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# Online machining error estimation method of numerical control gear grinding machine tool based on data analysis of internal sensors

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ABSTRACT

This paper presents an online estimation method of cutting error by analyzing of internal sensor readings. The internal sensors of numerical control (NC) machine tool are selected to avoid installation problem. The estimation mathematic model of cutting error was proposed to compute the relative position of cutting point and tool center point (TCP) from internal sensor readings based on cutting theory of gear. In order to verify the effectiveness of the proposed model, it was simulated and experimented in gear generating grinding process. The cutting error of gear was estimated and the factors which induce cutting error were analyzed. The simulation and experiments verify that the proposed approach is an efficient way to estimate the cutting error of work-piece during machining process.



## 1. Introduction

Measurement is an important process in manufacturing. It facilitates comparison and examines distinguishing quality of products. As the cutting process involves motion, vibration and chips, it is difficult to measure the cutting error of the work-piece directly in machining process. Traditionally, off-machine measurement and on-machine measurement are the two types of method that examine the manufacturing accuracy. Off-machine measurement takes place upon the completion of manufacturing [1]. It is a low cost but high precision metrology that uses manual sampling inspection to measure error. However, the measuring process is time consuming and the measured work-piece has to be removed from machine tool before carrying out the measurement. On the other hand, on-machine measurement is widely used in gear cutting machine tool [2,3]. However, such measurement can only be done while idling the machine, which prolong the whole manufacturing process. In addition, on-machine measuring devices are expensive which would incur higher production cost. The two above-mentioned methods both interrupt the production process and thus result in reduced productivity. These traditional methods also have the shortfall of inability to promptly detect any abnormal condition of machine tool.

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Abnormal behavior of machine tool that could be detected by monitoring tool condition is the direct cause for machining accuracy to alter. Information related to machining accuracy is therefore collected during cutting process instead of through direct measurement. At present, virtual metrology (VM) is prevalent in electronics industry such as semiconductor industry [4,4–6] and TFT-LCD industry [7]. The VM is a technology to predict dimensional accuracy using information relating to the state of machine in each machining process [8]. Ferreira et al. [9] presented a methodology for the VM module based on non-linear neural network for individual process applications in factory. If the VM prediction model is up-to-date and accurate enough, the VM method could output accurate measuring result of each work piece quickly. The machine is a time-varying system, of which the characteristics will change over time, therefore, the VM conjecture model should be tuned by a fresh measurement data of work piece to keep the precision of the VM results. However, the measurement results of parts could not be obtained in time, which result in the forecast error of the VM method. Cheng et al. [8] proposed a dual-phase VM scheme that take into accounts of both promptness and accuracy with accompanying Reliance Index (RI) and Global Similarity Index (GSI). The researchers have developed different algorithms or mathematical methods to build the VM models of production processes, few of which are used in factory [4,6,10,11]. Cheng et al. [5] proposed the concept of Automatic Virtual Metrology (AVM) and developed an AVM system to facilitate the VM application in factory. The VM is also applicable to be used in machine tool. Tieng et al. [12] proposed a VM scheme to predict the straightness precision and parallelism precision of machine tool with wavelet filter. The straightness and parallelism error are mainly caused by the geometry error of machine tool whose value doesn't alter much. The VM is a feasible method to forecast accuracy of specific manufacturing process, however, it is difficult to apply the VM in machine tool as it requires extensive experiences to adjust the VM model.

During cutting process, it is more important to determine if the product accuracy meets requirement than simply calculate value of cutting error. Using internal sensors that contain abundant information of dynamic characteristics of feed drive system [13,14] is an interesting approach to monitor the machining process. Repo et al. [15] developed a measurement method to identify the individual tooth on a milling cutter with its angular position and found correlations between the state of individual teeth on the milling cutter and measured internal signals during machining process. Internal signals are employed to monitor the wearing [16] and breakage of tool [17], motor fault [18,19], the collision [20], the lifespan of machine tool [13], force fluctuation of feed and cutting system [21], all of which are the error sources of feed system. It is possible to forecast the product accuracy during machining process with signals of internal sensors.

This paper presents an online error evaluation method to judge the accuracy status of work-piece and it is organized as follows: Section 2 mainly introduces the error extraction method and error estimation principle. Section 3 provides an outline of error evaluation implementation method in gear grinding process. The proposed method is simulated and experimented in Section 4 to test its efficiency and the reliability. Section 5 serves as the conclusion that sums up the main research findings of this paper.

## 2. The basic principle of online error estimation

### 2.1. Error source and extraction method of internal signal

In ideal circumstances, the accuracy of machine tool is stationary. However, the working conditions and wear condition induce error variation, which are the primary cause of unqualified product with error out of band, especially in precision machining process. The non-stationary error sources are recorded in the motion signals of the machine tool.

The error $e_d(s)$ that caused by the dynamics of feed system could be expressed in Laplace domain as [22]

$$e_d(s) = (Js^3 + Bs^2)x(s)/(Js^3 + (B + k_i k_f k_{pd})s^2 + k_i k_t k_{pp} s + k_i k_t k_{pi}) \tag{1}$$

where $J$ is equivalent inertia of feed system, $B$ is the viscous damping, $k_{pp}$,$k_{pi}$,$k_{pd}$ are the parameters of PID controller, and $k_i$ is the current gain of amplifier, $k_f$ is the force constant of motor. $x(s)$ is the command of system.

The error $e_{fd}(s)$ induced by disturbance such as cutting force, load and control characteristic could be described as

$$e_{fd}(s) = sF_d(s)/(Js^3 - (k_i k_f k_{pd} - B)s^2 - k_i k_t k_{pp} s - k_i k_t k_{pi}) \tag{2}$$

In closed loop machine tool, there are some factors that induce misalignment of theoretical spatial position and actual position. The misalignment $\delta p_i$ is calculated as follows

$$\delta p_i = p_{ti}(x, y, z) - p_{ai}(x, y, z) \tag{3}$$

where $p_{ti}(x, y, z)$ is the theoretical position, $p_{ai}(x, y, z)$ is the actual position, and the subscript $i$ is axis index. Consequently, according to Eqs. (1), (2) and (3), the dynamic error $e_i$ can be defined as

$$e_i = \delta p_i + e_{fdi}(t) + e_{di}(t) \tag{4}$$

In Eq. (4) the $\delta p_i$ is stable during machining process, hence, $e_d(s)$ and $e_{fd}(s)$ determines whether the machining precision is as expected or not.

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