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# Characterization of closed-loop measurement accuracy in precision CNC milling

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**Abstract**

This study investigates the closed-loop measurement error in computer numerical controlled (CNC) milling as they relate to the different inspection techniques. The on-line inspection of machining accuracy using a spindle probe has an inherent shortcoming because the same machine-produced parts are used for inspection. In order to use the spindle probe measurement as a means of correcting deviations in machining, the magnitude of measurement errors needs to be quantified. The empirical verification was made by conducting three sets of cutting experiments, followed by a design of experiment with three levels and three factors on a state-of-the-art CNC machining center. Three different material types and parameter settings were selected to simulate a diverse cutting condition. During the cutting, the cutting force and spindle vibration sensor signals were collected and a tool wear was recorded using a computer vision system. The bore tolerance was gauged by a spindle probe as well as a coordinate-measuring machine. The difference between the two measurements was defined as a closed-loop measurement error and the subsequent analysis was performed to determine the significant factors affecting the errors. The analysis results showed the potential of improving production efficiency and improved part quality.


*Keywords:* On-line and off-line inspection; Touch probe; CNC machining

## 1. Introduction

Discrete part manufacturing using computer numerical controlled (CNC) milling machines is common in modern manufacturing [1]. Depending on the accuracy and surface finish requirements, the machining parameters, which have a significant influence on part quality, need to be set properly [2,3]. Vibration in machining is particularly harmful in this regard [4], yet can be minimized through the use of computer simulation prior to the machining. The simulation can project the optimal range of cutting speeds and feed rates for a chatter-free machining, thereby producing less scrap and enhancing part quality. Since each machine tool exhibits disparate dynamic characteristics [5], the importance of pre-machining simulation is applied to each machine, especially when the machine is newly acquired. In this study, CutPro® milling simulation software accompanied by a hammer test was used to generate a set of vibration free-cutting parameters. Equally important in machining is the confidence in the measuring instruments from which part quality characteristics are ascertained. Part dimensional accuracy check has been largely based on the post-process inspection such as a coordinate measuring machine (CMM). CMMs are widely used in the manufacturing industry for precision inspection and quality control [6,7], and recognized as reliable and flexible gauges suitable for assessing the

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acceptability of machined parts [8]. The downside of this technique is that non-conforming parts can be produced between inspections since there can be a significant delay between the production and completion of inspection [3].

To remedy the problem, a machine-mounted touch probe has started gaining popularity, which has the similar working principles of CMM [9]. The probe enables the measurement of machined parts while they are still fixed on the machine. By providing part size information directly into a CNC controller, a closed-loop process control can be realized in the form of real-time automatic tool offset to correct deviations or prevent defects in machining [10]. This is particularly important for a modern, computer-controlled production environment, where very little human intervention is expected during the machining cycle. The accuracy of the probe, however, is affected by the machine tool's positional accuracy and positioning system [10,11]. Since the same machine, which produces the parts is used for inspection, there is an inherent problem in the accuracy of probe inspection. Therefore, in order for the probe data to be used for real-time control, the capability of probe needs to be analyzed and the factors affecting the probe data need to be ascertained. This step is important since the discrete part manufacturing industry is shifting towards 100% part inspection for zero defect.

## 2. Cutting experiments

To address the aforementioned problem, a newly acquired, state-of-the-art Cincinnati Arrow 750 CNC Vertical Machining Center was used to conduct the cutting experiments (see Fig. 1). Cutting experiments allow the production engineer to adjust the settings of the machine in a systematic manner and to learn which factors and interaction effects have the greatest impact on the part quality before the machine is put to use for production. This step is necessary, because in metal cutting, most process control models are based on the empirical data and no universal mathematical models exist [12–15]. The impracticality of theoretical models for predicting quality characteristics is well known in metal cutting [16–18].

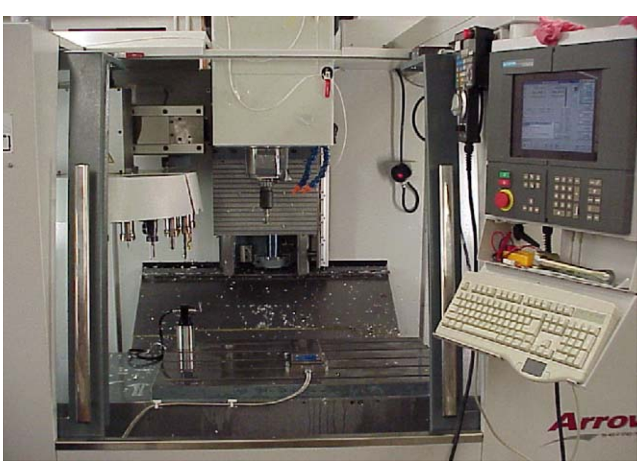

Fig. 1. Experimental setup showing the table mounted Kistler force dynamometer and the spindle housing mounted Kistler accelerometer.

Three material types that are widely used in both automotive and aerospace industry (6061-T6 aluminum, 7075-T6 aluminum, and ANSI-4140 steel) were selected. One-inch diameter end mill was fixed in the spindle and the hammering on the tool was analyzed to determine frequency response function of the machine tool structure. The stability lobe graph generated by the CutPro® software provided the combination of depth of cut and cutting speed for minimum chatter in machining. Consequently, the axial and radial depth of cut and cutting speed were tuned for a chatter-free machining. Each machined block has two stepped bores (65 and 50 mm diameter). The bores were selected as the critical quality characteristics because circularity and cylindricity of machined parts are regarded as the most fundamental geometric features in engineering [19]. To ensure the proper functioning of round parts, permissible deviations from the true circle are allowed in the form of tolerance zones bounded by two concentric circles [19], which dictate the desired dimensional and form accuracy [20]. The bores have a tolerance of $-0.1$ mm, corresponding to an ISO tolerance grade of IT10. Tolerances were measured using a spindle probe (a Renishaw MP 700 surface sensing wireless probe with 0.00001″ repeatability) and a newly calibrated Mitutoyo B403B CMM. Fig. 2 shows the sensors, the probe, and examples of machined blocks. The CNC mill was fitted with multiple sensors and data acquisition systems to collect cutting force measurements and spindle housing vibration/acceleration. Each measurement was further divided into components: $x$, $y$, $z$ cutting force components ($F_x$, $F_y$, $F_z$) and $x$, $y$, $z$ spindle housing vibrations ($A_x$, $A_y$, $A_z$). Those components were filtered and processed for both time and frequency domain features. The arithmetic averages, $F_v$ and $A_v$, were also calculated. For aluminum parts, a high-speed steel (HSS), 2-flute, cobalt end mill cutter was used until the tool wore out. For steel, an uncoated, 2-flute, tungsten carbide cutter was assigned. All cuttings utilized coolant to minimize friction and overheating.

After each block was machined, the tool was removed from the spindle and the wear on the cutting edges was measured using a computer vision system. A custom fixture was built to support the tool holder at a constant focal length. An integrated white LED light was used to illuminate the cutting edges. A DVT 540 CCD camera with $640 \times 480$ pixel resolution was connected to the