Pneumatic Non-contact Data Acquisition System For straightness Measurement of Cylindrical Parts

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Abstract—The surfaces obtained by machining deviate from the specified geometry. The standard ANSI Y14.5 requires the form error of a surface to be less than some set limits. Since the data achieved by different instruments have shown slight variation, the straightness errors calculated will not give the same result and so each measurement method will reflect its measurement error.

In this study, the straightness measurement for the cylindrical parts was carried out by using the computer aided pneumatic gauging system and compared with the measurements of other devices such as precision level, electronic comparator and autocollimator. Pneumatic gauging system can be used not only for straightness measurement but also in all profile measurements even in-process with suitable auxiliary devices. Increased production rate and quality systems require data recording and processing during the measurement. Therefore, the results of measurements achieved were transmitted into computer.

Keywords—Geometrical inspection, Air gauging, Straightness measurement, Data acquisition and evaluation.

I. INTRODUCTION

Traditionally, inspection has been mainly concerned with the measurement and gauging of linear dimensions and angles against the established standards and specifications. Generally, the features of the manufactured parts deviate in size and form. The accuracy of its size and form has a significant effect on the function of the final assembly. The features of manufactured parts are defined with their dimensions and tolerances. If form control is necessary then geometrical tolerances must be added to the engineering drawing. Geometrical tolerances, permitted deviation in form or position from desired geometry, should be specified for all requirements critical to the functioning and interchangeability of components. Expression of these tolerances refers to limits of size, flatness, straightness, concentricity, angularity, roundness, cylindricity, profile of a surface and profile of a line. Among these tolerance specifications straightness and flatness are more applicable in engineering designs. The geometric tolerance is, in essence, the width or diameter of tolerance zone within which a surface or axis of hole or cylinder can lie which results in resulting feature being acceptable for proper function and interchangeability. According to the ASME Y14.5M [1] standard, the purpose of geometric dimensioning and tolerance is to describe the engineering intent of parts and assemblies. Geometric tolerances affect dimensional tolerances. To evaluate the straightness errors from the measured points of the workpiece surface, the ideal lines have to be established from the actual measurement satisfying the requirements specified in the standard that defines the definitions and interpretation of dimensions and tolerances. However, ISO/R1101 [2] specifies the form errors in general scope.

Most instruments used in industry depend on discrete points to measure the specified dimensions and tolerances. The straightness tolerance is one of the fundamental geometric tolerances to be strictly controlled for guideways of machine tools, measuring machines, etc. The measured data do not give a direct assessment of form tolerance. The form tolerance is calculated according to the specified standard using the data obtained. Therefore, a number of methods have usually been applied for data acquisition in straightness calculation: laser interferometer with straightness optics, straight edge with displacement sensors and gap sensor, incremental angular measurement using autocollimator or angular measurement, pneumatic gauging with pressure transducer, etc [3, 4]. Different measuring instruments have been used to achieve the data for straightness error calculations. Since the data measured by different instruments have shown slight variation, it is clear that the straightness errors calculated will not give the same results. Consequently, each measurement method will reflect its own measurement error for straightness calculation.

Air gauges for dimensional measurement are known for the measurement and gauging of linear dimensions and angles. Air metrology instruments are the mainstay of production control in most industries. Air gauges are connected with pneumatic measuring devices able to generate control signals [5]. Air metrology instruments can provide comparative or quantitative measurements such as thickness, depth, interior and outer diameter, bore, taper and roundness with the properties of averaging and combining capabilities, adaptability to multiple dimension gauging, no sliding member, non-contact measurement and self-cleaning of the measured surface with the outflowing air [6]. Though nowadays advantageous measuring methods are developed, air gauging is still irreplaceable in many applications, especially...
in in-process control [7] and in unconventional measurements like measurement of extremely long microbores [8]. The air gauging system owing to capable of obtaining data continuously is used not only dimensional measurement but also used for measurement of form as static and dynamic. The technique used by Grandy at all. [9] is capable of rapid areal characterization of surfaces with roughness down to 0.8 μm $R_a$, at speeds as high as 200 m/min. For small changes in stand-off distance, the dynamic characteristics of a pneumatic sensor approximate to that of a linear, first-order system that can be modeled [10] with reference to its geometric parameters. Wooley [11] demonstrated the potential of pneumatic jets of diameter on the order of 75 μm to obtain two-dimensional spatial representation of a surface with a maximum peak to valley height of ~1 μm at speed of ~0.8 m/min.

Since the pneumatic system is non-contact gauging, cost effective and accurate enough for medium level straightness measurements and roughness estimating, it can be used widely in in-process control in industry. In this study, the data acquisition for the straightness profile measurement by non-contact pneumatic gauging system was introduced and carried out a test on the cylindrical part. Then, the results obtained were compared with the results of different methods such as precision level, electronic comparator and autocollimator.

II. DEFINITION AND EVALUATION OF STRAIGHTNESS

The majority of mechanical parts comprise of cylindrical features (internal and external). Two basic geometric characteristics that are used to control form and function of cylindrical features are cylindricity and straightness of an axis. Straightness error is defined as the maximum peak-to-valley distance from the ideal features. According to the standard mentioned above, straightness is a condition for which an element of surface is a straight line. A straightness tolerance specifies that each line element must lie in a zone bounded by two parallel lines separated by the specified tolerance and that are in the cutting plane defining the line element (Figure 1). For discrete measurement, straightness error is defined as the minimum separation between two parallel lines that enclose all the measured points. In addition, the feature must be within the specified limits of size and the boundary of perfect form at maximum metal condition (MMC).

Since the straightness profile is evaluated as the deviation of a given profile from a reference straight line, the measured profile is adjusted to give the straightness profile. Let $Y_j$ be a global profile, and $\delta Y_j$ be a straightness profile at $X_j$ position; the straightness profile $\delta Y_j$ can be evaluated as:

$$\delta Y_j = Y_j - AX_j$$

Figure 1: Specifying straightness of surface elements and straightness tolerance, $T_s$, is

$$T_s = \max (\delta Y_j) - \min (\delta Y_j)$$

where $A$ is the best-fit slope of the reference straight line for the measured profile.

There are presently three methods for the evaluation of straightness in the literature: least squares fit, end-point fit and minimum zone fit. Firstly, in the first method, the least-squares method (LSQ) is one of the commonly used techniques for form and profile errors evaluation [12, 13] due to its computational simplicity and solution uniqueness. It is to find the minimum sum of the squared errors of the measured points from the nominal feature. But, the objective function of LSQ is different from that of the minimum zone, whose objective is to minimize the maximum error between the measured point set and the fitted feature, and does not provide the minimum zone result. Therefore, LSQ provides sufficient initial values and the reduced computation time in the linear approximation technique.

As a way for overcoming the disadvantage of the end points fit, the slope $A$ can be evaluated using the points on the middle part as well as the end points. The slope of $A$ in equation (1) can be evaluated using LSQ technique, which is [14].

$$A = \left( N \sum_{j=1}^{N} X_j Y_j - \sum_{j=1}^{N} X_j \sum_{j=1}^{N} Y_j \right) \left[ N \sum_{j=1}^{N} Y_j^2 - \left( \sum_{j=1}^{N} X_j \right)^2 \right]$$

where $N$ is the total number of data points on measured profile.

Some of investigators [15, 16, 17, 18] have used to provide the minimum tolerance zone to verify the straightness and flatness of measured data points. Although, minimum zone methods (MZ) are mathematically complex and often computation time is slower, they become more common with the application of measurement devices. In MZ method the straightness tolerance is evaluated as the minimum distance between the two parallel straight lines enclosing the measured datum the slope $A$ can be determined so that the straightness tolerance (Equ. 4) is minimum. As a practical method,
Burdekin and Pahk [19] proposed the enclose tilt technique, where the slope can be evaluated using Equ. (4) if three enclosing points \( P_1, P_2 \) and \( P_3 \) are found with alternate signs.

\[
A = \frac{Y_{p3} - Y_{p1}}{X_{p3} - X_{p1}}
\]

(4)

Therefore, the straightness profile and straightness tolerance can be evaluated from equations (1) and (2). In order to obtain the desired results, reasonable initial estimates of the variables are required. Shunmugam [20] used the LSQ as the initial value and simplex search method to find the MZ solution.

III. DATA ACQUISITION TECHNIQUES FOR STRAIGHTNESS

The data for the same points predefined for straightness measurement have been obtained by using different kinds of measurement devices. In this study, four measuring device such as precision level, electronic comparator, autocollimator and pneumatic gauging have been used for straightness measurement. A grounded cylindrical part, 40 mm in diameter and 320 mm in length, was taken as sample. The scanning length was divided into 23 parts equally and the points obtained were marked.

A. Data Acquisition for Straightness by Precision Level

In the first straightness measurement, a precision level (Fowler 0.02 mm/m) which has 120 mm in length and 4 second in accuracy was used. Since the cut-off value and scanning length were selected as 8 mm and 180 mm, respectively on the testing machine (23 steps with intervals of 8 mm). The precision level was positioned on the first point of the part and set to zero, then, the edge of the precision level was moved to the next step with 23 overlap points. In order to move the precision level on the workpiece precisely, the gage blocks were used. For data acquisition the precision level was positioned as shown in Figure 2.

Figure 2: Position of precision level for data acquisition on workpiece

The measured data at each point were then converted into linear deviation and given at second column in Table 3.

B. Data Acquisition for Straightness Using Electronic Comparator

Electronic gauges use linear variable displacement transducer (LVDT), capacitance, inductive or other electronic probes to sense the distance or displacement of a contact or stylus. Mechanical gauges such as micrometers plug gauges and snap gauges may employ an integral electronic probe in addition to the mechanical gauging elements. The electronic comparator (Slyvac D25) 1-0.1 \( \mu \)m in accuracy was used for the second stage measurement. The technical specifications of the comparator are given in Table 1. The electronic comparator is equipped with LVDT to sense the distance or displacement of a contact or stylus.

Table 1: Technical specifications of the electronic comparator

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Specifications</th>
</tr>
</thead>
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<td>Measuring range</td>
<td>10 mm (+1 mm)</td>
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<tr>
<td>Accuracy</td>
<td>1 ( \mu )m / 0.1 ( \mu )m</td>
</tr>
<tr>
<td>Measuring force</td>
<td>0.6-0.9 N</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>1.0000\pm0.0005 mm</td>
</tr>
<tr>
<td>Probe contact point</td>
<td>( \varnothing )2 mm, ball, carbide</td>
</tr>
<tr>
<td>Influence of temperature</td>
<td>( \leq0.1 \mu m^\circ C ) within 0-70 ( \circ C )</td>
</tr>
<tr>
<td>Influence of humidity</td>
<td>Not important</td>
</tr>
</tbody>
</table>

In order to move the probe of electronic comparator accurately step by step on the workpiece a digital rule was employed and the electronic comparator was positioned as shown in Figure 3.

Figure 3: Position of electronic comparator system to collect data for straightness

After the comparator was set to zero at first measurement point, the probe (Slyvac probes P10) was moved step by step to other points on the part and the deviations from the first point data were read directly on the measurement unit recorded during machining. The tests were carried out at dry cutting conditions. The measured data points for 23 points are given at third column in Table 3.

C. Data Acquisition for Straightness Using Autocollimator

The autocollimator (Hilger-Watts 142/18) designed for mainly measuring small angular deviations was used for the third stage measurement. The descriptions and technical specifications of the Microptic Autocollimator are given in
The autocollimator was placed on a surface plate made of granite (Starret) and zero setting process of the reflector was positioned on the first point. The reflector was moved to the other points respectively as shown in Figure 4 and the data at each point was recorded as unit of second for the angular displacements. Then, these values were converted into linear displacement as in terms of the deviation from the first data and are given at fourth column in Table 4.

![Fig. 4. Position of autocollimator to obtain data on workpiece](image)

**Table 2. Technical specification of the autocollimator**

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
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<td>Range of measurement</td>
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<td>Direct reading</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1 sec in 1 min</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>1.0001±0.0005 mm</td>
</tr>
<tr>
<td>Approximate magnification</td>
<td>x21</td>
</tr>
<tr>
<td>Max. working distance</td>
<td>9 m</td>
</tr>
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</table>

The back-pressure type pneumatic gauging system is used as a measurement device for straightness measurement. This idea is an innovative extension of the principle of pneumatic gauging. The pneumatic probe is a non-contact device and it is independent from the cleanliness of measured surfaces. All the measurements are taken with high reliability and repeatability is excellent since the pneumatic sensors do not have any mechanical part for transmitting signals. The current work focused on adapting pneumatic gauging system for data acquisition from the cylindrical surface reliably. The back-pressure signal captured using the pressure gauge and the pressure transducer, then transferred to PC through signal amplifier and data acquisition system. The pressure transducer is connected to measuring chamber so dynamical properties of the transducer for data acquisition can be improved.

**D. Data acquisition by Using Pneumatic Gauging System**

The back-pressure type pneumatic gauging system is used as a measurement device for straightness measurement. This idea is an innovative extension of the principle of pneumatic gauging. The pneumatic probe is a non-contact device and it is independent from the cleanliness of measured surfaces. All the measurements are taken with high reliability and repeatability is excellent since the pneumatic sensors do not have any mechanical part for transmitting signals. The current work focused on adapting pneumatic gauging system for data acquisition from the cylindrical surface reliably. The back-pressure signal captured using the pressure gauge and the pressure transducer, then transferred to PC through signal amplifier and data acquisition system. The pressure transducer is connected to measuring chamber so dynamical properties of the transducer for data acquisition can be improved.

**D 1 Principle of pneumatic gauging**

Pneumatic gauging [7] is a well established technology that is being practiced extensively in industry since long for the measurement of fine displacement. Compressed air at a defined constant pressure flows into air gauge through a restriction into a measurement chamber, and then to atmosphere through one or more jets in pneumatic probe. Pressure in the chamber is extremely sensitive to changes due to variation of the gap between probe and workpiece, and the effect of any change in clearance is indicated on manometer calibrated in linear unit or a pressure sensor. Air gauges could be based on changes in pressure (back-pressure) or flow velocity. Back-pressure is used widely, but a lower range than flow systems. The contact between the measuring devices like probe with measured part produces external force to the measured surface [3]. This force may cause slight deflection on the measured part if the cross-section of the part is slim. For straightness and flatness evaluation, it is common to measure the parts having slim cross-section. In order to avoid the deflection errors, the non-contact measuring devices such as laser beam [21] and air gauging systems [22] to detect the measured part seem to be a good solution. The advantage of laser measuring system is its capability of detecting the moving targets. Lee and Kim [23] developed a real-time correction system using the non-contact measuring technique.

The air gauging sensor is non-contacting device that converts the stand-off distance into back-pressure. It has the advantage that the air flowing through the measurement orifice keeps the part surface clean, makes the sensor insensitive to effects of coolant and thus excellent device for in-process machining measurement. The back-pressure principle has been well established in metrology as a means of measuring small dimensional variations. Despite its success in post process inspection, its use as an in-process-measuring device is somewhat restricted because of its rather limited linear operating range. For wider operating ranges, the cone-jet sensor has been developed [24]. But, since the deviations in straightness measurement are in low values, the measurement range of back-pressure sensor is quite enough to obtain the deviations. The important thing in a jet sensor is to have a good linearity. The flow through the orifice should be laminar flow because of theoretical equations that are possible to derive easily from the laminar flow.

Air supplied at a constant pressure \( p_s \) passes through a control orifice and into a variable pressure chamber having measuring jet. If the workpiece surface closes the escape completely, \( d_i = 0 \), the back-pressure \( p_b \) in the measuring chamber will rise to supply pressure \( p_s \), as the stand-off distance \( d_i \) is increased the pressure drops to \( p_b \). The pressure in the measuring chamber depends on \( d_i \) between head of the measuring jet and measured surface. So, there is a relation but not exactly linear between \( d_i \) and \( p_b \). The stand-off distance should be as small enough in relation to the measuring jet opening (Fig. 5a). The maximum sensitivity corresponds to the optimum stand-off distance derived from the theoretical limit of an effective restriction by [5]:

\[
d_i = (0.14d_m^2) / d_m
\]

(5)
Various methods can be applied to measure the pressure in the measurement chamber. The air gauges are connected with pneumatic measuring devices able to generate control signals. If the device is to be included into the Quality Management System it requires recorded and processed data achieved during the measurement. Investigations led to the development of air gauges integrated with piezoresistive pressure transducers. In those systems the results of measurement are achieved in digital form, they are processed and recorded. Additionally, dynamical properties of integrated air gauges appear much better [5]. However, the piezoresistive sensor placed directly into the measuring chamber of the air gauges enables to minimize response time [9].

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Practical experiments have shown that the pneumatic system has an approximate linear relationship between $p_b / p_s$ and $A_m / A_c$, where $A_m$ is the measuring jet area and $A_c$ is the area of control orifice. Linearity extends approximately over a range of $p_b / p_s$ of 0.6-0.8 (Fig. 5b). Above this range

$$p_b / p_s = k A_m / A_c + 1.1$$  

(6)

For a given supply pressure and measuring diameter ($d_m$) the sensitivity of the system is given by

$$\frac{\text{Scale displacement}(\delta R)}{\text{Change in stand-off distance}(\delta d)} = \frac{\delta A_m}{\delta d} \frac{\delta p_b}{\delta p_b} \frac{\delta R}{\delta p_b}$$  

(7)

where $\delta A_m / \delta d$ is the sensitivity of the measuring head, $\delta p_b / \delta A_m$ is the pneumatic sensitivity, and $\delta R / \delta p_b$ is the pressure gauge sensitivity. Since $A_m = \pi d_m^2$, $\delta A_m / \delta d = \pi d_m$, and from Eqn. (6), [25]

$$\delta p_b / \delta A_m = k p_b / A_c$$

The pneumatic sensitivity is direct proportional to the supply pressure and but inverse proportional to the measuring jet area. Therefore, for high pneumatic sensitivity $A_m$ must be as small as possible. There are drawbacks to such instruments as measurement repeatability is influenced adversely by the contact force developed between the sensor, as well as the contact initiating chatter when measuring fine surfaces [6].

D2. Applying pneumatic gauging system for data acquisition

The back-pressure type pneumatic gauging system is used as a measurement device for straightness measurement. This idea is an innovative extension of the principle of pneumatic gauging. The pneumatic probe is a non-contact device and it is independent from the cleanliness of measured surfaces. All the measurements are taken with high reliability and repeatability is excellent since the pneumatic sensors do not have any mechanical part for transmitting signals. The current work focused on adapting pneumatic gauging system for data acquisition from the cylindrical surface reliably. The back-pressure signal captured using the pressure gauge and the pressure transducer (Foxboro 843 DP-A21), then transferred to PC through signal amplifier and data acquisition system. The pressure transducer is connected to measuring chamber so dynamical properties of the transducer for data acquisition can be improved.

The straightness measurements were carried out on a pneumatic gauging system developed by Mercer Company [26]. The experimental set up for straightness measurement is shown in Fig. 6a and 6b as schematic and photographic respectively.
The measuring head was positioned normal to the measured surface and to be concentric with the axis of measured object. The surfaces of the measured objects are circular and have the same finish. The sensor was then approached to the measured object with an accuracy of 0.01 mm and adjusted so as to change the clearance with a micro-adjustment with the resolution of 2 μm. The data point out that the diameter of control orifice (d_c) has to be determined taking into consideration of the stand-off distance.

In pneumatic measuring head the control jet has 0.7 mm in diameter and the measuring jet is 1 mm. Air is supplied at constant pressure (250 kPa) and the measuring indicator displaces 2 mm per 100 Pa change of pressure. The back-pressure in the measuring chamber was measured, in the range of 66-175 kPa, using pressure gauge and pressure transducer with the resolution of 10 kPa and 0.002 mm (10 kPa/μm) or 0.98-2.35 V respectively.

Linearity is one of the most important characteristics of the pneumatic system. In order to achieve linearity range, the stand-off distance was sensed at 0.05 mm as minimum and varied till 0.17 mm. The data between 50 and 70 μm is not good from the linearity point of view, but the linearity is highly accurate in range of 70-170 μm. For better understanding and to indicate static characteristics of pneumatic gauge, the variation of back-pressure values as in kPa and in volt corresponding to the stand-off distance is shown in Fig. 7. Therefore, the measuring range of the pneumatic probe can be assumed perfect between 70 and 170 μm (in of 100 μm). If we consider that the deviations in straightness are too small, this value can be accepted suitable for the measurement. The deviation from linearity at high pressure is imaginably a consequence of compressibility of air. It is found that, in the linear range, 0.1 bars can be represented by 0.01 mm and also 1mV by 7.85x10^{-3} micrometer. From Eqn. (7) magnification is calculated as 40.900.
For the straightness measurement by pneumatic gauging system, the sample was placed on the two V-blocks and also the pneumatic probe was positioned at the first marked point and set to zero. In order to move the pneumatic probe parallel to the part axis, the gage block 200 mm in length was used. The back-pressure signals were transmitted to the pressure gauge calibrated in linear unit and pressure transducer (Foxboro 843DP-A2I) simultaneously. The pneumatic probe was then moved to the 23 marked points step by step to obtain all the related data. Since the back-pressure could not be obtained at the desired accuracy on the pressure gauge, it was measured by the pressure transducer in V/mV and the data were transferred to the PC by means of charge amplifier (Weidmüller WASS PRO) and data acquisition card (PCI 1712) for straightness calculation. The signals recorded on the PC were then converted into linear deviations. In addition, the back-pressure signals can be read directly by using a voltmeter in V/mV as well.

**IV. RESULTS AND DISCUSSION**

The results of straightness measurement by four methods are given comparatively in Table 3. It is known that there are many factors affecting measurement results; these factors originate from operator and the structure of measurement system itself, and they may cause measurement errors. In order to take the measuring at the same point the instruments were positioned step by step for 23 points by a digital rule. For all four data acquisition methods the sample workpiece was kept at same position. Since the straightness measurements obtained by various methods are different, the straightness errors of each method will naturally be different, too.

According to their results, the straightness measurements obtained by electronic comparator and pneumatic gauging system is very close to each other. As a consequence, it is clear that the pneumatic gauging system can be used reliably for straightness measurement and for various geometrical profile measurements.

<table>
<thead>
<tr>
<th>Posit. No.</th>
<th>Precision level (µm)</th>
<th>Electronic comparator (µm)</th>
<th>Autocollim. (µm)</th>
<th>Pneumatic comparator (µm)</th>
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| Total     | 71.90                | 95.00                       | 61.50           | 57.30                    |
| $E_s$     | 17.6                 | 9.4                         | 7.8             | 9.3                      |
| $M_a$     | 2.9958               | 3.9583                      | 2.5625          | 2.3875                   |
| $D_s$     | 1.8940               | 2.4402                      | 1.3295          | 1.0313                   |

$E_s$: Straightness error; $M_a$: Arithmetic mean; $D_s$: Std. deviation

The results show that the numbers of measured points have more significant effect on the measurement uncertainty than other factors. This means that a large sample of data set gives more comprehensive information about the measured data, and solution closer to the real property of the measured part, and hence reduces uncertainty. In this respect pneumatic gauging system provides many data through the length of samples in a short time and. Since response time is too low so the values of straightness measurement captured from samples reflect the geometrical features at high accuracy. In addition those, because of the uncertainty of measurement, the data taken from the same part are always different from each other and give different evaluated values even though all calculations follow the minimum zone criterion.
V. CONCLUSION

Increased production rate requires measurement systems not only accurate and reliable but also able data acquisition and processing. In order to meet these demands the pneumatic gauging system can be used perfectly in dimensional and geometrical measurements even in-process. The system offer non-contact gauging-long life due to minimal frictional wear, high accuracy, repeatability, easy of operation, self-cleaning ability and far less measuring and quick response time. In addition to that the obtained back-pressure signal could be converted into electronic signal for registering and processing the data. The research introduced in this study has established proof-of-concept of non-contact pneumatic straightness measurement of cylindrical surfaces. The system sets up the pneumatic gauging system and relates the straightness of the surface to the back-pressure signal achieved using a manometer calibrated in linear unit and pressure transducer. Since the accuracy of straightness measurement depends on the measurement technique and measurement device used, its selection is very important. The more the accuracy of measurement method is, the less the straightness error. Although different algorithms are used to calculate the straightness error based on minimum zone or least squares method, the difference between the results obtained by them is considerably less. In this study, an efficient method for straightness measurement is proposed. The usage of pneumatic gauging system on straightness measurement was explained and tested then its results are compared with the others acquired three different devices.

The conclusions drawn from this study are as follows:

1. The proposed method was found to be useful for straightness measurement.
2. The accuracy and efficiency are demonstrated as simulation for the straightness measurement data.
3. In order to represent the profile of cylindrical surface in a short response and sufficiently, considerable more data can be taken and registered in-process. If a straightness evaluation program is loaded in the PC, straightness error can be calculated quickly.
4. Although the measurements were carried out as off-line further research can be focused on on-line measurement at last pass during machining.
5. Measurements can be carried out on the shop floor if required by machine operators thus minimizing the potential for manufacture of unacceptable components.
6. Further research can be directed to improve the linearity of the pneumatic gauging significantly.

REFERENCES