A pneumatic sensor for grinding wheel condition monitoring

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Abstract

This paper presents the proof-of-concept of a pneumatic sensor for monitoring the performance of grinding wheels. The system concurrently considers the static and dynamic components of the back pressure signal, which refer to the position and topography of the functional wheel surface, respectively. Auxiliary experiments and numerical simulations are presented to demonstrate that the dynamic back pressure variations do indeed correspond to wheel topographic features. The performance of the sensor is evaluated with respect to wheel dressing, progressive wheel wear and grinding burn. The monitoring capability of the sensor is confirmed to be not compromised by the application of a flood coolant.

1 Introduction

Material removal in grinding involves controlled mechanical interference between the wheel surface and the workpiece. The topography of the active wheel surface is hence of significant importance in ensuring productive grinding performance. Since grinding is commonly the final stage in a manufacturing process chain, the roughness, geometry and metallurgical integrity of the generated surface are critical. Considerable research effort has therefore been expended into wheel condition monitoring. The goal of these efforts has been to address the industrial challenge [1] of maintaining optimal wheel topography through the course of grinding, to enable robust process output in the face of such inevitable disruptive factors as wheel wear and wheel variability.

Grinding wheel monitoring systems resort to indirect or direct methods [2, 3]. Indirect methods refer to the measurement of grinding responses such as force/power and acoustic emission to infer the state of wheel topography. Direct methods have largely involved the application of a laser in both reflection and triangulation modes to assess the extent of wear-flat formation on the wheel surface; the practical application of
such systems is limited by the obscuring influence of grinding fluid and debris. There is hence a need [4] for a system to monitor wheel performance, and to determine optimal wheel dressing intervals towards mitigating potential process faults like grinding burn, with minimal loss of productive grinding time spent on redundant wheel dressing. Along these lines, this paper presents the proof-of-concept of a pneumatic sensor for wheel condition monitoring.

Pneumatic sensors have long been used in industry for static or quasi-static non-contact measurement of fine displacement [5]. The operating principle of the sensor may be understood with reference to the schematic shown in Fig. 1. Compressed air supplied at a constant pressure flows through a control orifice, variable pressure chamber and nozzle, to impinge on a work surface positioned adjacent to it. In view of its substantial influence on the flow of air through the nozzle, the stand-off distance $x_i$ can be measured with reference to the back pressure $p_b$ in the variable pressure chamber. The application of this sensor has of late been greatly expanded, by adapting it to situations wherein a dynamic change in $x_i$ arising from say a rough surface moving lateral to the nozzle, is sensed by examining the corresponding variations in $p_b$. Examples include the in-process detection of porosity that surfaces up in castings being machined [6], and the assessment of the roughness of cut [7] and ground [8] surfaces in motion. A sensitive piezoelectric pressure transducer was used in the applications above to capture dynamic changes in the back pressure and map them to topographic features on the surface. The present work explored the feasibility of further enlarging the application envelope of the sensor by extending it to grinding wheel condition monitoring, wherein the relative speed is an order of magnitude higher.

Wager [9] investigated the effects of roughness and velocity of the work surface on the performance of a pneumatic sensor. His work was motivated by the need to understand possible adverse effects of these factors during in-process gauging of workpiece diameter in cylindrical and centreless grinding processes. He observed these to be of influence only when the roughness and velocity exceeded about 13 $\mu$m $Ra$ and 30 m/s, respectively.

![Figure 1: Principle of pneumatic roughness assessment [7].](image)
While this indicated these factors to be of no detriment when measuring the displacement of ground surfaces in-process, it serendipitously pointed to the opportunity of using a pneumatic sensor for grinding wheel condition monitoring.

Previous work on the application of a pneumatic sensor in wheel condition monitoring [10, 11] have used stand-off distances of several millimeters, which refer to an operating domain wherein the sensor is the least sensitive [7]. In such an instance, the sensor essentially probes the boundary layer around the rotating wheel, with a view to tapping into the significant effect of wheel roughness on the flow field around it [12], for the purpose of monitoring. While such systems have been shown to be capable of discriminating between dressed and glazed wheel surfaces, their utility is limited when a grinding fluid is applied [10] or when coarse wheels are used [11].

The present work involves stand-off distances that are three orders of magnitude smaller, which brings about a significant enough enhancement [13] in the dynamic performance of the sensor that features comprising the wheel topography may be directly resolved. Positioning the nozzle tip close to the work surface further facilitates the removal of any coolant or grinding debris off the wheel surface by the air jet issuing from the nozzle. In addition to being simple, robust and inexpensive, this is an enabling advantage of the pneumatic sensor in terms of its application in a machine tool environment.

Given the nonstationary, stochastic nature of grinding wheel topography, to ascertain that the sensor is indeed responding to surface elements of the wheel, its performance was hence first tested and validated on a knurled surface that comprises well-defined topographic features of a comparable scale. The sensor was thereafter applied to vitrified and metal-bonded grinding wheels, and its performance was evaluated in terms of wheel dressing, progressive wheel wear, and the incidence of grinding burn. Sensor performance is further demonstrated to be not compromised by flood grinding fluid application.

2 Experimental

Fig. 2 shows the experimental setup with the nozzle located against and normal to the peripheral surface of a grinding wheel. The reference position of the nozzle tip with respect to the wheel was established by grinding it in-place. The nominal stand-off distance $x_i$ between the nozzle tip and the wheel periphery is typically 75 $\mu$m or less, but is shown vastly enlarged here for clarity. A gauge pressure transducer (Omega PX309-50G5V) was used to measure the static back pressure that corresponds to the stand-off distance. This was complemented by a dynamic pressure transducer (PCB Piezotronics 112A22) to capture the pressure fluctuations that refer to topographic features. A regulated air supply of 275 kPa pressure was used throughout.
The pneumatic sensor is a first-order dynamical system, the performance of which depends significantly on its geometry [5, 13]. In terms of its application in wheel condition monitoring, a smaller nozzle diameter refers to a higher dynamic sensitivity, as changes in the air escape area arising from topographic variations constitute a relatively larger proportion of the mean air escape area. The operational range of stand-off distance however scales with the nozzle diameter, which limits the application of smaller nozzles to vitrified grinding wheels, due to its porous structure. Relative to the nozzle diameter, a smaller orifice diameter enhances sensor sensitivity, but at the expense of an increase in rise time and a reduction in the useful range of stand-off distance.

Based on preliminary investigations that were conducted to maximize sensor performance in consideration of these conflicting effects and requirements above, experiments relating to the vitrified wheel (32A60HVBE) and knurled surfaces involved nozzle and control orifice diameters of 1.2 mm and 1.0 mm, respectively; the corresponding values for the metal-bonded diamond wheel (140/170 mesh grit at 75 concentration) that is not as porous as the vitrified wheel were 0.6 mm and 0.4 mm.

3 Results and discussion

Fig. 3a refers to a preliminary experiment, and shows the dynamic back pressure signal acquired at a rate of 50 kHz from a vitrified grinding wheel translating laterally past the nozzle at a peripheral speed of 20.3 m/s (21.6 Hz). The range of variation in voltage of about 200 mV maps to a back pressure fluctuation of approximately 26 kPa. To place this signal in perspective, back pressure variation for a stationary grinding wheel under identical operating conditions is depicted in Fig. 3b. The marked difference in pressure variation was a first good indication of the pneumatic sensor likely responding
Figure 3: Dynamic back pressure signal referring to: (a) rotating, and (b) stationary grinding wheels.

to features on the grinding wheel surface.

Examination of the dynamic back pressure signal seen in Fig. 3a in the frequency domain (Fig. 4a) revealed peaks repeating at multiples of the wheel rotational frequency of 21.6 Hz (Fig. 4b), which were discernible at frequencies as high as ≈25 kHz (Fig. 4c). The relative peak amplitudes were further found to be dependent on the location of the nozzle along the wheel width, but with no systematic trends, which reflects the stochastic structure of the grinding wheel. The peaks in the spectra aligning with the rotational frequency of the wheel indicates that the sensor is responding to one or more features on the wheel surface for each wheel rotation. It is however not certain if the peaks correspond to specific surface features on the wheel such as abrasive grains and pores, or if they are essentially harmonics of a lower frequency. Experiments were hence conducted on a knurled surface, considering it as a deterministic equivalent of a grinding wheel.

Figure 4: Frequency spectrum of the dynamic back pressure signal referring to a rotating grinding wheel.
These experiments verified the dynamic pressure variations to be driven by the defined geometric features on the knurled surface, as detailed in the following.

3.1 Experiments on a knurled surface

Fig. 5a shows the frequency spectrum of the dynamic back pressure signal from a rotating knurled cylindrical surface at a stand-off distance of 20 µm, with the knurl geometry corresponding to a pitch of 0.85 mm, a width of 1.25 mm, and a height of 0.35 mm. In comparison to the signal referring to a relatively smooth surface, this spectrum is differentiated by the presence of prominent peaks at frequencies of 485 Hz, 24,434 Hz and 24,919 Hz. This deviated from the expectation of a single peak at 23,529 Hz, in consideration of the surface speed of 20 m/s (34.7 Hz) and the nominal knurl pitch of 0.85 mm. An increase in the peripheral speed to 30 m/s (Fig. 5b) proportionally shifted the frequencies at which the said peaks appeared (728 Hz, 36,650 Hz and 37,378 Hz) with the rest of the spectrum essentially remaining in place, indicating the prominent peaks to reflect geometric features on the knurled surface. The frequency plots in Fig. 5 denoted another interesting feature that the difference between the frequencies of the high-frequency twin peaks is the same as the frequency of the peak manifest at the lower frequency; in Fig. 5a: \((24,919 - 24,434 = 485)\), and in Fig. 5b: \((37,378 - 36,650 = 728)\).

In order to understand this intriguing behaviour and to benchmark sensor performance, it was deemed essential to numerically simulate the ideal response of the

Figure 5: Frequency spectra of the dynamic back pressure signal from a knurled surface at speeds of: (a) 20 m/s, (b) 30 m/s.
pneumatic sensor in consideration of the geometry of the knurled surface. Referring back to Fig. 1, the back pressure $p_b$ is determined by the air escape area, which for a smooth and flat surface is given by the product of the circumference of the nozzle and the stand-off distance $x_i$. For a rough surface, on the other hand, the air escape area is obtained by integrating the distance between the surface and the nozzle tip along and around the nozzle circumference. As an example, for an ideal sinusoidal swept surface shown in Fig. 6a, the air escape area for a given nozzle position is obtained by integrating the profile shown in Fig. 6b, which represents the local distance between the nozzle and the surface along the perimeter of the nozzle.

Figure 6: (a) A model sinusoidal swept surface, and (b) schematic representation of the local stand-off distance around the nozzle circumference for a given nozzle position.

As the nozzle traverses lateral to the surface, the air escape area changes with the passing of each topographic feature, bringing about a corresponding change in back pressure that reflects the geometry of the surface. The practical implication of this interesting aspect is the capability of the sensor to resolve features on the surface that are small relative to the footprint of the nozzle. For instance, referring to Fig. 6a, the sensor can trace profiles that are of a wavelength smaller than the nozzle diameter. In consideration of the above, in order to simulate the ideal sensor response, a circle of the same diameter (1.2 mm) as the nozzle was projected over a geometric model of the knurled surface at a stand-off distance of 20 $\mu$m (Fig. 7a). The air escape area was calculated by integrating the local stand-off distance along nozzle circumference for each incremental position of the nozzle as it traverses laterally atop the knurled surface. Considering that the surface topography around and beneath the nozzle circumference is the complement of the corresponding air escape area, Fig. 7b represents the topography of the knurled surface for 3 consecutive nozzle positions. A depiction of 40 such successive increments can be seen to reconstitute the topography of the knurled surface (Fig. 7c). Just about two columns of knurls are evident in Fig. 7c as the simulated area is limited to the confines of the nozzle diameter.

To synthesise the corresponding dynamic back pressure signal, the change in the projected escape area at different instants of time was calculated for twenty thousand
increments, for conditions consistent with those referring to Fig. 5a. This information was then transformed into the frequency domain (Fig. 8) for a comparison with the experimentally obtained frequency spectrum (Fig. 5a). The correspondence is indeed good in so far as the appearance of a peak at the lower end of frequency at 491 Hz, as well as the two higher frequency peaks at 23,684 Hz and 24,175 Hz. As was the case in the experimental results (Fig. 5a and Fig. 5b), the separation between the high-frequency peaks was further identical to the frequency of the peak at the lower frequency (24,175 – 23,684 = 491). This clearly attests to the signal obtained from the pneumatic sensor (Fig. 5) to indeed refer to surface topographic features on which the air jet is

Figure 7: (a) Solid model of knurled surface, (b) knurled surface topography corresponding to three nozzle positions, and (c) visual representation of the knurled surface reconstructed by considering variations in escape area.

Figure 8: Frequency plot of the simulated dynamic back pressure signal corresponding to the knurled surface.
incident on. The simulated results (Fig. 8) further comprise three peaks at 47,368 Hz, 47,859 Hz, and 48,350 Hz: the first and third of which are harmonics, being twice that of 23,684 Hz and 24,175 Hz. The middle of the three is a consequence of the nozzle diameter being close to the width of the diamond knurls, thereby detecting staggered peaks from two adjacent columns. These peaks are not present in the corresponding experimentally obtained spectrum (Fig. 5a), which indicates the dynamic sensitivity of the pneumatic sensor to be insufficient to register these high frequency events.

In deciphering the origin of the prominent peaks at the lower end of frequency in Fig. 5, closer examination of the knurled surface indicated the lines of knurls to be not parallel, but oriented at an angle to the direction of nozzle traverse (see Fig. 9a), forming helices around the cylindrical disk. This causes the sensor nozzle to cross multiple columns of knurls as the disk rotates. In this instance, there were 14 columns corresponding to 14 helices on the surface of the knurled disk. The peak at the frequency of 485 Hz in Fig. 5a therefore reflects the presence of the helices and the rotational speed: $14 \times 34.7 \text{ Hz} \approx 485 \text{ Hz}$; the same rationale applies in Fig. 5b as well.

The orientation of the knurls relative to the nozzle traverse also explains the twin high-frequency peaks in Fig. 5 and Fig. 8. The effect of this difference in orientation is two-fold. Firstly, the frequency of back pressure pulsations is increased, since the knurl pitch in the direction of traverse is smaller than the absolute pitch of the knurls (0.85 mm) as seen in Fig. 9a. Secondly, individual knurls intersect the nozzle periphery at different locations around it. For instance, in the second quadrant of the nozzle (Fig. 9b), oncoming knurls will be detected incrementally further up and to the right in the clockwise direction, at the leading edge of the nozzle. The point of intersection therefore continually moves towards the approaching knurls, which increases the pulsation frequency. In the first quadrant of the nozzle, this effect is exactly the

![Figure 9: Effects of knurl column orientation relative to nozzle traverse direction.](image-url)
opposite, which decreases the frequency. The effect is also manifest in the trailing edge of the nozzle, with the frequency decreasing in the third quadrant and increasing in the fourth quadrant. For a circular nozzle, such a change in frequency follows a sinusoidal pattern. For a single line of knurls traversing the nozzle width in time $t$, this represents a total shift in frequency of $(1/t)$. For several lines of knurls as in our case, the separation between the frequency peaks will therefore be given by the product of the number of helices and the rotational frequency. This explains the manifestation of the high-frequency twin peaks, and the difference in the frequency between them being the same as the frequency of the peak at the lower end of the spectrum, as seen in Fig. 5 and Fig. 8.

With the experiments on the knurled surfaces above clearly demonstrating the capability of the pneumatic sensor to respond to small features and high speeds consistent with grinding, the next phase of experiments focused on grinding wheel condition monitoring.

### 3.2 Experiments on grinding wheel surfaces

The performance of a pneumatic sensor involves the nuance that the dynamic sensitivity of the sensor is affected by the static back pressure [7, 13], which in turn depends on the stand-off distance. This presents a problem in grinding wheel condition monitoring, considering that active wheel surfaces invariably entail simultaneous changes in position and topography during the course of grinding, due to such phenomena as grit wear/resharpening and wheel loading. For a given nominal stand-off distance, different wheel topographies would further correspond to different air escape areas and hence different back pressures, which would affect the dynamic response of the sensor. Ignoring this confounded influence can lead to an erroneous inference on the state of wheel topography. The stochastic nature of the wheel topography further dictates that the corresponding variation in dynamic back pressure along the wheel width be considered.

To ensure meaningful comparisons of dynamic response and to accommodate variations across the wheel width, a measurement system was devised to involve both the root mean square (RMS) value of the dynamic back pressure signal and the static back pressure, with multiple measurements realized at various stand-off distances and axial locations along the wheel width (Fig. 10). The state of the entire active grinding wheel surface is thereby quantified by the average RMS dynamic back pressure versus the average static back pressure characteristic (the RMS dynamic back pressure value was calculated using a time constant of 0.5 s, after high-pass filtering above 1 kHz to discard the influence of such factors as wheel runout).

This concept is illustrated in Fig. 11, which shows four such characteristics corre-
Figure 10: Measurement scheme involving multiple axial wheel locations and stand-off distances.

responding to as many wheel states of a metal-bonded diamond grinding wheel. The wheel states occur during the course of it being dressed at a speed of 20 m/s subsequent to truing, by feeding a set length of an alumina dressing stick into the wheel surface. The proposed measurement protocol facilitates a meaningful tracking of the RMS dynamic back pressure at a constant static back pressure, at say 3.6 V as indicated by the broken green line, and hence at a comparable dynamic sensitivity of the sensor. Comparing the interpolated values of the RMS value at a constant back pressure value further allows for not having to constantly adjust sensor position. The surface of the diamond wheel being rendered progressively rougher by the incremental dressing action is clearly reflected in the increasing RMS value of the dynamic back pressure signal. Similar results were obtained also for different topographies of a vitrified grinding wheel brought about by varying the dressing feed.

Fig. 12a depicts the sensor response in the case of a vitrified grinding wheel, under

Figure 11: Response of the pneumatic sensor when dressing a metal-bonded diamond wheel for various infeed of the dressing stick.
conditions of progressive wheel wear when grinding an annealed AISI O1 tool steel at a speed of 30 m/s, and after the occurrence of grinding burn. Each of the characteristics refer to 3 stand-off distances of 5 µm, 41 µm and 76 µm, and 7 axial locations spread over the grinding width of 25 mm, with no compensation for a change in the stand-off distance relative to the reference nozzle position. In terms of progressive wear, as compared to the dressed wheel, the characteristic is seen to have slid upward and to the left after 10 passes (each pass referred to 82.5 mm³ of material removal), indicating a rougher surface (an increase in the dynamic back pressure) that has nominally receded away from the nozzle tip (a decrease in the static back pressure).

This reflects the transient effects on the wheel topography associated with the first several grinding passes immediately after wheel dressing [14], during which there is a significant loss of abrasives and bond material from the wheel. Characteristics corresponding to passes 100, 200 and 400 indicate the wheel surface to further recede from the reference position, but at a relatively lower rate with just subtle changes in wheel topography. This is consistent with stable phase of wheel wear, during which time, a steady increase in grain wear induces periodic self-sharpening. Relative to the dressed wheel surface (Fig. 12b), the characteristic corresponding to grinding burn can be seen to have translated significantly to the top and to the right, referring to an increase in both the static and dynamic components of the back pressure signal. This is indicative of the wheel surface being rougher and having moved closer to the nozzle tip. Microscopic examination of the wheel surface confirmed this to be indeed the case, consequent to grinding burn-induced sporadic adhesion of comparably large, discrete clumps of burnt workpiece material on the wheel surface (Fig. 12c).

As alluded to in Sec. 1, the enabling aspect of the use of a pneumatic sensor in
Figure 13: (a) Sensor position relative to the zone of coolant application, and (b) effect of coolant application on the sensor response.

A machine tool is the capability of the air jet to mitigate the obscuring influence of machining debris and grinding fluid. To verify this feature, back pressure signals were obtained by locating the sensor displaced circumferentially about 220° clockwise from the grinding zone, towards which the flood coolant was directed (Fig. 13a). The application of coolant caused the wheel state characteristic to simply slide up alongside that corresponding to dry grinding (Fig. 13b), which indicates just an increase in the average static back pressure associated with a decrease in the nominal stand-off distance.

This was hypothesized to be caused by the rotating wheel transporting a thin layer of coolant all around its periphery, consequent to rejection of the fluid from the wheel surface due to centrifugal forces being never complete, as noted in Ref. [15]. This hypothesis was verified by an experiment in which an auxiliary air jet was designed to momentarily impinge on a rotating knurled disk just ahead of the sensor nozzle with a view to disrupting the fluid layer (Fig. 14a). Such an action was observed to instantaneously and repeatably displace just the datum of the back pressure signal, validating the hypothesis (Fig. 14b). The insignificant change in the magnitude of

Figure 14: (a) Experimental setup for coolant transport hypothesis testing, and (b) effect of the auxiliary air jet on the dynamic back pressure signal.
the dynamic back pressure (Fig. 13b & Fig. 14b) is reassuring in terms of the coolant application not compromising the ability of the sensor to monitor wheel topography.

4 Conclusions

The paper presented the proof-of-concept of the application of a pneumatic sensor for grinding wheel condition monitoring. Considering that this application involves concurrent changes in the position and topography of the active wheel surface, the proposed monitoring scheme entailed simultaneous measurement and appropriate consideration of both the static and dynamic components of the back pressure signal, which referred to the nominal stand-off distance and the wheel roughness, respectively.

Examination of the frequency characteristics of the dynamic back pressure signal from a grinding wheel indicated distinct peaks at multiples of the wheel rotational frequency, at frequencies as high as 37 kHz. Confirmatory experiments were conducted on a rotating knurled surface as a deterministic equivalent of a grinding wheel surface, at speeds of up to 30 m/s. A comparison of these results with those from a numerical model simulating the ideal output response of the sensor, validated the variations in the dynamic back pressure to indeed refer to wheel topographic features such as grains and pores. The performance of the sensor was thereafter assessed in terms of monitoring for wheel dressing, progressive wheel wear and grinding burn, referring to vitreous and metal-bonded wheels. Sensor capability was further demonstrated to be not affected by the application of a flood grinding fluid, which is an enabling aspect of this technology application in a machine tool environment.

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References


