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Pneumatic Non-Contact Measuring System for In-Process Dimensions Measurements

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Abstract

Pneumatic non-contact measuring systems are applied for automatic inspection for dimensions and forms. The dynamic characteristics of the systems were studied analytically and experimentally. Analytical relations considered the effect of the systems design parameters and measuring speeds on the system performance; measuring range, sensitivity and response time. Sets of experiments were performed at different measuring speeds on machined parts having different dimensions and forms. Comparison between the experimental and analytical results was performed. The experimental results showed conformity with those derived analytically. Pattern recognition methods were used to correlate the pressure variation with the measured dimensions and forms.

*Keywords:*metrology; measurement; in-process measurements

1. Introduction

Online part inspection plays an important role in the evolving concept of Industry Inspection and gauging systems applied in the case of in-process measurements may be mechanical, optical, or pneumatic in principle.Moreover, they can be integrated with the manufacturing system to initiate signals and relays for automatic gauging for online monitoring and control of the manufacturing process. The use of pneumatic gauging systems provides a non-contact technique, which can be advantageous for real time inspection of product dimensional and geometrical features.

The effect of design factorsof the back pressure type pneumatic system; the supplied air pressure value, the control and gauging nozzle diameters, and the volume of air enclosed in the air chamber on the system characteristics are presented [1]. The use of back pressure type pneumatic measuring system as a gauging for the measurement of diameters variation and hence roundness error of rotating cylindrical parts has been investigated [2]. Woolley [3] demonstrates the potential of pneumatic jets for mapping the two dimensional spatial profile with max, peak to valley height 0.001 mm at speed of 0.8 m/min. Development of the pneumatic gauge for dynamic applications has been receiving attention such as for the in-processdetection of surface porosity in machined castings [4]. Pneumatic non-contact roughness estimation by relating the frequency content of the backpressure signal to the micro geometry of the surface moving lateral to the nozzle tip has been investigated [5]. The principle of the measuring device for air gages dynamic characteristics in the measurement of the round profiles of motor cylinders is studied [6]. Analysis of the work conditions and the metrological characteristics of the air gauges dedicated for the roundness assessment is described [7]. A differential pressure pneumatic measuring principle is presented and employed for measuring the form error of the spool valve inner hole, some potential methods to improve the measuring accuracy are discussed [8]. The objective of the present work is to investigate the use of the back pressure type pneumatic systems for in-process dimension measurement in a dynamic setup. The investigation studies the change of the back pressure during the movement of the inspected surface as a result of the variation in the gap between the gauging nozzle

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and the surface to be inspected due to the surface geometry and the relative motion between the surface and the gauging nozzle. The study is carried out, both analytically and experimentally. Different surface geometries were used to create different conditions of gap variation; taper surface (ramp function), truncated groove (stepped form) and milled surface (wave form).

2. Analytical analysis

A scheme principle of the main elements of a back pressure pneumatic system is shown in Fig. 1. The air at a constant pressure (P_s) is supplied to a fixed flow restriction, control nozzle (d_c), and a variable flow restriction, gauging nozzle (d_n).The air flow from the gauging nozzle varied by the change of the air escaping peripheral area (A_e) between the nozzle tip and thesurface of the inspected part. The behavior of the pneumatic system in dynamic measurements is characterized by its operating characteristic relations which relate the change in back pressure (P_b) to the change of air escaping area. The escaping area ($A_e = \pi d_n c_m$) is in turn varied with thedisplacement (x) as the inspected surface moves laterally beneath the nozzle tip. For a limited range of motion, (P_b) is nearly proportional to change in the gap (c_m).

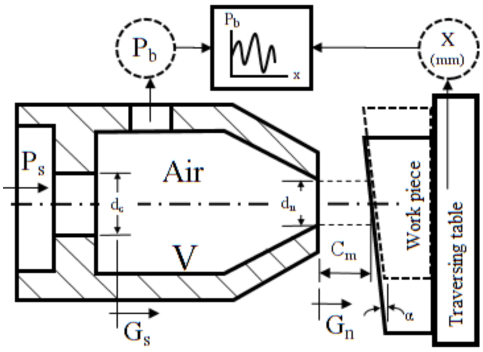

Fig. 1. Scheme of pneumatic in-process dimensions measurement

To study the behavior of pneumatic system for dimension measurement , the principle of conservation of mass (m) is applied to the air chamber of volume (V), the mass flow rate through the control orifice (G_s), depends on (P_b), and the mass flow rate through the gauging nozzle (G_n) depends on the pressure (P_b) and the escaping area (A_e).

To find out the equation governing mass flow rate through the gauging nozzle (G_n), it assumed that the process from (P_s, is for a perfect gas, work free and adiabatic. Also, the velocity of the gas in the volume (V), at pressure (P_b), is assumed zero. For time interval (t) the difference between entering mass and leaving mass must show up as an additional mass storage in (V) [9] therefore,

$$P_b = \frac{RT_b}{V}.m \qquad (1)$$

The operating point ($P_{b,}$) and ($c_{i,o}$) is in equilibrium condition, then G_s and G_n are equal to:

$$\frac{V}{RT_b}.\frac{dP_{b,p}}{dt} + (k_{np} - k_{sf})P_{b,p} = (-k_{nc})c_{i,p} \qquad (2)$$

To simulate the in-process measurement, an inclined surface of an angle α is assumed to move laterally beneath the gauging nozzle (Fig.1) with displacement (x), at speed (u) resulting in change in gap clearance at time interval (t): $t = c_{m,p} / u.\tan\alpha$

$$\frac{V}{RT_b}.\frac{dP_{b,p}}{dt} + (k_{np} - k_{sf})P_{b,p} = (-k_{nc})c_{m,p}.t \qquad (3)$$

Where $K_{nc} = \partial G_n/\partial c_i$, $K_{np} = \partial G_n/\partial P_b$ and $K_{sf} = \partial G_s/\partial P_s$are system constants that are determined experimentally, the change in the back pressure will be

$$P_{b,p} = K.u.\tan\alpha[\tau e^{-c_m/ut\tan\alpha} + \frac{c_m}{u\tan\alpha} - \tau] \qquad (4)$$

Equation represents the mathematical model of the dynamic characteristic of the back pressure type pneumatic system as a first order measuringsystem.The model relate the change in the back pressure (P_b) and the variation in the gap clearance (c_m) . The system time of response is given by:

$$\tau = \frac{V}{RT_b(k_{np} - k_{sf})} \qquad (5)$$

Minimizing the volume (V) and increasing of (k_{np}-k_{sf}) improves the system response.

3. Experimental scheme

An experimental rig was designed and built-up to simulate the conditions of the in-process measurement (as illustrated Fig. 1). It consists of constant pressure air supply (P_b), pneumatic measuring head, and traversing table. The air supply was fed to the measuring head at constant and predetermined pressure equal to 5 kPa. The contactless pneumatic measuring head contains the air chamber ***(V)*** of a volume of 11.1 cm^3, the control orifice and the gauging nozzle (dc and dn). A pneumatically actuated traversing air supported table was used as a driving mechanism for the measured parts. (u= 3 to 300 mm/min). A sensitive pressure and displacement transducers were used for pressure- displacement measurements. Pneumatic characteristics relations for sets of control orifices and gauging nozzles were investigated. The selection of the control orifice and the gauging nozzle combinations were based on this investigation to achieve appropriate values of sensitivity and range of measurement.

The experimental investigations were carried out to determine the back pressure displacement relations for surfaces having different dimensions and features. Three different workpiece geometries were used in the investigation. The first, is an angle gauge with an angle (α) = 0.01 rad. This was used to create measuring gaps of different values (ramp function). Besides that, the angle gauge provides reference dimension that can be considered as a calibrating experiments to determine the dynamic characteristics of the pneumatic system. Meanwhile, these results could be compared with those calculated using the analytical model (Eq. 4) to verify the applicability of the model to predict the system characteristics. The second is a surface with truncated groove. This was tested to simulate the inspection of geometry of complex form, and the third is a milled machined surface, which was used to provide inspection of surface topography.

The experiments were performed while the surfaces move beneath the gauging nozzle with different linear speeds ranging from 3 to 300 mm/min, at an average stand-off distance of 0.02 mm. Fig. 2 shows the stylus traces of the inspected truncated and milled surfaces.

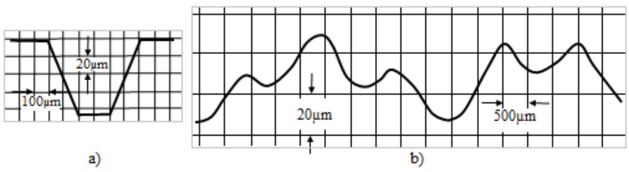

Fig. 2. Stylus traces of: a) truncated surface and b) milled surface

4. Results and discussion

The experiments were repeated five times to check the repeatability of the results. The mean variations in the experimental results were found to be 2.5%. Fig. 3 shows the experimental and the analytical results (Eq. 4) of the back pressure and surface displacement relations for inspecting an angle gauge with angle (α) = 0.01 rad (c_m = x tan α). The experiments performed at different surface speeds (U). Theresulted relations can be considered as the dynamic characteristics of the pneumatic measuring system. Additionally, the results show the effect of nozzles dimensions on both system sensitivity and range. The results are in good agreement with those calculated using the analytical model. The deviation between the experimental and the analytical results could be referred to the assumption of landless gauging nozzle in the analytical study.

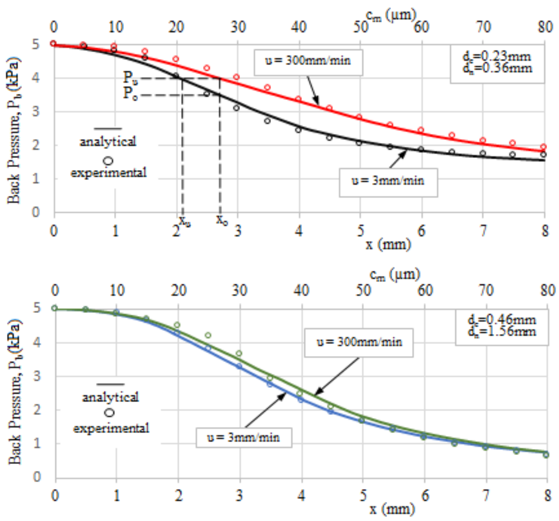

Fig. 3. Analytical and experimental pressure displacement relations

Referring to Fig. 3, the corresponding pressure for position (x_o) at a speed 3 mm/min is (P_o), while the pressure at speed (u) of 300 mm/min is (P_u). The time difference between positions (x_o) and (x_u) measures the response time (i.e. lag time) of the system. The response time can be determined experimentally, where $\tau = (x_o - x_u)/u$

The response times (τ) were determined from the experimental results are compared with those calculated using (Eq. 5) are shown in Fig. 4. Fair agreements between these results in the range of linear portion of pressure displacement relations are existed.

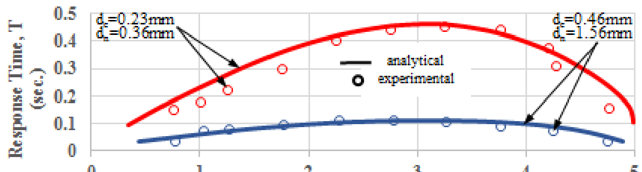

Fig. 4. Analytical and experimental results for system time response

The experiments were extended to inspect surfaces with complex geometry. Fig. 5 shows the pneumatic traces, pressure-displacement relations, for truncated groove and milled surfaces at different speeds.The results illustrate both the vertical and horizontal dimensions of the inspected surfaces.The conformity between the results of the stylus and the pneumatic traces (Fig. 2 and Fig. 5) for the inspected surfaces are remarkable.For the milled surface, nozzles sizes dc=0.23 mm. and dn=0.36mm., result in better detection of amplitude and spacing parameters, at speed of 125 mm/min.,which is equal to response rate of 8.33Hz. On the other hand, the pneumatic traces of the truncated groove were able tofairly illustrate their form and dimensions (w and h).

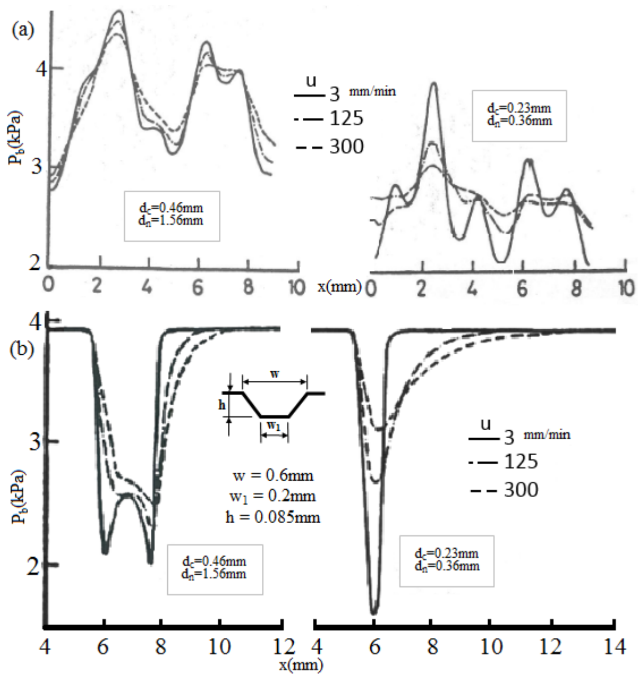

Fig. 5. Experimental results of pressure- displacement for:
a) Milled surface and b) Truncated surfaces

For complex surfaces, changes in surface height as the surface transverse past the nozzle tip, leads to a variation in the air escape area, which is reflected in the back pressure measurement. Fig. 6 demonstrates the variation in the air escape area (Ae), with the nozzle positions (a, b and c) for truncated surface. The peripheral escape area could be defined as the surface resulted from the intersection between an imaginary cylinder of diameter (dn) and the geometry of the inspected surface. For nozzle position (a) and stand-off distance (c), the escape area will be the area of the developed surface of an arc of length (Lx), which varies according to the position of nozzle tip relative to the inspected surface.

$$A_e = \pi d_n c_m + \int_0^h L_x \, dh \qquad (6)$$

Fig. 7 shows the deduced relations for surface displacement (x) and escape area (Eq. 6). According to the measuring system dynamic characteristics (Eq. 4), the corresponding change in P_b can be determined. Also, it can be seen that the groove width (H) in the pneumatic mapping can be expressed as a function of the groove width (w) and nozzle diameter d_n.

$$H = w + d_n \qquad (7)$$

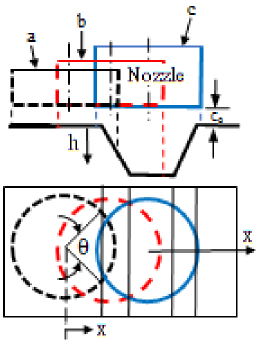

Fig. 6. Scheme of air escaping area variation for truncated surface

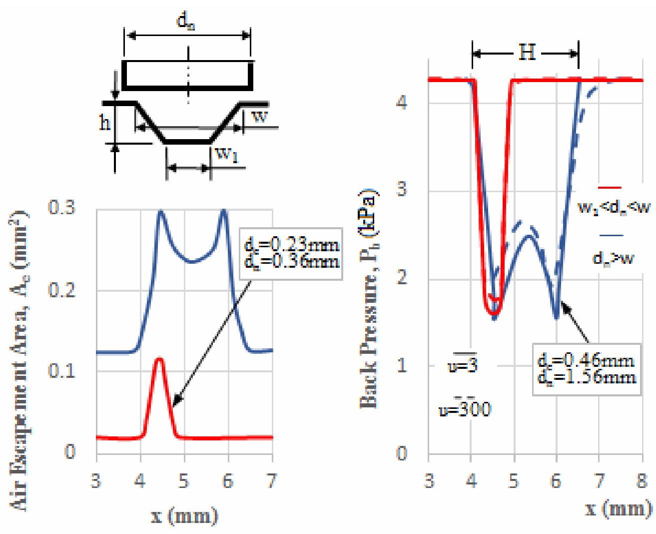

Fig. 7. Deduced air escaping area and pressurefor truncated surface

The deduce relation between pressure (P_b) and displacements (x). Fig. 7 shows good agreement between analytical and experimental results. The deviation between the deduced and the experimental relations could refer to the assumption of land less nozzle, system response and speed of measurements

This approach can be used as a pattern recognition technique to detect the surface dimensions, both vertically, and horizontally according to the measured pressure displacement relations of the inspected. Besides that, this approach can be beneficial in the real time or in-process monitoring and inspection of the machined surface with reference to the CAD model for online corrective action and tool path modification in multi-axis manufacturing.

5. Conclusion

The non-contact pneumatic measuring techniques provide an inspection system to measure the dimensions and form of the surfaces. Analytical relations considered the effect of the systems design parameters and measuring speeds on the system performance are presented. The experimental results of the system dynamic characteristic relations show good conformity with those deduced analytically. The measuring system show good capabilities either for measuring dimensions orfor predicting surface geometry. Apattern-recognition methods based on the correlation between the air escaping area and back pressure are introduces the results of measuring surfaces with different configurations simulate practical application showed good agreement between the analytical and the experimental results.

References

[1] Evans J., Morgan I, Principle of Pneumatic Gauging,Notes on Applied Science,vol.34, National Physical Laboratory,Middlesex,19
[2]Molle, R,1956, Recent Tendencies in Pneumatic Metrology, Microtecnic,vol. 10: p.p. 167.
[3]Woolley R, Pneumatic method for making fast, high resolution non-contacting measurement of surface topography, Proceedings of SPIE,1573:205-215,1992.
[4]Menzies I, Koshy P. In-process detection of surface porosity in machined castings. International Journal of Machine Tools and Manufacture;2009;49:530–5.
[5] Grandy D, Koshy P, Klocke F. Pneumatic non-contact roughness assessment of moving surfaces. CIRP Annals 2009; 58:515–8.
[6] Jermak G, Rucki Dynamic of the non-contact roundness measurement with air gage ,actamechanica et automatic, 20016. Vol.10, no.3
[7] Jermak G, Rucki M static characteristic of air gauge applied inthe roundness assessment. Metrology and measurement system, 2016Vol.xxii ,no 1 85-96
[8] Liu, J., et al. (2012). Design and accuracy analysis of pneumaticGauging for form error of spool valve hole. Flow Measurement andInstrumentation, 23, 26–32.
[9] Doebelin EO (2003) Measurement Systems: Application and Design.McGraw Hill, New