An ANOVA method of evaluating the specification uncertainty in roughness measurement

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Abstract

The specifications of roughness used in industry are normally incomplete, and the incompleteness can induce a significant uncertainty, called specification uncertainty. It's important to know the magnitude and effect of this uncertainty, but there are yet no standard methods of evaluating the specification uncertainty. In this paper, we propose an ANOVA method to estimate the specification uncertainty. In this method, ANOVA is used to separate specification uncertainty from measurement uncertainty, and the sampling method of GR&R (gauge repeatability and reproducibility) is applied. A case study is given to demonstrate how to use this method to evaluate the specification uncertainty of measuring roughness with PGI (Phase Grating Interferometer) when the filter type is not specified.

1 Introduction

1.1 Specification uncertainty

Specification uncertainty is one of the important uncertainties in the geometrical product specifications and verification (GPS) system. It is the uncertainty inherent in a specification when applied to a feature (point/ line/ plane), which quantifies the ambiguity in the specification [1]. In ISO/TS 17450-2 it is distinguished from measurement uncertainty and defined as the uncertainty arises from the incompleteness of the specification. In practice, most of

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specifications used in engineering drawings are incomplete. For example, the specification of a shaft, Ø10±0.1 is incomplete, since the association criteria (such as largest two-point diameter, minimum circumscribed sphere, least square sphere) is not specified. Due to this incompleteness, the measurement results can be different when the interpretation of the specification varies, even if the measurement uncertainty was zero.

It is important to understand and quantify the effect of the incompleteness of specification. A specification is designed to achieve some functional requirement. If the interpretation of the specification is largely biased from the original intention of the designer, the functional requirement may not be achieved by the parts controlled by the biased specification. For instance, the difference of the measured values of Ø10±0.1 between two possible interpretations, such as largest two-point diameter and smallest two-point diameter, can be even larger than the tolerance interval (depends on the roundness of the shaft), which means the measurement results and their conformity (accept or reject) can be totally different when the ambiguity of the specification is too large. Moreover, it is necessarily to know how large the ambiguity is, since it is not feasible to make each specification complete. Hence, we need to quantify the ambiguity in terms of specification uncertainty, which should be of the same nature as measurement uncertainty, so that it can be compared with the size of tolerance and the total variation to reveal how large it is. If the specification uncertainty is too large, the specification should be revised to be more complete.

The problem is how to evaluate the specification uncertainty. There is no standard method given in ISO/TS 17450-2. Only an example is given ([1], p.9):

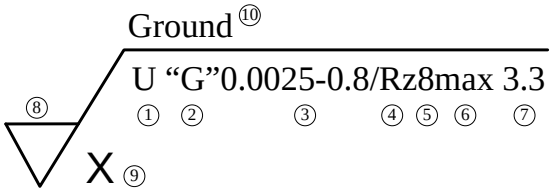
> If a specification for a sphere is SØ30±0.1,...The specification uncertainty is derived from the range of values that can be obtained when different association criteria (such as minimum circumscribed sphere, smallest two-point diameter, least squares sphere) are applied to data extracted from an actual workpiece (not perfectly spherical), because the specification does not prescribe which association criterion is to be used.

This implies that specification uncertainty can be evaluated according to the measured values of all the possible interpretations of the (incomplete) specification. One can then, similar to measurement uncertainty, use standard deviation or variance of the measured values to quantity the specification uncertainty. This method is applied in the paper of Lu ([2], p.5) to evaluate the specification uncertainty of the diameter of a shaft. However, there is inevitably some measurement uncertainty involved in the measured data, which is also a source of the variance of the measured values. Moreover, the specification uncertainty obtained by this method is relevant to the measured workpiece only. For another workpiece, the evaluated uncertainties can be different. For example, the specification uncertainty of Ø10±0.1 for a shaft with good roundness is small, but for a shaft with poor roundness is much larger. In manufacturing, we normally need to find out the specification uncertainty with regards to a whole lot of workpieces, thus the variation of the workpieces should also be considered. Therefore, specification certainty should be evaluated according to the measured

values of a set of workpieces using a measuring equipment base on all the possible interpretations of the specification.

The difficulties of evaluating specification uncertainty consist in (i) listing all the possible interpretations, (ii) removing the effect of measurement uncertainty, and (iii) making it compatible to the variation of workpieces. The method of finding all the possible interpretations is discussed in [3]. The aim of this paper is to propose an easily applicable evaluation method of specification uncertainty, which can solve the second and third difficulties.

1.2 Specification of roughness measurement



①Indication of upper (U) or lower (L) specification limit
②Filter type
③Transmission band
④Profile parameter
⑤Evaluation length as the number of sampling length
⑥Comparison rule
⑦Limit value in micrometres
⑧Type of manufacturing process
⑨Surface texture lay
⑩Manufacturing process

Figure 1: Control elements in the specification of surface roughness

Surface roughness is a good example of the complexity of a complete specification, which shows why specifications are normally incomplete. It is well known that a specification of roughness normally denotes in the form as $\sqrt{3.0}$ or $\sqrt{Ra3.0}$. But in ISO 1302:2002 [4], a complete specification of roughness consists of ten control elements, see figure 1. The specifications of roughness given in a engineering drawing are normally incomplete, and it's usually not necessary to specify all the ten control elements. Some of those elements affect the conformity with specification (accept/reject), which are the element s (1), (6) and (7) in figure 1; and some of those control the machining process and the appearance of the surface texture, which are (8), (9) and (10), Others, i.e. (2), (3) (4) and (5), affect the measured values. For the measurement of workpieces, only the control elements (2) to (5) could affect the measured values. For the evaluation of specification uncertainty, all the possible settings of elements (2) to (5) should be considered. This does not imply that the other elements are not important. Actually elements (7) and (8) are compulsory to be specified. When element (1) is not specified, by default, it should be understood as a upper tolerance limit [4]. 16%-rule is the default setting of element (6) in

ISO 1302. And if elements (9), (10) are not specified, it means any surface texture lay and machining process are acceptable.

2 Principle of the method

In industry, thousands of parts (workpieces) are manufactured in one lot according to the specifications. The features of these parts are simlar, but certainly not the same. Each feature varies among different parts with a certain variation, called *part variation*. This variation can be estimated by the variance of the measured values of some amount (e.g. 32 pieces) of randomly selected samples. But, in the measured values, there are two sources of variations: the variation from different parts and the variation from the measurement error of the measurement system. if the latter is significant, it is not reliable to estimated part variation directly from the variance of measured values. The measurement error of a measurement system can normally arise from two sources: the measuring equipment and the operators or inspector taking the measurement. In measurement system analysis, the variation in measurements caused by the random error of an equipment is named as *repeatability*, and the variation caused by different operators is named as *reproducibility*, they both contribute to the measurement uncertainty [5]. A standardized and commonly used method to study the repeatability and reproducibility is *Gauge R&R* (gauge repeatability & reproducibility). Gauge R&R can be used to distinguish the part variation and the variation from the measurement uncertainty, which is similar to the 2nd difficulty mentioned in chapter 1, hence the principle of gauge R&R should be useful for evaluating specification uncertainty.

There are two different statistical approaches to conduct Gauge R&R study. One is called average & range method, the other is *ANOVA* (analysis of variance) *method*. The former is simpler in term of calculation, but it's not suitable for the situation when some interaction variance (such as the interaction of operators and parts) occurs in the measured values. According to MSA 4th [6], the ANOVA-method is preferred; the average & range method should only be used if no PC is available for the calculations.

ANOVA is a statistical tool used to analyzing the observed data affected by several *factors*. The observed data varies with each factor, and each factor has different *factor levels*. When the levels of each factor changes, some variance can be observed from the data. ANOVA can be used to partition the observed variance into components attributable to different factors and their interactions (covariances). The processes of conducting ANOVA can be found in the text books of Montgomery [7]. And it can be implemented by statistical software, such as Minitab, SPSS, and Excel.

In gauge R&R, the parts, the equipment, and the operators are the three factors contribute to the variance of the measured values. To conduct a gauge R&R study, a set of samples (normally ten or twelve pieces) are randomly selected to be measured by two or three operators with an equipment. Each sample is measured by each operator repetitively two or three times to test the repeatability. So a set of measured values, say 12x3x3, can be obtained. The

twelve samples are numbered from 1 to 12, each one corresponding to one factor level of the 'part' factor. Similarly, the three operators are the three levels of the 'operator' factor, and the three repetitive measurements (called trials) are the three levels of the 'equipment' factor. The measured values can be indexed as $d_{i,j,k}$, where *i, j, k* are the indeces of the levels of the three factors, and organized in a table (see table 1). With the data (measured values) properly input into the table, the variance of the data can be partitioned into thrre parts: repeatability, σ_e^2, reproducibility, σ_o^2, and part variation, σ_p^2 by using ANOVA.

To determine whether the R&R of the measurement system is acceptable, the the ratios of R&R to the total variation (%R&R), and to the tolerance (%P/T) are calcuated as following [5].

$$\%\mathrm{R\&R} = \left(\sqrt{\sigma_e^2 + \sigma_o^2} \,/\, TV\right) \times 100\% \tag{1}$$

$$\%\mathrm{P/T} = \left(6 \times \sqrt{\sigma_e^2 + \sigma_o^2} \,/\, \mathrm{tolerance}\right) \times 100\% \tag{2}$$

If both ratios are lower than 10%, the measurement system is generally considered to be acceptable. It may be acceptable for some applications, when the ratios are betweem 10% to 30%. Otherwise, it is considered to be unacceptable [6].

Table 1. Gauge R&R datasheet

Operator	A -			B -			C -		
Sample #	1st Trial	2nd Trial	3rd Trial	1st Trial	2nd Trial	3rd Trial	1st Trial	2nd Trial	3rd Trial
1									
2									
3									
⋮									
12									

For the situation of evaluating specification uncertainty, as mentioned in the introduction, the data to be analyzed should be the measured values of a set of samples corresponding to all the possible interpretations of the specification. So the part variation and the random error of the measuring equipment are also involved in the total variation of the data. In this evaluation, it's not necessary to consider the effect of different operators, since the data can be collected by a single operator. Instead, another source of variation is contributed by the different interpretations of the specification. The effect of different interpretations to the measured values varies from part to part, which is actually similar with the effect of different operators in the sense that both effects are random. So the specification can also be taken as a factor (of the variance of data) with the different interpretations as its factor level. Hence a experiment can be designed similarly with the gauge R&R study, by replacing the 'operator' factor in gauge R&R with the 'specification' factor. The sample size of parts and

the number of repetitive measurements can be the same as gauge R&R, which are proved to be enough for statisical inference [5]. And by using ANOVA, the specification uncertainty can then be partitioned from the total variation of the data. The detail of this evaluation method is discussed in the next chapter.

3 A case study in roughness measurement

In this case study, we'll evaluate the specification uncertainty of the following specification on the surface of iPad metal cover.

$$\sqrt{\text{Ra } 1.2}$$

To demonstrate the evaluation method, assume that the metal cover of iPad is manufactured according to this specification. The Taylor Hobson PGI (Phase Grating Interferometer) is used for measuring the roughness in the way of contact stylus measurement.

According to ISO1302:2002, this specification means: the surface to be machined by removing material (e.g. milling); unilateral upper specification limit, maximum roughness average (*Ra*) is 1.2μm. By ISO4288:1998, The default sampling length of *Ra* 1.2 is 0.8mm, the default evaluation length should be five times the sample length (i.e. 4mm), and the cut-off long-wave length shall be chosen equal to the sampling length [8]. And by ISO3274:1996, the corresponding transmission band shall be 0.0025-0.8mm [9]. The filter type is not specified, and in ISO 1302:2002, it states that

> The standardized filter is the Gaussian filter (ISO 11562). The former standardized filter was the 2RC-filter. In the future, other filter types may be standardized. In the transition period it may be convenient for some companies to indicate the filter type on drawings.

Hence the Gaussian filter is recommended, but other filter types may also acceptable. According to those ISO standards mentioned above, one can then derive a much more complete specification from the original specification:

$$\sqrt{\text{U}0.0025-0.8/\text{Ra}5\ \ 1.2}$$

To get this derived specification, the inspector needs to have the knowledge and understanding of the four ISO standards, which is actually hard to be guaranteed. There is normally a knowledge gap between the ISO standards and the inspectors. So the ambiguity of an incomplete specification still exists, even if the complete specification can be derived base on some standards.

In this evaluation, we assume that the operator has the knowledge of the related standards, and thus the derived specification is obtained. Filter type is the unspecified control element which affects the measured values. There are three options of filter type in the software of PGI: Gaussian, 2CR-PC, and ISO-2CR, which can be taken as the three factor levels of specification. So the specification uncertainty to be evaluated is the variance of the measured values caused by the variation of filter types.

The experiment is designed in the following steps:

1. Mark twelve evenly distributed areas of the size 6x3mm^2 on the surface of the metal cover, and take these areas of surface as twelve samples. The part

variation in this case is contributed from the surface inhomogeneity (since the authors do not have twelve iPads).

2. Set the traveling distance of the stylus of each measurement to be 6mm, and set the transmission band to be 0.0025-0.8mm in the interface of the PGI.
3. Use the PGI to measure the *Ra* of the twelve areas. The measurement of each area shall repeat three times along the same path.
4. For each measurement, set the filter type to be Gaussian, 2CR-PC, and ISO-2CR in sequence to obtain three values of *Ra*.
5. Record and fill the 108 (12x3x3) measured values in table 2.
6. Input the values into the datasheet of SPSS (or some other software), and obtain specification uncertainty from the partitioned variance components (see table 3).

Table 2. Datasheet of roughness measurements in *Ra* (μm)

Filters	**Gauss**			**2CR-PC**			**ISO-2CR**		
Sample #	**1st Trial**	**2nd Trial**	**3rd Trial**	**1st Trial**	**2nd Trial**	**3rd Trial**	**1st Trial**	**2nd Trial**	**3rd Trial**
1	0.9621	0.9635	0.9621	0.9627	0.9649	0.9642	0.9732	0.9767	0.9765
2	0.9955	0.9985	1.0015	1.0006	1.0034	1.0058	1.0109	1.0122	1.0146
3	1.0071	1.0092	1.0103	0.9873	0.9897	0.9907	1.0325	1.034	1.035
4	1.0705	1.0717	1.0726	1.0449	1.0456	1.0463	1.0861	1.0873	1.0882
5	1.0373	1.0416	1.0433	1.0404	1.0448	1.047	1.0259	1.0316	1.0358
6	0.9799	0.982	0.9833	0.9856	0.9872	0.9873	1.0032	1.0053	1.0067
7	1.0951	1.0984	1.0998	1.0883	1.0918	1.0934	1.1100	1.1123	1.1126
8	1.0322	1.0336	1.0342	1.0273	1.0296	1.0309	1.0457	1.0480	1.0485
9	1.1127	1.1207	1.1255	1.1202	1.1292	1.135	1.0987	1.1065	1.1115
10	1.0772	1.0816	1.0828	1.0642	1.0687	1.0695	1.0736	1.0777	1.0783
11	1.0441	1.046	1.0463	1.0419	1.0438	1.0443	1.0336	1.035	1.0358
12	1.0611	1.0625	1.0631	1.0468	1.0478	1.0478	1.0386	1.0399	1.0411

Table 3. ANOVA results

Component	StdDev	Variance	% Contribution
Equipment	0.00278	0.0000077	0.37%
Specification	0.003806	0.0000145	0.70%
Parts	0.043726	0.001912	92.59%
Spec*parts	0.011438	0.0001308	6.33%
Total	0.045443	0.002065	100.00%

Table 3 shows the results of the variation components contributed from equipment, specification (different filters), different parts, and the interaction of

specification and parts in terms of standard deviation, variance, and percentage of contribution in the total variance.

The specification uncertainty is the sum of the variance of specification and covariance of specification and parts. From the results in table 3, it is 0.0001453 in terms of variance, σ_S^2 , and it is 0.012055μm in terms of standard deviation, σ_S . The specification uncertainty can be compared with the total variation and the tolerance by replacing the $\sqrt{\sigma_e^2 + \sigma_o^2}$ in equation (1) and (2) with σ_S . The results are 26.53% to the total variation, and 6.03% to the tolerance. Comparing with tolerance it is acceptable, but it is significant and may not be acceptable comparing with the total variation.

4 Conclusion

An ANOVA method of evaluating specification uncertainty based on the principle of gauge R&R is demonstrated. This method can be applied not only in roughness measurement but also for any other incomplete specifications. In the case study, the specification has three possible interpretations. In some cases, this number can be higher. For example, if the specifcation has five control elements, two of them are not specified, and each of the two has five options. Then there are 25 possible interpretations. In this case, the specification uncertainty can still be calculated in the same ANOVA method, but it will be very time consuming to take so many (12x25x3) measurements to collect the data. Although, it takes fewer measurements to analyze the two control elements separately, it is not correct to combine their uncertainties together to estimate the specification uncertainty, unless they are completely independent.

Reference:

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