Title:
Application of an Iterative Learning Control Algorithm to Volumetric Error Compensation for CNC Machines

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Introduction:
There are two types of error usually considered in CNC machine applications, linear displacement error and volumetric error. Linear displacement error is the positioning error in the axis directions; usually, this error is caused by pitch errors of the leadscrews or linear encoders. Volumetric error is positioning error in a spatial direction that is not necessarily in the axis direction; usually, this error is a given by a vector and its components are linear error, vertical straightness, and horizontal straightness. Because the measured linear displacement error in the diagonal directions of the machine volume is sensitive to the error parallel and perpendicular to the linear motion axes, reduction of linear displacement error cannot completely remove volumetric error. Therefore, to provide precise machining results, both measurement and compensation of volumetric errors must be carefully considered in CNC machines [4].

In recent decades, because of the growth of laser measurement technologies, volumetric error measurement algorithms and devices have been proposed and implemented [1],[2],[5]. There are many advanced CNC machine controllers that provide functions to compensate volumetric errors. However, machines with conventional CNC controllers that are widely utilized in manufacturing mechanical parts usually do not support volumetric error compensation. The machining quality of such machines is thus limited because pitch error compensation in each linear motion axis cannot reduce error caused by volumetric factors. In order to apply volumetric error compensation to machines with conventional CNC controllers and to improve their machining quality, a method to compensate volumetric error by software (the software compensation method), was developed in this study.

Volumetric Error Compensation Using an Iterative Learning Control Algorithm:
The software compensation method developed here modifies CNC part programs based on relations between volumetric errors and the motion of moving axes, and thus can be applied to conventional CNC machines. The design concept of the software compensation method is to calculate the volumetric error caused by moving axes and to compensate the axial motion commands by applying the calculated volumetric error. The volumetric error of the CNC machine must be carefully measured in advance and an interpreter and an interpolator are required to interpret NC codes in part programs and perform fine interpolation for motion of the moving axes. CNC machine simulation is employed in this study to generate precise motion commands compensated by the calculated volumetric error. The precisely compensated motion commands are used instead of the original ones to provide more precise motions, and thus, the original CNC part programs are modified. In contrast to existing approaches, the software compensation method developed here not only can be directly applied to conventional CNC machines which do not support volumetric error compensation, but also utilizes the concept of iterative learning control to precisely calculate motion commands by referring to the volumetric error

obtained. Iterative learning control (ILC) [3] is a methodology that was originally used to address the problem of transient response in control systems that operate repetitively. In this study, ILC is employed to precisely calculate motion commands and to significantly reduce volumetric error deviating from the planned machining contours described by CNC part programs. The ILC formula used for volumetric error compensation is shown in Eqn. (2.1).

$$u_{k+1}(t) = u_k(t) + \gamma \cdot e_k(t), \quad t = 1, \ldots, n \tag{2.1}$$

where $u_k(t)$ and $u_{k+1}(t)$ are respectively the axial motion commands at the $(k)^{th}$ and $(k+1)^{th}$ iterations for the $(t)^{th}$ command point; $e_k(t)$ is the volumetric error at the $(k)^{th}$ iteration for the $(t)^{th}$ command point; γ denotes the ILC gain that affects the rate of convergence during the iterative learning processes and n denotes the number of command points. Based on the measured volumetric errors, the developed software compensation method first calculates the volumetric error $e_k(t)$ caused by the axial motion command $u_k(t)$ at the $(k)^{th}$ iteration for the $(t)^{th}$ command point and then generates the compensated axial motion command $u_{k+1}(t)$ by the ILC formula shown in Eqn. (2.1) for the $(k+1)^{th}$ iteration. All the command points t from 1 to n are extracted from NC codes in part programs, which construct the planned machining contours. CNC machine simulation is further employed to calculate the entire set of motion commands $u_{k+1}(t)$. For each iteration period, the software compensation method calculates the compensation error, i.e. the difference between compensated and uncompensated machine motions obtained from CNC machine simulation using compensated axial motion commands and original motion commands. The ILC formula is executed iteratively until the volumetric error of the compensated machine motion is minimized.

Experimental Results:

The developed software compensation method was implemented with a LEADWELL MCV-OP CNC milling machine with an ITRI-0M/0T PC-Based CNC controller. Travel distances were 405mm for the X axis and 270mm, for the Y and Z axes. An OPTODYNE MCV-500 LDDM instrument was used to measure volumetric error. For testing the developed software compensation method, a circle on the X-Y plane of the machine volume was divided into 10 parts in order to generate eleven command points; Fig. 1. shows the experimental results using CNC machine simulation. The developed software compensation method has significantly reduced the volumetric errors during axial motions of the CNC machine, with a reduction of 54.5%. The volumetric error obtained from all axial motion commands is collected to form a volumetric error vector. The norm of the volumetric error vector $\|\mathbf{e}\|$ is considered as the performance index to evaluate the learning performance of ILC. Thus, the experimental results validate the developed software compensation method for volumetric error compensation of CNC machines and they also demonstrate the feasibility of this method for significantly improving the spatial motion accuracy of CNC machines.

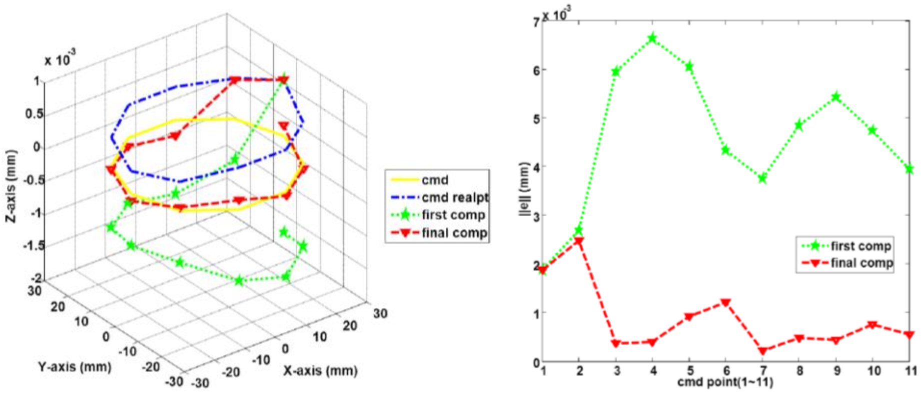

Fig. 1: Experimental results using developed software compensation method: (a) command contour (cmd, yellow); contour with pitch compensation (pitch comp, green); compensated contour with volumetric compensation (final comp, red); (b) volumetric error.

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