

A NON-DESTRUCTIVE PNEUMATIC APPROACH FOR MEASURING INNER ROUNDNESS OF MILLIMETER-SCALE METAL SLEEVES

Pensiri Tongpadungrod¹, Wiwat Maneekongkla¹, and Chantaraporn Phalakornkule^{2*}

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Abstract

This research work presented a non-destructive pneumatic method for measuring the inner roundness of millimeter-scale metal sleeves. An air micrometer with 2 air jet outlets was placed inside a metal sleeve at the center of the sleeve. In an instant, the air jet nozzle injected an air jet stream toward the inner wall of the metal sleeve, yielding the distance between the air jet nozzle and the inner wall of the sleeve. The measured distances were converted to the inner diameter of the metal sleeve based on its cylindrical geometry. As the air jet nozzle rotated 360 degrees around the axis of the cylindrical sleeve sample, multipoint inner diameter data of the sleeve sample were collected. These diameters were used to construct the inner roundness of the sample using the peak to peak principle. In this study, the roundness of the metal sleeve samples was determined using the non-destructive pneumatic instrument and compared with those obtained by a commercial contact type roundness measuring instrument. The comparison showed good agreement (<10% difference) when a workpiece was conforming (roundness <1 μm). However, higher deviations were obtained when a workpiece was non-conforming (roundness >1 μm).

Keywords: Inner roundness, motor sleeve, pneumatic measuring device, peak to peak principle

¹ Department of Production Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, 1518 Pracharat 1 Road, Bangsue, Bangkok 10800, Thailand. E-mail: pensiri.t@eng.kmutnb.ac.th

² Department of Chemical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, 1518 Pracharat 1 Road, Bangsue, Bangkok 10800, Thailand. E-mail: chanphalakornkule@gmail.com

* Corresponding author

Introduction

Metal sleeves are essential components of machines with rotating parts. The roundness of the metal sleeves ensures their function and the maintenance of a lubricating film between mating components. As a consequence, the roundness of a metal sleeve is a critical parameter to verify whether its specification has been met. Verification of the roundness of each metal sleeve is necessary in some applications such as in a hard disk component. Most roundness measuring instruments are contact types which require a relatively long setup time and operation time, a highly skilled operator, and may cause scratches on a workpiece's surface. In the last 2 decades, considerable research has been performed to develop roundness measuring systems, in particular non-contact type roundness measuring systems. Horikawa *et al.* (2001) described a system for measuring roundness in which the accuracy was not dependent on the motion accuracy of the rotary element. The system consisted of a rotary table, non-contact gap sensors, and a computer system. Another example described by Mohamed *et al.* (2011) was a vision-based inspection system for roundness error measurement of a cylindrical part. Mekid and Vacharanukul (2011) described an in-process out-of-roundness measurement probe for turned workpieces. The principle of roundness measurement was based on the light intensity which varied according to the displacement between the probe and a reflective object. Not only has the focus been on development of instrumentation hardware, methodologies for determining roundness have also been reported (Guo Gao and Kiyono, 1997; Muralikrishnan *et al.*, 2005; Sun, 2009; Janusiewicz *et al.*, 2011; Sui and Zhang, 2012; Adamczak *et al.*, 2017).

An air micrometer is a non-destructive instrument widely used in the electronic device industry for measuring inner and outer diameters as well as the taper of a workpiece with an accuracy of 0.1 μm . It utilizes air flow and the resistance created between the object under test and the air gauge's sensing probe. The air resistance creates back pressure which

changes with the distance between the air gauge's sensing probe and the object under test. Therefore, the back pressure can be related to the distance between the air probe and the object. Sleeves are one of the most crucial parts whose inner diameters are examined with an air micrometer. The pneumatic device offers a large number of measurements in a limited time with acceptable accuracy and precision.

This article described a non-destructive pneumatic instrument developed in-house for measuring the inner roundness of millimeter-scale metal sleeves. Multipoint inner diameter data of a sleeve sample were collected using an air micrometer with 2 nozzles rotating 360 degrees around the workpiece's axis. These diameter data were used to construct the inner roundness of the sample using the principle of "peak to peak". Two types of sleeve samples were used: (1) conforming (roundness < 1 μm) and (2) non-conforming (roundness > 1 μm). The rotational speed of the air gauge's sensing probe was the main operating variable affecting the accuracy of the instrument. The roundness of the metal sleeve samples was compared with the roundness obtained by a commercial contact type roundness measuring instrument, and the accuracy and precision of the instrument were evaluated.

Materials and Methods

Commercial Contact Type Roundness Measuring Instrument and Description of the Non-destructive Pneumatic Instrument

The commercial contact type roundness measuring instrument, Rondcom 60 A model (Tokyo Seimitsu Co. Ltd., Tokyo, Japan), was used as a reference. Figure 1 shows the diagram of the non-destructive pneumatic instrument. The main components of the instrument were an air micrometer acting as a gauge sensor (model CAG-2000, Nidec Tosok Corp. Zama City, Japan), a fixture for mounting the nozzle of the air micrometer and holding a sample, and 2 servo motors controlling the rotational

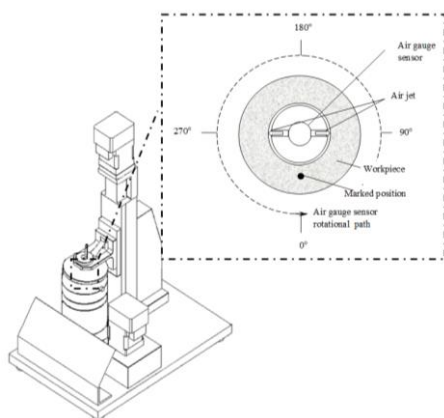


Figure 1. Diagram of the non-destructive pneumatic instrument for measuring inner roundness of millimeter-scale metal sleeve

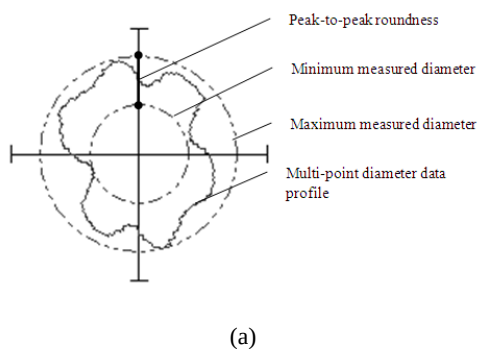
and the vertical linear motions of the air nozzle. The air micrometer required an air supply pressure of 0.196 MPa and a source pressure of 0.3 MPa or higher. Before starting the roundness measurement, the air micrometer was calibrated with 2 standard workpieces with known diameters of 3.9949 and 3.9989 mm. The nozzle of the air micrometer was located inside at the center of a metal sleeve with 2 air jet outlets located 180 degrees apart from each other. In an instant, the air micrometer injected an air jet stream toward the inner wall of the metal sleeve, yielding the distance between each air jet outlet and the inner wall of the sleeve. The measured distances were converted to the inner diameters of the metal sleeve based on its cylindrical geometry. As the air jet nozzle rotated 360 degrees around the axis of the cylindrical sleeve sample, multipoint inner diameter data of the sleeve sample were collected. These diameter data were used to determine the inner roundness of the sample using the peak to peak principle described in a later section .

Determination of Roundness from Multipoint Inner Diameter Data

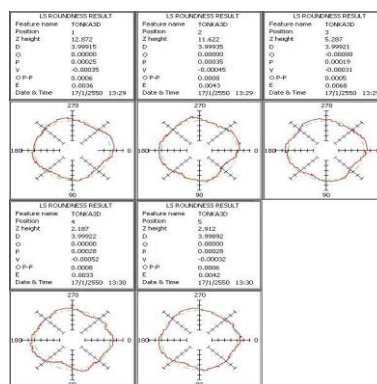
The roundness of each sample was calculated according to Equation (1) based on the peak to peak principle (Reeve, 1979).

$$\text{Roundness} = \text{maximum measured diameter} - \text{minimum measured diameter} \quad (1)$$

Figure 2(a) shows the profile of the multi-point diameter data with the indication of the maximum and the minimum measured diameters and the calculated peak to peak roundness. An algorithm based on LabVIEW's maximum and minimum functions was used to determine the maximum and the minimum measured diameters from the multipoint inner diameter data of the sleeve samples.



(a)



(b)

Figure 2. Profile of multi-point diameter data (a) with the indication of the maximum and the minimum measured diameter and the calculated peak to peak roundness and (b) obtained from the instrument

Measuring Experiments

The cylindrical metal sleeves had the following specifications: an inner diameter of 4 mm and a height of 17.685 mm. Ten metal sleeve samples were used in this study. Six of the samples conformed to the roundness requirement (roundness $<1 \mu\text{m}$) (Samples 1-6), and the other 4 samples (Samples 7-10) did not conform to the roundness requirement (roundness $>1 \mu\text{m}$).

To study the effect of the rotational speed of the air gauge's sensing probe, the speed of the stepping motor was varied at 5, 8, 10, 12, 15, and 18 pulses per second yielding the numbers of collected data points of 1,200, 1,020, 900, 780, 600, and 420 data points, respectively.

To study the effect of the position of the air gauge's sensing probe or the air jet nozzle, the roundness measurement was performed at 4 different positions along the cylindrical length; position 1 at 12.872 mm, position 2 at 11.622 mm, position 3 at 5.287 mm, and position 4 at 2.187 mm measured from the base of the metal sleeve sample.

Analysis for Accuracy of Non-destructive Pneumatic Instrument

The Gauge Repeatability and Reproducibility (GRR) statistical methodology was used to measure the precision and variation present in the non-destructive pneumatic instrument. There are 2 components which comprise the GRR: repeatability and reproducibility. Repeatability refers to the ability of the instrument to give consistent results (precision) under repeated tests in the same manner. Reproducibility refers to the ability of the instrument to provide repeated results regardless of the operator performing the test (variation among operators). Repeatability (equipment variation, EV) and reproducibility (appraiser variation, AV) were calculated according to Equation (2) and Equation (3), respectively:

$$EV = k_1 \bar{R} \quad (2)$$

where

EV = repeatability (equipment variation),

k_1 = a constant that depends on the number of trials ($k_1 = 4.56$ for 2 trials), and

$\bar{R} = \frac{\bar{R}_1 + \bar{R}_2 + \dots + \bar{R}_n}{n}$, in which n = the number of operators,

$\bar{R} = \frac{R_1 + R_2 + \dots + R_N}{N}$, in which N = the number of samples and

R = the appraiser part range = Appraiser part Max - Appraiser part Min

$$AV = \sqrt{(k_2 R_p)^2 - (EV^2 / nr)} \quad (3)$$

where

AV = reproducibility (appraiser variation),

k_2 = a constant that depends on the number of trials ($k_2 = 3.65$ for 2 trials),

$R_p = \bar{x}_{part \max} - \bar{x}_{part \min}$, in which $\bar{x}$ = the part average,

r = the number of trials, and

n = the number of operators

The GRR is a combined value and can be calculated according to Equation (4):

$$GRR = \sqrt{EV^2 + AV^2} \quad (4)$$

The part variation (PV) is determined by multiplying the range of the part average (R_p) by a constant (k_3), as shown in Equation (5):

$$PV = k_3 R_p \quad (5)$$

where

PV = the part variation,

k_3 = a constant that depends on the number of parts ($k_3 = 0.3146$ for 10 parts), and

$R_p = \bar{x}_{part \max} - \bar{x}_{part \min}$, $\bar{x}$ = the part average

The total variation (TV) is a combined value and can be calculated according to Equation (6):

$$TV = \sqrt{GRR^2 + PV^2} \quad (6)$$

where

TV = the total variation,

GRR = the gauge repeatability and reproducibility, and
PV = the part variation

In order to justify a measurement system, the repeatability (EV), the reproducibility (AV), and the combined value gauge repeatability and reproducibility (GRR) must be compared to the variation in part which can be calculated in terms of the percentage of the total variation (TV) according to Equations (7)-(9):

$$\%EV = 100(EV/TV) \quad (7)$$

$$\%AV = 100(AV/TV) \quad (8)$$

$$\%GRR = 100(GRR/TV) \quad (9)$$

In the analysis of the gauge repeatability and reproducibility of the instrument, the measurements were performed on 10 samples with 2 operators. Each measurement was repeated twice.

Results and Discussion

Repeatability of the Non-destructive Pneumatic Instrument

Figure 2(b) shows an example profile of the measured multi-point diameter data created by the developed instrument. Figure 3 shows the roundness values of 3 representative samples, Samples 1, 2, and 10, obtained from the 10 repeated experiments with the rotational speed of 10 pps and the position of the air jet

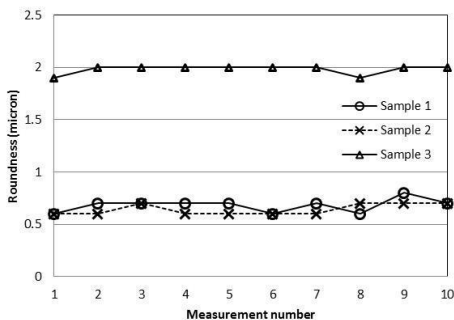


Figure 3. Repeatability of the non-destructive pneumatic instrument (Samples 1, 2, and 10 at the rotational speed of 10 pps)

nozzle along the longitudinal axis of the cylindrical coordinate at P2, P1, and P5, respectively. The mean roundness of Samples 1, 2, and 10 were 0.68, 0.64, and 1.98 μm , respectively, whereas the standard deviations of the roundness values obtained from the 10 measurements were 0.063, 0.052, and 0.042 μm , respectively. The standard deviations were 2.1-9.3% of the mean values, suggesting that the roundness measurements by the non-destructive pneumatic instrument were repeatable.

Effects of Rotational Speed of the Air Gauge's Sensing Probe on the Measured Roundness

The rotational speed was directly related to the frequency of detection and thus the number of inner diameter data points. The lower the rotational speed, the higher the numbers of collected inner diameter data points. However, the lower rotational speed required a longer processing time, which is not desirable in practice. Therefore, an optimal rotational speed that yields a sufficient collection of the inner diameter data points for accurate analysis of an object's roundness should be employed. Figure 4 shows the effect of the rotational speed of the air gauge's sensing probe on the measured roundness of Sample 10.

Figure 4 shows that the roundness of the sample varied remarkably with the position of

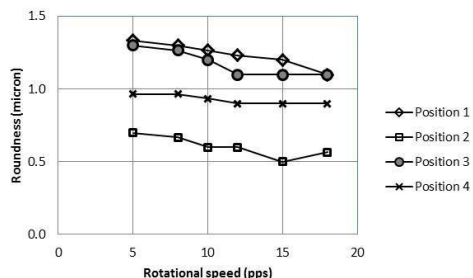


Figure 4. Effect of the stepping motor speed (rotational speed) and the position of the air gauge's sensing probe along the cylindrical length of the sample on the calculated peak to peak roundness (Sample 10)

the air gauge's sensing probe along the longitudinal axis ($\pm 0.5 \mu\text{m}$). The experimental data suggested the heterogeneity in the roundness measurement of the metal sleeves along the longitudinal axis.

It was found that the roundness measured by the instrument dropped with an increasing rotational speed. An analysis of variance (ANOVA) was performed in order to test this observation. The ANOVA results were tabulated in Table 1. The F-value of 76.68 suggested that the rotational speed significantly affected the measured roundness. Furthermore, a pair test was performed in order to compare the roundness obtained at the rotational speed of 5 pps and those at other speeds. The pair test results were tabulated in Table 2. The statistical results of the pair test in Table 2 show that the test statistics (t_c) were less than the critical values ($t_{0.025, \nu}$) when comparing between the roundness measured at 5 pps and those measured at 8 and 10 pps, but were greater than the critical values when comparing between the roundness measured at all rotational speeds greater than 10 pps. This result suggested that the roundness measured with the rotational speed of 5 pps was not different from those

measured at 8 and 10 pps. However, the measured roundness at all rotational speeds higher than 10 pps were significantly different from that measured at 5 pps. Therefore, the rotational speed of 10 pps was selected as the optimal rotational speed of the air gauge's sensing probe for the roundness measurement.

Comparative Roundness Values Measured by the Contact and Non-Destructive Pneumatic Instrument

Figure 5 shows the comparison of the roundness values of 10 samples measured by the contact and non-destructive pneumatic instruments. For the conforming samples (Samples 1-4), the measured roundness values were 0.550-0.905 μm with the contact instrument and 0.40-1.00 μm with the non-destructive pneumatic instrument. For the non-conforming samples (Samples 5-10), the measured roundness values were 1.060-5.285 μm with the contact instrument and 1.10-5.78 μm with the non-destructive pneumatic instrument. The different roundnesses measured by the contact and non-destructive pneumatic instruments were 0.09- 0.35 μm with a mean of 0.18 μm for conforming samples and 0.04-2.58 μm with a mean of 0.75 μm for the non-conforming

Table 1. Analysis of variance: Sample 10 roundness measured at speeds of 5, 8, 10, 12, 15, and 18 pps

One-way ANOVA: 5, 8, 10, 12, 15, 18					
Source	DF	SS	MS	F	P
Factor	5	1.23533	0.24707	76.68	0.000
Error	54	0.17400	0.00322		
Total	59	1.40933			
Level	N	Mean	St Dev		
5	10	1.9700	0.0483		
8	10	1.9600	0.0516		
10	10	1.9800	0.0422		
12	10	1.8200	0.0919		
15	10	1.7700	0.0483		
18	10	1.5800	0.0422		

Table 2. Pair test of roundness obtained at the rotational speed of 5 pps and at other speeds

	Pair test at different rotational speeds (pps)				
	5 vs 8	5 vs 10	5 vs 12	5 vs 15	5 vs 18
Degree of freedom (ν)	17.9219	17.8513	13.6196	18.0000	17.6816
$t_{0.025, \nu}$	2.1010	2.1010	2.3650	2.1100	2.1010
t_c	0.4474	-0.3761	5.1870	9.2591	19.2286

samples. With the exception of Sample 7, the higher the degree of non-conformity was, the higher the deviation of the 2 instruments. The reason for the remarkably high deviation in the roundness values of Sample 7 obtained from the 2 instruments was the existence of deep scratches on the surface of Sample 7 (Figure 6). In this case, the air jets might not have been able to penetrate into the deep scratches, and thus the measurement of the real maximum diameter was missing. An explanation for the inaccuracy of the non-destructive pneumatic instrument was that the air micrometer was only calibrated with the standards of diameters in the range 3.9949-3.9989 mm that may not include the dimension of the scratches. Without a thorough calibration of the instrument, at this stage, the non-destructive pneumatic instrument can be used for determining whether the workpieces met the roundness specification or not. In addition, for the workpieces within the roundness specification, the roundness values can be accepted as valid values.

Accuracy and Precision of the Non-destructive Pneumatic Instrument

The measuring system with the developed instrument yielded the %EV of 1.8341, the %AV of 1.4045, and the %GRR of 2.3103. It is not the absolute level of the GRR that is important but rather the comparative value. The acceptability of the GRR is expressed as a percentage ratio of the TV. Typically, the acceptability criteria of a measuring system expressed in terms of the %GRR are marginal for %GRR <30%, good for %GRR <20%, and excellent for %GRR <10%. The resultant %GRR was well below 10% suggesting the developed measuring system was excellent for use.

Conclusions

The rotational speed of the air gauge's sensing probe was the main operating variable affecting the accuracy of the instrument. For the current configuration of the instrument, the optimal rotational speed of the air gauge's sensing probe was found to be 10 pps. The comparison showed good agreement (<0.18 μm difference)

between the commercial contact type and the non-destructive pneumatic instrument when a workpiece was conforming (roundness <1 μm). However, higher deviations were obtained when a workpiece was non-conforming (roundness >1 μm). At the current stage, the non-destructive pneumatic instrument was acceptable for determining whether the workpieces met the roundness specification or not. With a minor control alteration, the instrument can also be adapted to determine the cylindricity of a workpiece as the mounting configuration of the sensing probe also provided a vertical motion.

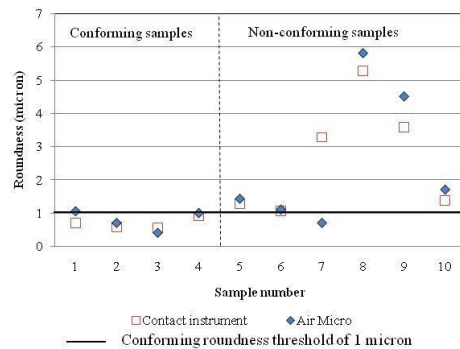


Figure 5. Comparative measured roundness from the contact and the non-destructive pneumatic instruments

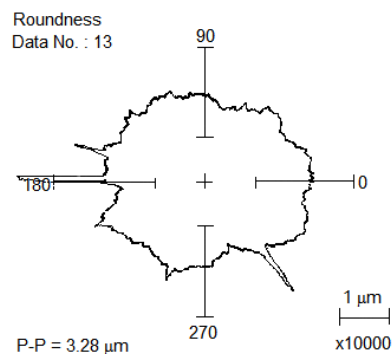


Figure 6. Profile of multi-point diameter data obtained from the the instrument of Sample 7 with deep scratches

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