A Comparison of Force and Acoustic Emission Sensors in Monitoring Precision Cylindrical Grinding

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Abstract
Aerostatic spindles are used in precision grinding applications requiring high stiffness and very low error motions (5 to 25 nm). Forces generated during precision grinding are small and present challenges for accurate and reliable process monitoring. These challenges are met by incorporating non-contact displacement sensors into an aerostatic spindle that are calibrated to measure grinding forces from rotor motion. Four experiments compare this force-sensing approach to acoustic emission (AE) in detecting workpiece contact, process monitoring with small depths of cut, detecting workpiece defects, and evaluating abrasive wheel wear/loading. Results indicate that force measurements are preferable to acoustic emission in precision grinding since the force sensor offers improved contact sensitivity, higher resolution, and is capable of detecting events occurring within a single revolution of the grinding wheel.

Introduction
AE measurement has been the most popular approach used to monitor grinding processes for the last two decades. AE sensors offer advantages such as low cost and easy installation, with no reduction in machine tool stiffness. Dornfeld and Gomes de Oliveira’s 2001 AE review paper showed that acoustic emission sensors may be used to monitor the following grinding processes: contact and collision detection, workpiece runout, defect detection, grinding burn/damage, radial wheel wear, wheel runout and profile measurements, wheel sharpness, chatter/vibration, dressing tool wear, and workpiece thermal deformation [1]. Despite the promising demonstrations for detecting grinding phenomena with acoustic emission sensors, industrial applications are mostly limited to contact detection [2].

Force-measuring instrumentation is generally more expensive than acoustic emission sensor systems, so it is most often used in research applications. For cylindrical grinding operations, researchers historically built custom force measurement systems, although commercial rotating dynamometers are now available [3]. In this work, we use non-contact, high sensitivity capacitive displacement sensors to measure relative displacements between the rotor and stator of the workpiece spindle. This approach is stable, robust, accurate, and offers excellent resolution for the low forces encountered in precision grinding. The instrumented spindle built for this work provides real-time force measurement with 25-mN resolution and 300 Hz bandwidth.

Experimental Setup
Figure 1 shows the instrumented spindle designed specifically for measuring radial forces in the normal and tangential directions during cylindrical grinding. The design features an aerostatic spindle (Professional Instruments 4R Twin-Mount) with a frameless, brushless, DC motor and a 1024 count rotary encoder (Heidenhain) for synchronized data acquisition. Two stator-mounted, high-resolution capacitive displacement sensors (2 mV/nm Lion Precision C1-C) target the rotor in orthogonal directions. Figure 1 also shows the mounting location of the acoustic emission sensor (Kistler 8152B2), which is located as close to the workpiece as possible.

It is important to note that AE sensors are most effective when located near the point of grinding. In conventional grinding, this means that the AE sensor is located on the housing of the work or wheel spindle. In precision and ultra-precision grinding, which usually use aerostatic spindles, a thin film of high-pressure air supports the spindle rotor. As a result, the AE signals are significantly attenuated due to lack of mechanical contact between the stator and rotor.

All experiments were carried out on a two-axis grinding machine (Moore 450) with a programmable resolution of 0.1 micrometers. During experiments, the grinding area is generously flooded with an emulsion coolant. Both the acoustic emission sensor and the capacitance probes are protected from the flood coolant by a shield that is not shown.
The grinding experiments conducted for this research are on the outer diameter of cylindrical workpieces. The results and approach are also applicable to inner diameter grinding, which is notoriously difficult to monitor because of the low force levels. The cylindrical workpieces are Ø25 mm by 18 mm long and made of 416 or hardened 440C stainless steel. The work spindle rotates at 500 RPM. The abrasive wheel is a 7-inch diameter, ½-inch wide aluminum oxide wheel (Norton 38A46-H8VBE) rotating at 3300 RPM. The wheel is dressed with a single-point diamond tool at 375 mm/min and only 3 mm of the wheel width is used. The feed rates and radial depths of cut vary and are reported individually for each experiment.

**Experimental Results**

The first experiment explores the resolution and sensitivity of the instrumented spindle. In this experiment, successive low-force grinding passes were made on the outer diameter of a cylindrical 416 stainless steel workpiece as the radial depth of cut is increased. In the first pass the grinding wheel is actually retracted from the workpiece by one micrometer so that the only interaction between the workpiece and wheel is through the grinding coolant. The traverse speed is 375 mm/min.

Several trends are observed in this experiment. First, the signal from the AE sensor erroneously detects contact since its signal is affected by the machine noise and/or workpiece-coolant interaction as shown by the non-grinding (-1.0 micrometer) pass. In contrast, the force measurement is not sensitive to this interaction and achieves more accurate contact detection. Second, the RMS AE signal does not correlate well to depth of cut, especially below 0.4 micrometers where the RMS value only increased above the noise floor by 1 mV. Third, the section view of the 1.6 micrometer pass displays the intra-revolution characteristics of each signal for fifteen workpiece revolutions. The force signal clearly shows a repeatable, cyclical wheel-workpiece interaction synchronous with the rotation of the grinding wheel. This same wheel-synchronous fluctuation is commonly seen in surface grinding force measurements taken with three-component dynamometers. In contrast, it is difficult to correlate the AE signal with the grinding process for a single revolution of the workpiece or grinding wheel. The final observation is that notable spikes are observed in the AE signal of Figure 2 for the three heaviest depths of cut. The source of the spikes is unknown, but they could result from abrasive grain fracture.

The second experiment examines the ability of the sensors to detect workpiece defects. The defect is a small flat milled into the outer diameter of the 416 stainless steel workpiece. The initial depth is 0.18 mm, which corresponds to a 3 mm flat width $w$. The total part length is 19 mm and the flat length is 8 mm. The outer diameter of the workpiece is ground at a traverse rate of 150 mm/min with five-micrometer radial depths of cut until the flat is completely removed (36 passes).

Figure 3 shows 3D plots of the normal grinding force superimposed (wrapped) around the cylindrical geometry of the workpiece. A slice from the 3D plot gives a polar plot showing the normal force as a function of the angular orientation of the workpiece. The flat is clearly detectable since the normal force drops to zero as the wheel passes over the flat. The sequence of 3D plots demonstrates the elimination of the defect as the flat is removed by successive grinding passes. The higher frequency (helical) undulations are caused by repeatable variations in the grinding wheel and are synchronous with the wheel spindle (which does not rotate at an integer multiple of the work spindle).
Figure 2: Force and AE output from eight consecutive grinding passes at increasing radial depth of cut.

Figure 4 shows the unwrapped force data for a single grind ($w = 1.7$ mm) on the workpiece. The figure shows that the workpiece defect is plainly visible in the normal force data, but almost completely absent from the AE sensor. The defect is easily detected in the force data where the abrasive wheel loses contact and the force goes to zero. The defect is more difficult to see within the AE data and the signal does not show the full loss of wheel contact seen in the force signal. This characteristic is best examined in the section view of the graph.

The third experiment compares the ability of the sensors to detect changes in the condition of the grinding wheel that loads and wears over time. The experiment is performed with a hardened 440C stainless steel workpiece, which wears the wheel much more rapidly than 416 stainless steel. For this experiment, the abrasive wheel is freshly dressed, and the workpiece is ground while simultaneously recording the force and RMS AE signal over 45 consecutive passes. The radial depth of cut is three micrometers and the axial feed rate is 225 mm/min. Figure 5 shows the low-pass filtered normal force, tangential force, and AE signals for each of the 45 passes. Both the AE and the force sensors can detect changes in the wheel condition during the grinding process, but the AE sensor consistently shows an unexplained drop off in the middle of the workpiece.

Figure 3: 3D force maps of the normal force when a defect is present in the workpiece.
Conclusion
Monitoring cylindrical grinding is advantageous in optimizing process conditions, improving process control, and producing high quality parts. This is challenging in several precision applications where aerostatic spindles and small depths of cut are common. Detecting small forces with a conventional force sensor requires a compliant element in the machine’s force loop, which reduces machine stiffness and degrades precision. AE sensors, which do not degrade machine stiffness, are therefore more common in industry, but they are less sensitive when grinding with aerostatic spindles, where rotor vibrations are not transferred to the spindle housing via mechanical contact. For precision cylindrical grinding of inner or outer diameters, feedback from a force-sensing spindle provides higher measurement sensitivity than acoustic emission, and the measurements correlate with physical aspects during the grinding process.

References