Application of Measurement System R&R Analysis in Ultrasonic Testing

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Abstract

Measurement system analysis (MSA) technique is an important method which is used to analyze statistical discreteness and measurement capability of a measurement system, and also one of quality improvement techniques. The paper describes analysis principle and methods of repeatability and reproducibility (R&R) in MSA, introduces MSA techniques into the field of non-destructive testing (NDT). Based on an example of ultrasonic testing, the value of R&R is calculated and discussed. The results show that MSA technique can evaluate effectively measurement capability of ultrasonic testing system, and also can be applied in other NDT system.

Keywords: Measurement system analysis, Ultrasonic testing, Repeatability, Reproducibility

Quality data is an important basis to carry out quality analysis and diagnosis. It is obtained by the application of measurement system in measurement procedure. The accuracy of a measurement system will have a direct influence on the right judgment for product and process quality. Measurement system, which is different from the traditional measurement instrument, consists of the measured part, measurement method, measurement process, measurement instrument, reference standards, and measurement environment. It means the entire measurement process. Because of various reasons, each element of measurement system is possible to bring variation and discreteness into the measurement results, and affect the measurement accuracy. In order to ensure the reliability of measurement system, it's necessary to analyze the measurement system so as to determine and control the variation sources. So far research work on the statistical discreteness in measurement system is rarely implemented. If the discreteness is great, it will increase the measurement error.

In the view point of mathematical statistics, the evaluation indexes of measurement system include bias, stability, linearity, repeatability and reproducibility, etc[1]. Among them the repeatability and reproducibility(R&R) is an important quality index which can reflect measurement capability and precision, namely the discreteness caused by statistical random effect. The discreteness must be controlled within a certain range to ensure that measurement results are reliable.

Ultrasonic testing is one of the most important testing techniques in NDT. Ultrasonic testing system consists of inspector, ultrasonic flaw detector, ultrasonic probe, part, testing method, testing environment, technical standards and reference blocks, etc. The flaw detector

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and inspector are two important factors to determine the probability by which the flaw can be detected. Thus, applying the R&R analysis method to analyze their influence on testing results, consequently taking actions, the testing deviation can be effectively controlled. This paper is aimed to focus the discussion on application of R&R analysis technique in the industrial ultrasonic testing system.

1. Repeatability and reproducibility of measurement system

Most measurement systems (include ultrasonic testing system) are influenced mainly by the inspector and measurement instrument. So, it is necessary to analyze the repeatability and repeatability of measurement system.

1.1. Repeatability

Repeatability is the variation between measurement values which are obtained when one or several inspectors repeatedly measure a same parameter of the same kind of parts by using a same instrument. It usually indicates the variation caused by measurement instrument.

1.2. Reproducibility

Reproducibility is the variation between mean values which are obtained when different inspectors repeatedly measure a same parameter of the same kind of parts by using a same instrument. It usually indicates the variation caused by inspectors.

2. R&R Analysis model

Supposing the quality data X is distributed as normal distribution $N(\mu,\sigma^2)$, then the total variance of X is composed of the variance caused by measurement system and variance caused only by process variation without measurement errors [1].

$$\sigma^2 = \sigma_p^2 + \sigma_{MSE}^2$$

$$\sigma_{MSE} = \sqrt{\sigma_{AV}^2 + \sigma_{EV}^2}$$

where $\sigma_{EV}{}^2$ is the repeatability variance, $\sigma_{AV}{}^2$ is the reproducibility variance.

For σ_{MSE} ,it is necessary to first analyze σ_{EV} and σ_{AV} of the measurement system. Select randomly m inspectors, n tested parts, and then measure each part r rounds by each inspector.

2.1. σ_{EV} calculation

The range obtained by measuring each part r rounds by each inspector is given by

$$R_{ij} = \max\{X_{ijk}\} - \min\{X_{ijk}\}, \quad (i = 1,2,\ldots,m \quad j = 1,2,\ldots,n)$$

where X_{ijk} is the observation value .

The mean value of range is given by

$$\overline{R} = \frac{1}{m \times n}\sum_{i=1}^{m}\sum_{j=1}^{n} R_{ij}$$

then

$$\sigma_{EV} = \frac{\overline{R}}{d_2^*}$$

Where d_2^* is statistical constant of which the value depends on the sample number used to the range calculation and range number. With 99% confidence probability, repeatability is represented as

$$EV = 5.15\sigma_{EV}$$

2.2. σ_{AV} calculation

The mean values of the observation values measured by each inspector are given by

$$\overline{X_i} = \frac{1}{n \times r} \sum_{j=1}^{n} \sum_{k=1}^{r} X_{ijk}, i = 1, 2, \cdots, m$$

The range R_0 of the mean $\overline{X_i}$ obtained for different inspector is

$$R_0 = \max\{\overline{X_i}\} - \min\{\overline{X_i}\}, i = 1, 2, \cdots, m$$

Then

$$\sigma_{AV} = \sqrt{\left(\frac{R_0}{d_2^*}\right)^2 - \frac{\sigma_{EV}^2}{n \times r}}$$

With 99% confidence probability, reproducibility is represented as

$$AV = 5.15\sigma_{AV}$$

2.3. Variation between parts

There is difference between arbitrary two tested parts, which can be reflected by the measured results. The range R_p of the mean value for the tested parts is

$$R_p = \max\{\overline{X_j}\} - \min\{\overline{X_j}\}$$

where $\overline{X_j}$ is the mean value obtained by measuring the j th part r rounds by m inspectors.

$$\sigma_p = \frac{R_p}{d_2^*}$$

2.4. $R \& R$

The percentage of the $R \& R$ in the total variation is an important index that can be used to evaluate whether a measurement system should be accepted or not. The repeatability and reproducibility, R&R, of a measurement system is defined as:

$$R \& R = 5.15\sigma_{MSE} = \sqrt{EV^2 + AV^2}$$

$$R \& R\% = \frac{\sigma_{MSE}}{\sqrt{\sigma_{MSE}^2 + \sigma_p^2}} \times 100\%$$

According to general requirement, measurement capability of the system is considered enough and acceptable if $R \& R\%$ is less than 10% and is not enough and should be improved if $R \& R\%$ is greater than 30%. However, its measurement capability is ambiguous if $R\&R\%$ falls within 10% to 30%. In this case, whether the system is acceptable or not depends on the practical application.

3. R&R analysis for ultrasonic testing system

Take the ultrasonic testing system as an application example. As stated early, this system consists of ultrasonic flaw detector, probe, inspector, part, etc. We carried out thickness measurement of steel plate, based on the result, and evaluated the R&R of the measurement system. The experiment used PXUT-27 ultrasonic flaw detector calibrated by 1:1 beam path,2.5MHz×20 straight-beam probe, and employed two different inspectors (m=2) to measure three rounds (r=3) the thickness of each of five same steel plates (n=5) by single surface and single probe testing method. The thickness data are shown in table 1.

Table 1 The thickness data for steel plate (mm)

Part n	inspector 1					inspector 2					$\overline{x}_j$
	round r			$\overline{x}_{ij}$	R_{ij}	round r			$\overline{x}_{ij}$	R_{ij}	
	1	2	3			1	2	3			
1	45.2	45.2	45.1	45.17	0.1	45.0	44.9	45.0	44.97	0.1	45.07
2	45.0	44.8	45.0	44.93	0.2	44.8	44.8	45.0	44.87	0.2	44.90
3	45.1	45.0	45.1	45.07	0.1	45.0	45.0	45.1	45.03	0.1	45.05
4	45.6	45.4	45.4	45.47	0.2	45.6	45.6	45.6	45.6	0	45.34
5	45.1	45.1	45.0	45.07	0.1	44.9	44.9	45.0	44.93	0.1	45.00
mean	---	---	---	**!Division durch Null**	0.14	---	---	---	14	0.10	---

Before the R&R analysis is conducted, measurement process should be stable. Therefore, it is the first step to use the repeatability range control chart to verify whether the measurement system is stable. The range control chart should be plotted by the range data obtained by repeated measurement, as shown in the figure 1. From the chart, it's seen that all of the ranges are under control, and the measurement process is stable, then the R&R analysis can be conducted for the measurement system.

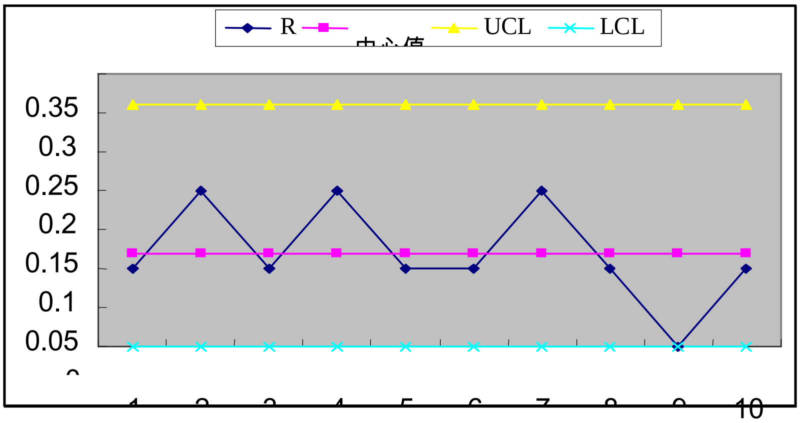

Figure1 Range control chart plotted by the range data

3.1. Repeatability calculation

When m=2, n=5, r=3, we can find $d_2^*(3, 2\times5) = 1.72$ from the statistical constant table[2-3], the repeated measurement variation σ_{EV} and the repeatability EV are calculated as follow:

$$\sigma_{EV} = \frac{\overline{R}}{d_2^*} = \frac{\left(\overline{R_1} + \overline{R_2}\right)}{2d_2^*} = \frac{(0.14 + 0.1)}{2\times1.72} = 0.07$$

$$EV = 5.15\sigma_{EV} = 0.36$$

3.2. Reproducibility calculation

From table 1, $\overline{x_1} = 45.14, \overline{x_2} = 45.08$ .so the range

$$R_0 = 0.06$$

From the Statistical constant table, $d_2^* = d_2^*(2,1) = 1.41$, then σ_{AV} is

$$\sigma_{AV} = \sqrt{\left(\frac{R_0}{d_2^*}\right)^2 - \frac{\sigma_{EV}^2}{n\times r}} = \sqrt{\left(\frac{0.06}{1.41}\right)^2 - \frac{0.07^2}{5\times3}} = 0.039$$

The reproducibility is

$$AV = 5.15\sigma_{AV} = 0.198$$

$$\sigma_{MSE} = \sqrt{\sigma_{AV}^2 + \sigma_{EV}^2} = \sqrt{0.039^2 + 0.07^2} = 0.08$$

The value of R&R is given as

$$R\&R = \sqrt{EV^2 + AV^2} = 0.41$$

3.3. Variation between different parts

From table 1, $R_p = 0.44$.With $d_2^* = d_2^*(5,1) = 2.48$, variation between parts σ_p is

$$\sigma_p = \frac{R_p}{d_2^*} = \frac{0.44}{2.48} = 0.18$$

Therefore

$$R\&R\% = \frac{\sigma_{MSE}}{\sqrt{\sigma_{MSE}^2 + \sigma_p^2}} \times 100\% = \frac{0.08}{\sqrt{0.08^2 + 0.18^2}} \times 100\% = 0.41 = 41\%$$

Because the value of R&R is above 30%, measurement capability of the ultrasonic testing system is insufficient, and the system can not be used again. Through further analyzing the results above, we know the value EV of this testing system is great, which indicates that the repeatability of the system is bad. The possible reasons resulted in it are that the periodic maintenance is not done when the detector is in service, its precision is poor, or there are bad physical contact etc.

4. Conclusion

In practical measurement process, the inspector only pays attention to the accuracy of measurement instrument itself. In other words, the accuracy is improved only by the periodic calibration, but statistical discreteness of measurement system is rarely analyzed. The calibration of measurement instrument can only tell the status of instrument itself, but not judge the measurement error and measurement capability of the system. Besides the R&R , measurement system analysis also includes other statistical quantities, for example, bias, stability, and linearity, etc. The R&R is an important index that reflects the capability of measurement system, therefore this paper does not do further analysis for other indexes. In foreign countries, the MSA technology is widely used to improve product quality in the large company in the field of automobile industry, aeronautical and aerospace industry, electronic industry, etc. NDT is an important method for quality control, the reliability of ultrasonic testing, electromagnetic testing, radiographic testing, and other new NDT methods are related to the measurement capability of measurement system. This paper has introduced the MSA technology into NDT, and discussed its application in ultrasonic testing system. The analysis method and results in this paper also can be used as the reference to analyze and evaluate other ultrasonic testing systems.

Reference

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