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Pneumatic non-contact topography characterization of finish-ground surfaces using multivariate projection methods

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ABSTRACT

This paper reports on the application of multivariate analysis methods for the non-contact topography assessment of finish-ground surfaces of roughness in the range of 0.1–0.8 μm *Ra*. The roughness information is extracted from the frequency spectrum of the back pressure signal acquired using a pneumatic gauge as the surface traverses past the nozzle. Principal components analysis is demonstrated to be effective in the unsupervised classification of lapped and ground surfaces of an identical nominal roughness of 0.1 μm *Ra*, even under conditions that the corresponding frequency spectra are contaminated with noise and affected by vibration. Projection to latent structures analyses are further shown to be capable of discriminating cylindrical ground surfaces based on along-the-lay measurements from a rotating component, and formulating multivariate regression models appropriate for process monitoring.

1. Introduction

The roughness of a surface has a critical influence on its function and performance in numerous applications relating to such phenomena as friction, lubrication, reflectivity, corrosion and fatigue. At the present time, roughness is predominantly quantified using mechanical stylus or optical instruments that are well suited for measurements in a laboratory. They do not however lend themselves to in situ or in-process application in the typical harsh confines of a manufacturing environment. In this context, recent research efforts have focused on the development of alternative systems for the assessment of surface roughness [1,2].

One such system entails the application of a pneumatic gauge that is widely used in industry for the measurement of fine displacement. The application of a pneumatic sensor for assessing surface roughness was motivated by the observation that the reliability of pneumatic displacement measurement deteriorates significantly when the peak-to-valley height of the surface being gauged exceeds 3–5 μm [3]. The first work in this regard appears to be due to Nicolau [4] who utilized an air jet to relate the roughness of a surface to the back pressure measured using a water manometer. Further developments can be attributed to Hamouda [5] who conceived a twin jet co-axial gauging system with a view to expanding the measurement range, and to Tanner [6] who designed a pneumatic analogue of the Wheatstone bridge. Wang and Hsu [7] reported a linear relationship between the average voltage output of the pneumatic gauge and the corresponding *Ra* value of the surface characterized using a stylus instrument.

The reports above refer to the pneumatic sensor in contact with the workpiece, and the roughness estimated with respect to the nominal value of the back pressure signal. There are drawbacks to these techniques as measurement repeatability is influenced by the contact force developed between the sensor and the surface, as well as the contact initiating chatter when measuring fine surfaces. Furthermore, the surface being measured is stationary, with the unfortunate implication that it cannot be applied in-process. Woolley [8] demonstrated the application of fine pneumatic jets for mapping the two-dimensional spatial profile of a surface in a non-contact manner, at a relative speed of ~0.8 m/min and a stand-off distance of several microns; the fidelity of the system was shown to deteriorate at higher relative traverse speeds.

Development of the pneumatic gauge for dynamic applications has been receiving attention of late [9], such as for the in-process detection of surface porosity in machined castings [10]. A recent work [11] focused on adapting this technology for non-contact roughness estimation by relating the frequency content of the back-pressure signal to the microgeometry of the surface moving lateral to the nozzle. In light of the air jet being impervious to the influence of cutting fluid and machining debris, the significant potential of the system for in situ application in a machine tool environment was also demonstrated. The technique was further shown to be capable of rapid areal characterization of turned and milled surfaces with a roughness higher than ~0.8 μm *Ra*; in the case of finer surfaces, the

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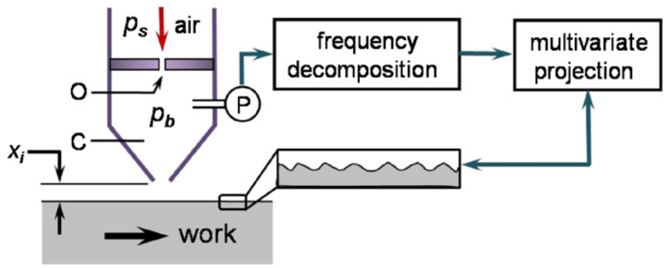

Fig. 1. Pneumatic roughness assessment of ground surfaces.

noise in the pneumatic signal was noted to obscure the signatures that correspond to roughness.

Following up on this limitation, the research presented in this paper refers to the pneumatic characterization of finish-ground surfaces of roughness ranging from 0.1 to 0.8 μm *Ra*. The frequency content in the back pressure signal is processed using multivariate projection methods [12] so as to identify and isolate the features pertaining to the surface topography. This process entails several steps including feature extraction and reduction, and calibration followed by empirical model development. The applicability of the methods for classification, discrimination and regression are demonstrated, as a step towards integrating the pneumatic system into a manufacturing stream for enabling real-time, in-process assessment. This is envisaged to facilitate 100% inspection and/or adaptive process control, which would concurrently enhance both manufacturing productivity and product quality.

2. Working principle

The operation of the roughness sensor (Fig. 1) involves the supply of compressed air at constant pressure p_s through a control orifice O to the atmosphere through a nozzle, past a variable pressure chamber C so as to impinge on a work surface adjacent to it. A change in the stand-off distance x_i between the nozzle tip and the work surface due to relative normal displacement between them alters the flow of air as it leaves the nozzle. This is reflected as a highly sensitive change in the back pressure p_b measured using a sensitive dynamic piezoelectric pressure transducer P. As the nozzle translates lateral to the surface, the change in back pressure corresponds to the change in the air escape area, which is determined by the surface topography. The escape area is obtained by integrating the local distance from the nozzle tip to the surface over the circumference of the nozzle. The effects of the nozzle geometric parameters and operating variables on the sensor characteristics can be found in [11,13].

As indicated previously, for cut surfaces of a relatively coarse finish, frequency decomposition of the back pressure signal alone was sufficient to characterize the surfaces in terms of the amplitude of the dominant peak and the area under the frequency plot (see Fig. 2). For the assessment of finish-ground surfaces, the addition of an analysis module referring to multivariate projection methods (Fig. 1) was required in order to handle issues with the pneumatic noise and the effect of vibration. There have been attempts [14–17] at numerical modeling of the performance of pneumatic gauging systems, however, these works do not consider a surface moving lateral to the nozzle. Given the lack of a fundamental physical model, it has been expedient to pursue an empirical approach in the present work.

The advantages of such a pneumatic system are several. The hardware is simple, rugged and inexpensive, and is maintenance-free on account of there being no moving parts. The sensor is also applicable to all work materials independent of such characteristics as reflectivity, and is amenable to application in confined

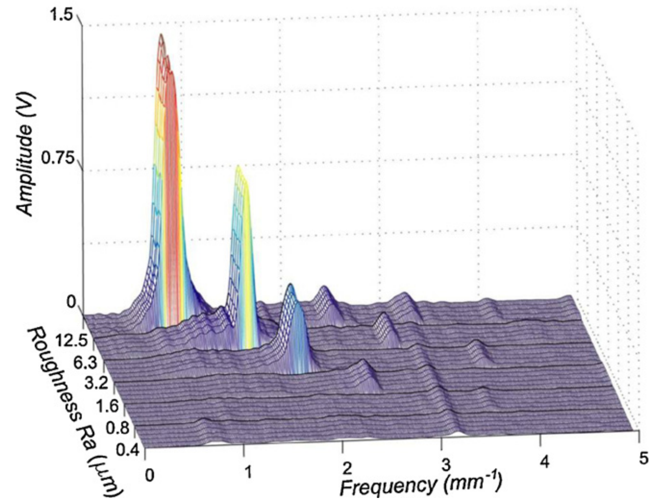

Fig. 2. Waterfall frequency plot of pneumatic signals from milled surfaces [11].

spaces such as bore holes of a high aspect ratio that could otherwise be inaccessible. In light of it being non-contact, the technique further circumvents problems arising from contact forces and friction, thereby facilitating the assessment of moving surfaces, with potential for in-process application.

3. Experimental

The objective of the experimental work was to establish the proof of concept of pneumatic non-contact roughness assessment of moving finish-ground surfaces. To this end, the first set of experiments focussed on the capability of the system to distinguish surfaces with the same numerical roughness but different topographic attributes. For these tests, planar lapped and ground surfaces of a nominal roughness of 0.1 μm *Ra* were used, and measurements were taken at a traverse speed of 0.4 m/min. Following this, experiments were conducted in situ on an external cylindrical grinding machine tool to collect pneumatic samples from two plunge ground surfaces of roughness 0.3 and 0.5 μm *Ra*, to test system performance when measurements are taken along the lay. The peripheral linear speed of the workpiece of diameter 58 mm was 1.5 m/min, with the nozzle traversing along the workpiece axis at a feed rate of 12.5 mm/min such that the measurement trace was practically along the grinding lay. The last set of experiments were conducted to formulate and evaluate a multivariate regression model suitable for process monitoring. This model was created using across-the-lay measurements at a traverse speed of 0.4 m/min on flat surfaces of roughness in the range of 0.1–0.8 μm *Ra*, which were generated in a surface grinding operation.

In all experiments, the pneumatic traces corresponded to a length of at least 10 mm, and several samples were collected to capture the variability in the surface. Experiments involving flat surfaces were conducted on a die sinker with the sensor mounted on the ram of the machine tool. Back pressure measurements entailed a dynamic piezoelectric pressure transducer (Model 112A22, PCB Piezotronics) with a rise time of less than 2 μs, and a low frequency response and a resonant frequency of 0.5 Hz and 250 kHz, respectively. All experiments corresponded to nozzle and control orifice diameters of 1.5 and 0.5 mm, respectively, and a supply pressure p_s of 138 kPa. A stand-off distance x_i = 25 μm was chosen in consideration of the requirements referring to a non-contact application and sensor sensitivity [11,13]. The precision machine tools on which the experiments were conducted allowed the control of x_i with a resolution of 0.1 μm. The volume of the variable pressure chamber in the pneumatic sensor was ∼300 mm^3.