

Precision Measurement Method of Circumferential Length and Uncertainty for Steel Ring in CVT-pushing Belt

Kenta UMETSU* Hiroyoshi MIKOGAI*

ABSTRACT

The accuracy of the circumferential length of the metal rings used in CVT-pushing belts need to be controlled on the micrometer level to help ensure the durability of the belts. The principle used in measuring the circumferential length of the metal rings is the measurement of infinitesimal differences in length between a master ring for circumferential length and the ring being examined. A highly accurate measurement method and a method of evaluating the uncertainty of these measurements are therefore necessary for the master ring for circumferential length.

In the measurement method discussed in this paper, the master ring for circumferential length is positioned between two rollers, the length between the centers of the rollers and the radii of the sections of the rollers around which the ring winds are measured, and the circumferential length of the ring is quantified. A high level of accuracy has been realized in the two sets of measurements through the use of a high-accuracy three-dimensional coordinate measuring machine (CMM). In addition, the uncertainty of the measurements of the length between the centers of the rollers and the radii of the rollers is quantified using gauge block and gauge ring measurements.

Because gauge blocks and gauge rings are instruments of a standard length with a specified level of dimensional uncertainty, the measured results for the master rings for circumferential length based on this measurement method are traceable with a high degree of accuracy.

1. Introduction

CVT-pushing belts are made up of layers of multiple metal rings. To help ensure belt durability, it is necessary to precisely control the circumferential length of the rings. The principle used in the measurement of the circumferential length of the metal rings is the measurement of infinitesimal differences in length between a master ring for circumferential length (MRC) and the ring being examined.

The accuracy of the circumferential length of individual rings is on the micrometer level. This level of accuracy depends significantly on the accuracy of the MRC. However, the accuracy of measurement of the MRC has not to date been sufficiently discussed. This is because issues itemized below arise in the measurement, during which the MRC is placed between two rollers, the length between the centers of the rollers and the radii of the

rollers at the sections around which the ring winds are measured, and the results are taken to represent the circumferential length of the MRC.

- (1) The achievement of increased accuracy in the measurement of the length between roller centers
- (2) Complexity of evaluation of uncertainty in measurements

The method of precision measurement of MRC to be introduced in this paper employs a high-accuracy three-dimensional coordinate measuring machine (CMM) in order to measure the length between the centers of the rollers and the radii of the rollers at the sections around which the ring winds. A practical method of evaluating the uncertainty of CMM measurements involving comparative measurements using calibrated workpieces is also proposed in ISO/TS 15530-3⁽¹⁾.

Following ISO/TS 15530-3, by means of this method of evaluating uncertainty, the uncertainty of measurements of the length between the centers of the rollers and the

* Automobile R&D Center

radii of the rollers at the sections around which the ring winds can be quantified, respectively, from gauge block and gauge ring measurements. Gauge block and gauge ring measurements display a low level of uncertainty, and help to ensure traceability of length at a high level of accuracy for MRC measurements.

With today's globalization of production systems, the importance of technologies enabling efficient quality control in the distribution of parts is increasing. The integration of methods of evaluating reliability and methods of evaluating uncertainty, in particular methods based on ISO standards, is beginning to spread widely.

This paper will discuss a method of evaluating uncertainty, and will present an evaluation of the uncertainty of MRC measurements as an example of the application of the method.

2. Principle of Measurement of Master Ring for Circumferential Length and Uncertainty

2.1. Method of Quantification of Uncertainty and Method of Part Inspection

Uncertainty expresses the range of variation within which the true value of a measurement result exists. Standard deviation, σ , is used as the statistic quantitative expression for the degree of uncertainty. For example, if the uncertainty of a measurement result "a" is 2σ , then there is a high level of confidence - a probability of 95.4% - that the true value exists in the range defined by $a \pm 2\sigma$. The procedure for quantifying uncertainty can be summed up simply as follows.

- (1) The multiple factors in the uncertainty relating to measurement subject $Y(x_1, x_2 \dots x_n)$ are enumerated.
- (2) A mathematical model of measurement subject Y is formulated using the variables $x_1, x_2 \dots x_n$.

$$Y = f(x_1, x_2 \dots x_n)$$

- (3) The uncertainty of each factor x , $u(x)$, is quantified individually, and if there is no correlation between the factors, the combined standard uncertainty of Y , $u(Y)$, is expressed as follows:

$$u(Y) = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 u^2(x_1) + \dots + \left(\frac{\partial f}{\partial x_n}\right)^2 u^2(x_n)}$$

The standard for judging the conformance of the part, including measurement uncertainty, is provided by JIS B0641 (Geometrical Product Specifications (GPS) – Inspection by measurement of workpieces and measuring equipment – Part 1: Decision rules for proving conformance or nonconformance with specifications)⁽²⁾.

As Fig. 1 shows, the conformance of the part in

relation to the specification zone 1 is judged within the scope that is not excluded by measurement uncertainty (U). Because of this, when measurement uncertainty is high, the conformance zone 3 is small. When the conformance of the same part is judged in different production facilities, it is necessary to consider the traceability of the evaluation of uncertainty.

2.2. Measurement of the Master Ring for Circumferential Length

Figure 2 shows the components of a CVT-pushing belt. The belts are made up of multiple layered metal rings and elements. The MRC is arbitrarily selected from the metal rings.

Figure 3(a) shows an overview of the MRC measurement device. The MRC, with a circumferential length of approximately 650 mm, is wound around rollers 1 and 2, which have diameters of approximately 110 mm. A 20 kg weight is attached to the slider, and, because it is a mechanism that moves translationally in the Y direction, the slider, which is positioned at roller 2, exerts tension on the MRC.

The degree of rotation of roller 1 is measured using a rotary encoder. This device is positioned on the plate of the CMM when the length between the centers of the rollers is measured. In this paper, the CMM measurement accuracy, U , is $U = 0.4 + L_E/1000 \mu\text{m}$, where L_E is the millimeter-level evaluated length.

When the MRC is positioned between rollers 1 and 2, and the rollers rotate with the tension exerted by the

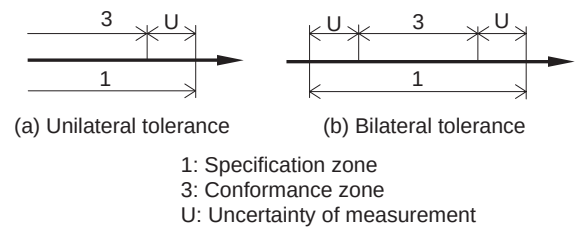


Fig. 1 Product inspection considering uncertainty of measurement

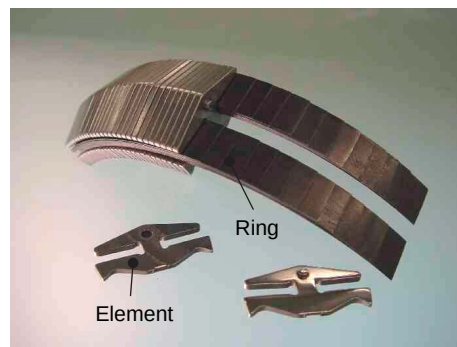


Fig. 2 Components of CVT-pushing belt

weight, due to the centering effect of the surface of the inner circumference of the MRC and the arcs of the cylindrical surface of the rollers, the apex of the arc of the inner circumference of the MRC, S_1 , and the apex of the arc of roller 1, H_1 , match, as shown in Fig. 3(b). In the same way, S_2 for the inner circumference of the MRC and the apex of the arc of roller 2, H_2 , also match.

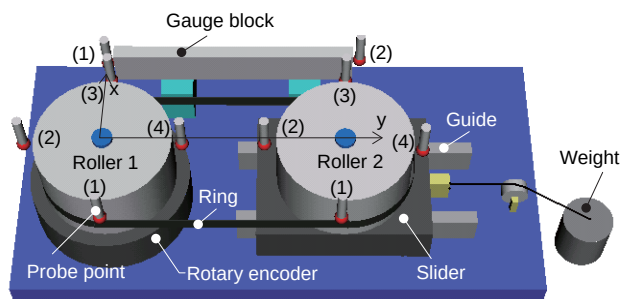
The height of the rollers is adjusted in order to reduce the difference between the positions of the apices of their arcs, Z_1 and Z_2 , to 0.1 mm or less. By this means, the cosine error for the length between the centers of the rollers is reduced to 0.03 μm , enabling it to be ignored.

Measurement of the coordinates of the centers of rollers 1 and 2 at this time enables the length between the centers of the rollers, E , to be calculated. If the measured figures for the radii of the apices of the arcs around which the MRC is wound are termed R_1 and R_2 for rollers 1 and 2 respectively, the circumferential length of the MRC, L , can be expressed as Eq.(1). According to the principle of propagation of uncertainty^{(3),(4)}, the uncertainty of L , $U(L)$, can be expressed as Eq.(2), where there is no correlation between E , R_1 , and R_2 , and k is the coefficient of inclusion.

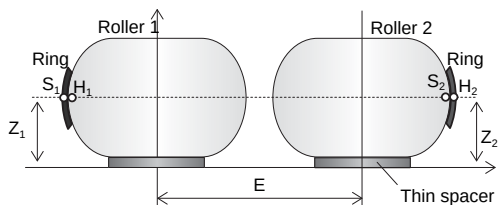
$$L = 2E + \pi (R_1 + R_2) \quad (1)$$

$$U(L) = k \times \sqrt{4U^2(E) + \pi^2 (U^2(R_1) + U^2(R_2))} \quad (2)$$

The coordinates of the centers of rollers 1 and 2 are calculated from measurements taken at four measurement points equi-positioned on the cylindrical surface of each



(a) Probe points position for measurement of length between two rollers using CMM



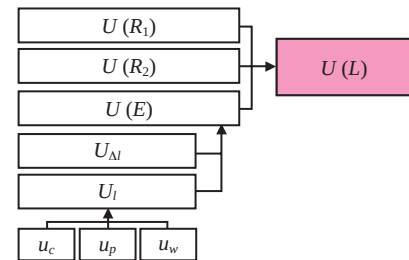
(b) Adjustment of roller's height for reducing cosine error

roller [Fig. 3(a)]. In order to compensate for the effect of the eccentricity of rollers 1 and 2 on the length between the centers of the rollers, E , the rollers are synchronized and E is measured for multiple 15 deg rotations of the rollers.

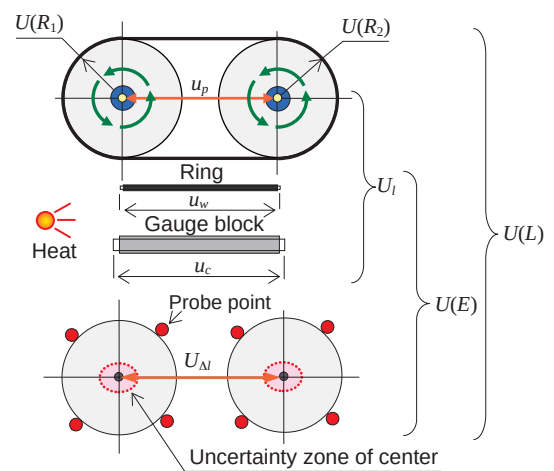
The data obtained displays a systematic fluctuation due to eccentricity that is dependent on the angle of rotation of the rollers. The length between the centers of the rollers can be numerically corrected. For the present measurements, the length between the centers of the rollers was measured after every 15 deg rotation for 24 times.

In addition, when the length between the centers of the rollers is measured, the length of a 150 mm gauge block, equivalent to the length between the centers of the rollers, is measured in order to compensate for the effect of thermal expansion on the scale in the CMM. The position of the end of one side of the gauge block is aligned with the center of roller 1, and the gauge block is positioned parallel to the line connecting roller centers.

The gauge block length measurements enable the uncertainty of the length measured by the CMM to be



(a) Combination of uncertainties for ring circumferential length measurement



(b) Classification of uncertainty sources

Fig. 3 Schematic diagram of instrument for CVT ring circumferential length measurement

Fig. 4 Classification of uncertainty sources and combination for uncertainty of ring circumferential length measurement

known and the uncertainty of the measurement of the length between the centers of rollers to be evaluated.

The purpose of this measurement method is to quantify the uncertainty of the circumferential length, L , expressed by Eq. (1). As shown in Fig. 4(a), there are three broad factors generating uncertainty in this measurement method: the uncertainty of the radius of roller 1, $U(R_1)$, the uncertainty of the radius of roller 2, $U(R_2)$, and the uncertainty of the length between the centers of the rollers, $U(E)$. $U(L)$ from Eq. (2) is a synthesis of these factors.

Figure 4(b) shows a classification of the factors generating uncertainty in $U(L)$. u_c is the uncertainty of the calibrated value from the gauge block and the compensation for thermal expansion, u_p is the uncertainty of the length between the centers of the rollers originating in change of the contact faces between the rollers and the ring due to the rotation of the rollers, and u_w is the uncertainty of compensation for thermal expansion of the metal rings. U_l is the combined standard uncertainty synthesized from u_c , u_p , and u_w .

$U_{\Delta l}$ is the uncertainty of the length between the centers of the rollers originating in the uncertainty of the roller center coordinates, which are determined solely by the position and number of the measurement points used in the CMM circular measurements, and the accuracy of the shapes of the subjects of the measurements.

3. Results of Measurement of Master Ring for Circumferential Length and Evaluation of Uncertainty

Figure 5 shows the results of measurements of the length between the centers of the rollers and the results following compensation for the eccentricity of the rollers. The median value of the measurements prior to compensation and following compensation for 1st-order eccentricity error is 158.2306 mm in both cases, but the standard deviation declines from 2.5 μm prior to compensation to 0.4 μm following compensation.

The same MRC was repositioned in the measurement

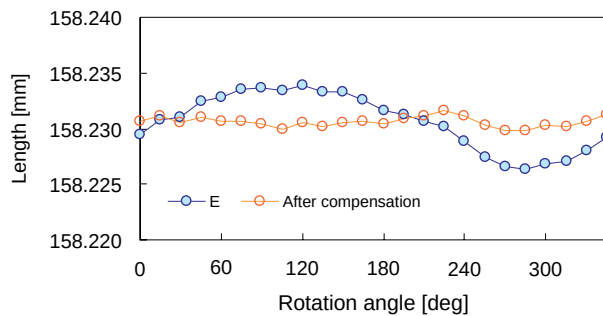


Fig. 5 Measurement of length between two rollers and compensation of perpendicular eccentricity of rollers

device and re-measured after 24 hours. The difference between the median values of the first and second sets of data was 0.1 μm , indicating that the measurement method achieves a sufficiently high level of reproducibility.

The evaluation of the uncertainty of the MRC measurements employed a comparative measurement method with the calibrated values for the gauge block and gauge ring as reference values, in accordance with ISO/TS 15530-3.

Figure 6 shows an overview of ISO/TS 15530-3. The uncertainty of the measurements, U , is calculated from repeated measurements of a calibrated workpiece (CW) of the same shape and dimensions as the subject of the measurements.

u_c is the uncertainty synthetically evaluated from the uncertainty of the calibrated values for the CW and the compensation for thermal expansion. u_p is the uncertainty of the CW measurements after 20 or more repetitions. u_w is the uncertainty synthetically evaluated from the uncertainty of the compensation for thermal expansion and the uncertainty in alignment of the subject of measurement. The uncertainty, at this time, U , is calculated from the sum of squares of u_c , u_p , and u_w , which can be evaluated independently.

Table 1 shows the factors generating uncertainty in MRC measurements and their uncertainty. The table also shows the calculated uncertainty of the measurement of the length between the centers of the rollers, $U(E)$, of the calculation of the coordinates of the centers of the rollers from roller measurements, $U_{\Delta l}$, and of the measurement of the radii of the rollers, $U(R)$. The uncertainty of both $U(E)$ and $U(R)$ was approximately 0.5 μm .

The uncertainty of the coordinates of the centers of the rollers determined solely by the position and number of measurement points for circular measurements affects $U_{\Delta l}$. For example, if measurement points are established uniformly following a circular form, the uncertainty of the coordinates of the centers tends to diminish as the number of measurement points increases. In the present measurement method, the time and accuracy of

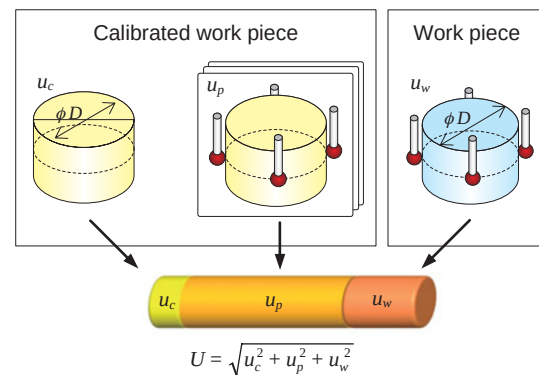


Fig. 6 Uncertainty estimation method based on ISO/TS 15530-3

Table 1 Uncertainty budget for circumferential length of ring measurement

Source	Symbol	Nominal value	Standard uncertainty	Distribution
Gauge block				
Length of gauge block	g^0	150 mm	50 nm	Normal
Linear coefficient of expansion	α_G	$10.8 \times 10^{-6}/K$	$\pm 0.5 \times 10^{-6}/K$	Normal
Temperature of gauge block	t_G	-0.627 K	0.1 K	Rectangular
CVT metal ring				
Length between two rollers	E	158 mm	—	—
Linear coefficient of expansion	α_R	$11 \times 10^{-6}/K$	$\pm 0.8 \times 10^{-6}/K$	Normal
Temperature of ring	t_R	-0.682 K	0.06 K	Rectangular
u_p [μm]			0.40	
u_w [μm]			0.14	
u_c [μm]			0.16	
$U(E)$ [μm]			0.45	
$U(R)$ [μm]			$U(R_1) = 0.46, U(R_2) = 0.60$	
U_t [μm]			0.37	
U_M [μm]			0.26	
$U(L)$ [μm] ($k=1$)			2.6	

measurements were optimized, and four measurement points were employed. Because of this, U_M was approximately 0.3 μm .

The temperature gauge used to compensate for thermal expansion in the gauge block, gauge ring, and MRC was calibrated in advance at an uncertainty of 0.0025 K. The uncertainty of the MRC measurements, $U(L)$, when k is 1 was 2.6 μm .

4. Conclusion

The measurement method discussed in this paper is a highly rational method, which can be used in place of direct measurement of the MRC, involving combined measurement of linear and circular forms that can be machined and measured with a high degree of precision.

In the area of judgment of product conformance, the necessity for quantification of the uncertainty of measurements is increasing, as exemplified by JIS B0641, and the importance of specifying processes of calculating uncertainty can also therefore be considered to be increasing.

High-accuracy measurements and evaluation of the

uncertainty of these measurements are necessary for numerous auto parts. The establishment of principles of measurement that consider the evaluation of uncertainty is demanded for highly important parts to which existing measurement methods cannot be applied.

This study of the precision measurement of MRC and the evaluation of the uncertainty of these methods produced the following results:

- (1) A combination of linear and circular shapes, representing the simple geometric form of the MRC, was measured using a high-precision CMM. The uncertainty of the measurements was 2.6 μm . The difference between first and second sets of measurements was 0.2 μm , indicating good reproducibility.
- (2) The employment of a method of evaluation conforming to the standard for evaluation of the uncertainty of CMM measurements, ISO/TS 15530-3, enabled quantification of the uncertainty of MRC measurements allowing traceability of length.
- (3) The provision of MRC with specified measurement uncertainty can be expected to contribute to quality management in mass production facilities and boost traceability between places of business.

References

- (1) ISO/TS 15530-3: 2004, Geometrical Product Specifications (GPS)-Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement- Part3: Use of calibrated work pieces or standards
- (2) ISO 14253-1: 1998, Geometrical Product Specifications (GPS)-Inspection by measurement of workpieces and measuring equipment-Part 1: Decision rules for proving conformance or nonconformance with specifications
- (3) Izuka, K.: Keisoku niokeru Futashikasa no Hyougen Guide, Nihonkikakukyoukai, p. 50 (1996) (in Japanese)
- (4) BIPM, IEC, IFCC, ISO, IUPAC, OIML: Guide to the expression of uncertainty in measurement, ISO First edition (1993)

■ Author ■



Kenta UMETSU



Hiroyoshi MIKOGAI