suspended from a robust machine frame (Figure 4). In this concept, the tool changer is positioned directly under the spindle. In the machine development, symmetry was sought, because it ensures even thermal growth (i.e., minimum distortion) of the machine. The Y-axis has two ballscrews that operate in harmony under cross-coupling control [15]

Finite element analysis (FEA) was applied to investigate static and dynamic characteristics. Through FEA, stiffness of the machine at the spindle nose in the orthogonal machine directions was computed. Natural frequencies and mode shapes of the machines were also investigated by FEA. Finite element models of the machines were generated in NISA, Display III from EMRC. Over 8000 elements including 3D solid elements (NKTP 4), 3D transitional spring elements (NKTP 17), and 3D general spring elements (NKTP 38) was applied to model the machines.

Stiffness of the spindle bearings, the tool holder, the Y-axis roller screw systems, the X-axis ball screw system, and the roller guides were considered in the model and simulated through the use of spring elements. The connections of servo motors and the bridges to the main body of the machine were simulated by applying rigid elements. Servo motors and the spindle box were modeled by a simple box structure with appropriate density to simulate their weight.

Through iterative analysis and design modification, the design was modified over ten times to increase the static stiffness (from 10 N/μm to 50 N/μm) and the lowest natural frequency (from 15Hz to 38 Hz). This was accomplished by careful consideration of the FEA and adding strength/increasing inertia without adding substantial mass, thereby decreasing the natural frequency. By making modifications in the design parameters it was possible to eliminate most of the undesirable modes of vibration. Graphical output was also helpful in understanding the sources of compliance in the designs.

5 ERROR ANALYSIS AND COMPENSATION

The six geometric errors affecting each axis of motion can be described in two different ways. The errors are either defined with reference to successive translated and rotated axes (succesive approach) or with respect to a fixed set of coordinate axes where the orientation does not change. The second approach is more experimentally viable, since the error is measured with respect to the same set of fixed reference axes.

With the resultant error motions known for all six geometric errors, the total resultant error equation was found by the superposition of component errors. The results of the calculations implied that with the maximum angular error of 10.0 arc-sec or less, the error correction scheme had to be capable of correcting errors in excess of 50 μm [16].

It was also important to determine how each geometric error, i.e. linear displacement error, roll, pitch, yaw, ∂X, ∂Y, contributes to the overall tool tip error. Clearly, the pitch and yaw errors have the highest contributions, which is due to the fact that these angular errors are amplified with the excessively long cantilevered boring bar. The roll error has the smallest effect.

To carry out an active error compensation scheme, additional degrees of freedom (DOF) in the machine structure need to be introduced. This additional DOF for this purpose implemented by use of the dual linear actuator system in the Y direction for correction of large pitch errors. Concept of this mechanism is shown in Figure 5.

The dual ball screw system can be effectively used for correcting pitch error, as well as linear errors in the Y direction by using cross-coupling control (CCC) [17]. The CCC algorithm is based on comparing the position error of the two leadscrews and utilizing the error-difference as an additional input to each control loop. The CCC algorithm has a twofold advantage: (1) it reduces the Y-axis position error in normal operation, and (2) it assists in controlling the tool angle when needed as explained below. In the presence of an angular pitch error, the platen carrying the tool can be rotated in the opposite direction due to a differential motion between the two ball screws.

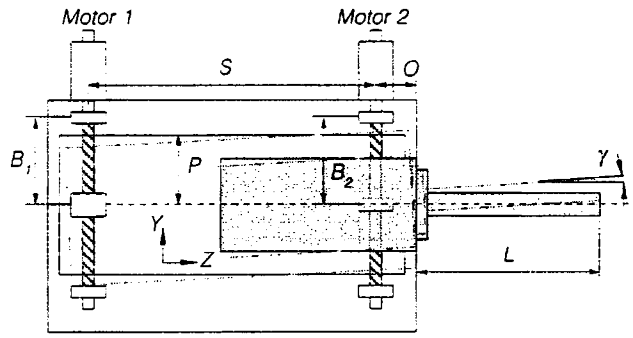

Figure 5: Dual ball screw error compensation mechanism.

Ball screws are typically manufactured with a constant pitch. When installed on a machine tool, a ball screw is rotated by a servomotor with an attached rotary encoder that has certain measurement resolution *e* (typically 64,000 divisions per revolution). The resolution of the encoder is one of the factors affecting positioning accuracy.

When two ball screws are used to move a common axis, incremental differences induce an angular motion to the moving platen (see Figure 5). Based on the known machine geometry, the angular displacement is

$$\gamma = \text{atan}\,[(B_2 - B_1)/S] \qquad (1)$$

and the resultant motion at the tool tip is equal to:

$$Y = (B_2 - B_1)(S + O + L)/S \qquad (2)$$

Using two ball screws with 20 mm pitch and encoder resolution of 64,000 division gives the resolution for pitch correction $\Delta\gamma$ = 2.308 arc-sec and linear error correction at the tool tip ΔY = 0.00052 mm. Further improvement of the resolution can be obtained by use of ball screws with different pitches (although use of this approach requires modification of motion control algorithms). For example, using one ball screw with pitch of 20 mm, and another with 15 mm pitch, leads to pitch compensation resolution of $\Delta\gamma$ = 0.577 arc-sec and linear error correction resolution of ΔY = 0.0001326 mm.

6 PC-BASED, OPEN CONTROLLER

The line boring station is equipped with a PC-based, and intelligent controller that utilizes several control algorithms [18]. It includes a combination of traditional algorithms [19], combined with CCC and feedforward algorithm as well as the integration of the smart tool controller with the main machine controller. The purpose of the intelligent boring controller is: (1) to tune the controller and the machining parameters to their optimum conditions despite changing environment conditions, such as temperature and load, (2) to provide the system with the ability to autonomously respond to irregular, unanticipated events which may occur during the boring process, and (3) to provide a platform for integration of multiple, non-standard control and monitoring functions (e.g., thermal and geometric error compensation). A block diagram of the controller is shown in Figure 6.

The CNC controller is based on the Cranfield Precision "CUPROC 6400" CNC Controller. It controls and coordinates all machine I/O functions and motions. The controller architecture is very generic and open, thus allowing the control

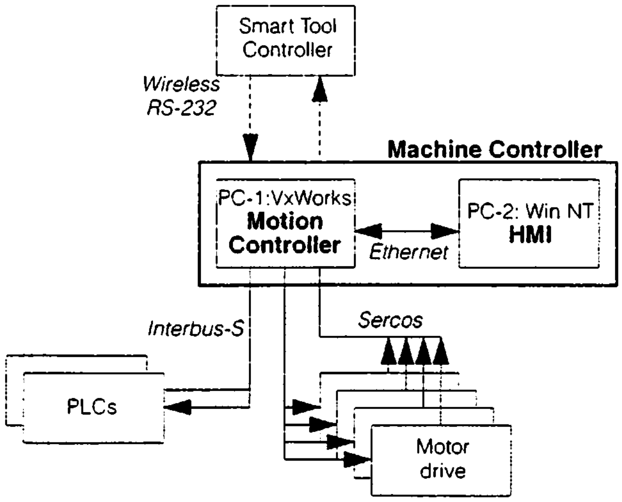

Figure 6: Block diagram of the machine control.

of the Agile Line Boring station to be customized for particular user needs.

The controller utilizes a dual ISA computer bus configuration, each with a single board Pentium computer and ethernet adapter card to connect the two platforms. Such architecture provides: (1) an open Windows NT environment for Human-Machine Interface (HMI) and third party software, and (2) deterministic hard real-time environment for trajectory planning, interpolation and transmitting position commands to the intelligent digital drives over the SERCOS drive network with 1 kHz frequency. The main controller functions, integration of which was enabled by the open-architecture of the controller, include modules for compensation of: (1) geometric errors, and (2) thermal errors.

7 SUMMARY

Detailed analysis of process requirements and extensive assessment of existing line boring machine have led to a radically new machine tool concept. In this new design static stiffness was improved approximately 5 times (over existing designs), which allowed the increase of the first natural frequency of the machine to 38 Hz (75% improvement). A scheme for compensation of geometric errors was developed based on the specifics of the line boring process. Machine control and compensation algorithms were implemented on an open-architecture, PC-based controller platform. Future efforts will explore extensive cutting, performance assessment and system endurance evaluations, refinement of the thermal and geometric compensation modules.

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