

# POLYGON-BASED LARGE DIAMETER MEASUREMENT WITH MODULAR GAUGES

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## 1. INTRODUCTION

Measurement of large diameters ( $\geq 500\text{mm}$ ) may encounter some difficult problems. It is due to the large dimension of the workpiece to be measured, which leads to the in-step increase of the volume and weight of the measuring apparatus. Thus, a series of problems occur to that apparatus: much difficulty of operation, large deformation of self-weight and temperature, high cost and poor versatility and so on<sup>1</sup>. The typical instances are large external and internal micrometers. On the other hand, those apparatus that employ the indirect methods such as height-chord gauge, saddle-shaped gauge and  $\pi$ -tape, although relative small, usually suffer the problem of limited accuracy<sup>1-3</sup>. Recently, grating, laser and some other advanced techniques have been used to this application; however, many problems remain unresolved<sup>4-8</sup>. Finally, although heavy coordinate measuring machine is a good tool to measure large diameters, it is too expensive, and the workpiece is sometimes too large to be taken into the working space of it.

In this extended abstract, a new method of measuring large diameters is described. By assembling *in situ* the measuring units around the circumference of the workpiece with magnets, any large size of external or internal diameters can be measured. In addition, the measuring apparatus has the advantages of compactness, simple structure and low cost and so on. More important, the precision of the method is very high.

## 2. PRINCIPLE

As shown in Fig.1, several identical but independent measuring units (large diameter gauges) are placed and, with magnets, fixed around the circumference of the workpiece to be measured. Each gauge has a ball and a roller at its two ends as the positioning elements. The gauges are arranged in such a way that the contacting elements between the adjacent gauges are one ball and one roller, so that the contacting area is always a point in theory. The diameters of the ball  $d_1$  and the roller  $d_2$  and the central distance  $l$  of each gauge are known. If the centers of all balls and rollers of each gauge are linked, such a polygon will be formed that all of their side lengths are known except for the last one. Therefore, if the closing size  $lc$  is determined by some other method, for example, with internal micrometer, the diameter of the workpiece  $D$  can be solved from the following equation according to the Cosine law:

$$\sum_{i=1}^n \cos^{-1} \left[ \frac{(D+d1_i)^2 + (D+d2_i)^2 - 4l_i^2}{2(D+d1_i)(D+d2_i)} \right] + \sum_{i=1}^{n-1} \cos^{-1} \left[ \frac{(D+d2_i)^2 + (D+d1_{i+1})^2 - (d2_i+d1_{i+1})^2}{2(D+d2_i)(D+d1_{i+1})} \right] + \cos^{-1} \left[ \frac{(D+d2_n)^2 + (D+d1_1)^2 - 4lc^2}{2(D+d2_n)(D+d1_1)} \right] = 2\pi \quad (1)$$

where  $n$  is the total number of the gauges that surround the workpiece. It can be seen that Eq.(1) is an implicit function, so the diameter  $D$  should be solved by numerical methods such as the iterative method.

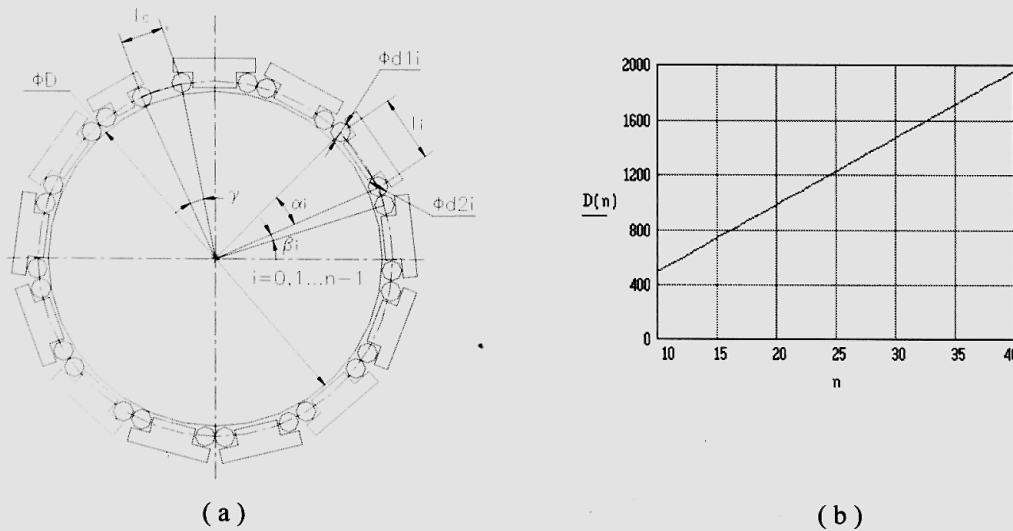


Fig.1 (a) Principle of the method; (b) Relation of measured diameter versus the total number of the gauges that surround the workpiece, where  $d=27mm$ ,  $l=127mm$  for all gauges and  $lc=100mm$ .

There are two basic ways to place (assemble) the gauges upon the circumference of the workpiece. The first way, named the circling way, is to put the gauges one by one until the space between the first and the last gauges is not large enough to be put into another one gauge. This way usually needs many gauges especially when the diameter of the workpiece is very large, while the second way (alternating way) just employs a few of the gauges. If there are only three gauges available, it works like this: put the three gauges upon the circumference of the workpiece firstly. Then while keeping the first and the third gauges being unmoved, take the second gauge off slowly and place it again upon the workpiece but behind the third gauge. Afterwards, while holding the second gauge being unmoved, take the third gauge off slowly and put it again upon the workpiece but behind the second gauge. It is not stopped until the space between the first and the last gauges (the second or the third gauge) is not large enough to be placed into another one gauge.

### 3. EXPERIMENTAL RESULTS

Two kind of the experiments have been carried out. The first is the repeatability experiments. The aim is to evaluate the uncertainty introduced by the random factors such as the contacting deformations between the positioning elements of the adjacent gauges, the deviations of each gauge from the cross section of the workpiece and so on. The second is the comparison experiments, in which the results obtained by the method of this paper were compared with those obtained by some other methods. The uncertainty contributed by those factors of systematic ones can be found by the comparison experiments. Those factors include the calibrated diameter uncertainties of the balls and rollers of each gauge, the non-circularity of the workpiece and so on.

Table 1 Results of the repeatability experiments\* Unit: mm

No.	lc	D	No.	lc	D
1	97.679	1279.988	6	97.678	1279.988
2	97.680	1279.989	7	97.690	1279.990
3	97.684	1279.990	8	97.684	1279.990
4	97.682	1279.989	9	97.677	1279.987
5	97.679	1279.988	10	97.674	1279.987
Standard deviation of D: 0.0011					

\* Measured object: outside diameter of a bearing

Measuring parameters: d=27mm, l=127mm, n=26, m=7

Table 2 Results of the repeatability experiments\* Unit: mm

No.	lc	D
1	99.958	2553.926
2	99.960	2553.927
3	99.955	2553.925
4	99.955	2553.925
5	99.957	2553.926
Standard deviation of D: 0.0008		

\* Measured object: outside diameter of a disk

Measuring parameters: d=27mm, l=127mm, n=52, m=7

### 3.1 Repeatability experiments

Table 1 and 2 give two results of the repeatability experiments. It shows that the standard deviation of the measured diameter is very small. This means also that the contact deformation between the positioning elements of the adjacent gauges is very small and stable. It is an important conclusion, because it is the precondition and basis of the method of this paper.

It is worth mentioning that the repeatability experiment (Table 1) was done in a workshop without air-conditioner and lasted for several hours. The recorded temperature change of the workpiece was over 4°C during the measurement process, which means that the diameter change of the workpiece (steel) was close to 0.05mm. However, the experimental data did not respond to this change. It indicates that the expansion of the gauges (steel also) matched correspondingly to that of the workpiece. The reason lies in that the gauges and the workpiece are always holding contacted by the magnets during the measurement process, accelerating the heat exchange. Besides, the gauge is small, so the temperatures of them are easy to keep same.

Table 3 Results of the comparison experiments\* Unit: mm

D1	D2	
First measurement: 1220.598	0° direction	1220.599
	45° direction	1220.600
Second measurement: 1220.598	90° direction	1220.590
	135° direction	1220.587
Mean: 1220.598	Mean	1220.594

\*Measured object: outside diameter of a bearing

Comparison instrument: the caliper gauge with a dial at its end zeroed with blocks

Measuring parameters: l=127 mm, d=27mm, n=25, m=7

D1: obtained diameter with the large diameter gauge

D2: obtained diameter with the comparison instrument

Table 4 Results of the comparison experiments\* Unit: mm

D1	D2	
First Measurement: 978.872	0° Direction:	978.889
	90° Direction:	978.870
Second Measurement: 978.874	Mean: 978.880	
Third Measurement: 978.874		
Mean: 978.8733		

\* Measured object: outside diameter of a turbine rotor

Comparison instrument: large external micrometer zeroed With the length bar

Measuring parameters: l=127mm, d=27mm, n=20, m=7

D1: obtained diameter with the large diameter gauge

D2: obtained diameter with the comparison instrument

### 3.2 Comparison experiments

Table 3 and Table 4 show two results of the comparison experiments. The differences between the results obtained by the large diameter gauge and those obtained by the comparison instruments are  $4\mu\text{m}$  and  $6.3\mu\text{m}$ , respectively. In other words, the corresponding relative differences are  $3.3\times 10^{-6}$  and  $6.4\times 10^{-6}$ , respectively.

## 4. CONCLUSIONS

A new method of measuring large diameters has been presented. It has many valuable properties, such as that both external and internal diameters can be measured and there is no upper limitation of measuring range in theory. In addition, the measuring apparatus is compact and portable. Its structure is simple and cost is low. The theoretical estimation of uncertainty (omitted in this extended abstract) pointed out that, without considering the non-circularity of the workpiece, the extended uncertainty ( $3\sigma$ ) will be  $(0.002+1\times 10^{-5}D)$  mm or less. The results of the repeatability and comparison experiments proved this conclusion.

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