Abstract

The correctness of important decisions concerning products quality, need of process interventions, suitability of given technology etc. considerably depends on quality of measured data. Quality of measured data is determined by the properties of used measurement system (e.g. stability, bias, repeatability, reproducibility etc.), which are assessed by means of measurement system analyses. Paper deals with possibilities of confidence improvement of measurement system repeatability and reproducibility analyses (GRR analyses) results. With using Ishikawa diagram they are identified factors, which can influence on the GRR analysis results. These factors are divided to them, which influence on GRR analysis results values, and them, which influence on GRR analysis results confidence. Special attention is paid to the factors affecting GRR analysis results confidence, concretely to the number of operators, number of samples and number of trials. For the cases of two and three operators there is analysed the influence of number of samples and number of trials on the distance of upper limit of GRR confidence interval from GRR point estimate (in percentages), which characterises GRR analysis results confidence. Appropriate dependences are processed graphically and numerically with using non-linear regression analysis. Obtained results make possible to optimize conditions of GRR analyses and to improve the confidence of analyses results.

Keywords: measurement system, repeatability, reproducibility, GRR, confidence interval

INTRODUCTION

Many of decision processes, which results depend on the quality of measured data, are realised during products quality control. They include, for example, choice of the best technology, process control, products quality inspection, assessment of corrective actions efficiency etc. In the cases of insufficient quality of measured data these important decisions can be incorrect and can cause high financial losses. Quality of measured data is determined by measurement system properties. Verification of measurement systems acceptability is an important part of quality planning and improvement and e.g. in the automotive industry it is strictly required.

1. REPEATABILITY AND REPRODUCIBILITY OF MEASUREMENT SYSTEM

Repeatability and reproducibility, which represent two basic components of measurement system variability, are very important properties of measurement system. While repeatability (equipment variation – EV) is defined as variability of repeated measurements of the same quality characteristic in constant conditions, reproducibility (appraiser variation – AV) represents variability of mean values of sets of repeated measurements realised in various conditions. Average and range method (A&R) is most commonly used for measurement system repeatability and reproducibility assessment in the practice. Required data are obtained by repeated measurements of product samples realised by various operators. With using defined procedure, which includes both numeric and graphical evaluation, repeatability (EV) and reproducibility (AV)
are determined [1, 2]. On the basis of their values it is possible to calculate combined repeatability and reproducibility (GRR) according to the relation (1).

\[
GRR = \sqrt{(EV)^2 + (AV)^2}
\]  

(1)

As criteria of measurement system acceptability the percentage share of GRR in total variation and number of distinct categories (ndc) are used. They are calculated with using relations (2) and (3).

\[
\%GRR = \frac{GRR}{TV} \cdot 100
\]  

(2)

\[
ndc = 1.41 \cdot \frac{PV}{GRR}
\]  

(3)

where:

TV – total variation
PV – parts variation

Measurement system is considered as fully acceptable in the cases, when \%GRR value is lower than 10% and at the same time ndc value is 5 minimally.

GRR analysis results can be influenced by the many of various factors. Identification of these factors was carried out with help of Ishikawa diagram (see Fig. 1). It can be seen that number of affecting factors is rather high and they are related to the various areas. For simplification these factors can be divided to the two groups:

- Factors affecting values of GRR analysis results
- Factors affecting confidence of GRR analysis results.

2. FACTORS AFFECTING THE VALUES OF GRR ANALYSIS RESULTS

The importance of factors affecting the values of GRR analysis results consists in the fact that they may significantly influence the resulting value of combined repeatability and reproducibility of measurement system and subsequently its percentage share in total variability of the process. The most important factors are, for example:

- Coverage of production range
- Meeting the same measurement procedure
- Meeting the same measurement conditions
- Outliers
- Way of total variation expressing
- Other properties of measurement system

3. FACTORS AFFECTING THE CONFIDENCE OF GRR ANALYSIS RESULTS

The resultant values of GRR analysis are just point estimations and their real values lie with the predetermined probability in the confidence interval round this point estimation. So the width of the confidence interval characterizes the quality of analysis results and its knowledge should be considered when comparing the acquired results with the limit values. Due to the point estimation, the confidence intervals are asymmetric with a greater distance to the upper limit which is important for the assessment of plausibility of measurement systems. The enhancement of quality of GRR analysis results is dependent on
possibilities of narrowing the confidence intervals of the results from this analysis. Apart from the selected level of significance, the size of coincidence intervals of the results from GRR analysis executed by means of Average and Range Method (A&R) on the following parameters:

- The number of operators taking measurements
- The number of measured samples
- The number of trials

All workers taking measurements of the given quality characteristic should take part in the GRR analysis. In practice, the number of operators is given by the number of shifts in production. All the operators should take measurements by the same method and under the same measurement conditions.

The minimum number of samples for GRR analysis was fixed to 5 measured pieces and the recommended number to 10 measured pieces in the third issue of MSA handbook [1]. The latest, fourth issue of MSA handbook, have increased these numbers to 10 or 15 measured samples respectively. All the measured samples to be analysed, should be selected so as to represent and cover the overall production range of the measured attribute uniformly.

For needs of the GRR analysis, each operator is required to take measurements of the selected pieces twice at least. The measurements are taken in random order and the operators should not know which piece they measure, and they should not know previous results when measurements are taken repeatedly.

The effect of changes in values of the above described parameters was subsequently assessed pursuant to the data from GRR analysis taken from work [2]. The values of upper GRR confidence limits for various samples and repeated measurements were computed using Statgraphics Centurion v.15 software and their distance from the point estimation was then recounted to percentages of point estimation.

The dependences of distance of the upper GRR confidence limits from the point estimation (in percentages of point estimation) on the numbers of samples and trials implemented for the study case by two or three operators are presented in Fig. 2. The figure indicates that the distance of the upper GRR confidence limit is cut down with the increasing number of samples. This function is more accentuated with a smaller number of

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Fig. 1 Ishikawa diagram of factors affecting GRR analysis results.
operators, which can be explained by a smaller sum total of measurements. When comparing the individual curves, it is apparent that the appropriate distance can be cut short more significantly by the growing number of trials than by the growing number of samples (and to increase the confidence of the determined GRR value). It is probably connected with the dominating influence of interval estimation of the standard deviation of repeatability.

![Distance of upper GRR confidence limit from its point estimate depending on the number of samples.](image)

**Fig. 2** Distance of upper GRR confidence limit from its point estimate depending on the number of samples.

![Response surface of the distance of upper GRR confidence limit from its point estimate in relation to the number of samples and number of trials.](image)

**Fig. 3:** Response surface of the distance of upper GRR confidence limit from its point estimate in relation to the number of samples and number of trials (two operators).
With aim to describe the dependence of the distance of upper confidence limit of GRR from its point estimate on the number of samples and number of trials by the means of suitable functional relation the non-linear regression analysis was used. It was found that in the case of two operators appropriate distance can be calculated according to the relation:

\[ d_{U,GRR} = 7.782 + 598.243 \cdot n^{-1.229} \cdot r^{-0.838} \]  \hspace{1cm} (4)

where:
- \( d_{U,GRR} \) – distance of upper GRR confidence limit from its point estimate, %
- \( n \) – number of trials
- \( r \) – number of samples

This regression function ensures very good conformity between determined and calculated values of distance. Correlation index is 0.996 and all function parameters are on the significance level \( \alpha = 0.05 \) statistically significant. This dependence was graphically described with using response surface (see Fig. 3). Response surface shape confirms fact, that increasing number of trials has more considerable influence on GRR confidence than increasing number of samples.

For the case of GRR analysis with three operators it was found that appropriate dependence of the distance of upper GRR confidence limit from its point estimate can be described with using this function:

\[ d_{U,GRR} = 4.468 + 308.302 \cdot n^{-1.034} \cdot r^{-0.715} \]  \hspace{1cm} (5)

Also this regression function assures very good conformity between determined and calculated values of distance. Correlation index was 0.997 and all function parameters were on the significance level \( \alpha = 0.05 \) statistically significant.

4. POSSIBILITIES TO INCREASE THE RELIABILITY OF RESULTS FROM REPEATABILITY AND REPRODUCIBILITY MEASUREMENT ANALYSIS

As mentioned in the previous chapter, it is possible to achieve the increase in confidence of results of GRR analysis by changing the values of parameters of this analysis. In practice, the number of operators is given and that is why the increased confidence of the determined GRR value can be achieved by increasing one or both of the remaining parameters. When analysing figures 2 and 3, it is apparent that the number of trials has a stronger influence on the width of the confidence interval. Fig. 4 illustrates how this influence takes effect in the event that the total of measurements remains the same. This figure illustrates the distance of the upper GRR confidence limit from its point estimate depending on the same total of measurements which is achieved by different numbers of samples and repeated measurements for two operators.

For example, the total of sixty measurements can be achieved in practice in the event that two operators will measure fifteen samples in two repeated measurements or ten samples in three repeated measurements. For the first combination of parameters based on a larger quantity of samples the distance of upper GRR confidence limit from its point estimation is 35.69% whereas in the situation based on a larger number of repeated measurements, this value is lower by 6.6 percentage points. In terms of confidence of the achieved GRR results, it is more advantageous to increase the number of repeated measurements to 3 than to increase the number of samples to 15 if implementing the study with 10 samples and two repeated measurements.
CONCLUSIONS

In organizations executing the analysis of the measurement system, making decisions on the values of GRR analysis parameters is carried out on the basis of seeking a compromise between the requirement for top quality of the results acquired and the demand for the least financial and temporal demandingness when executing this analysis. In this sort of decision making, it is also necessary to consider the character of the given process, type of measured value, importance of the given measurement and other aspects specific to each process, organization or type of production. The results of the analysis themselves and their confidence are influenced by a series of factors, the most important of which are described in this article. The experiments carried out, the results of which are analysed in previous chapters, discover the possibilities of increasing or maintaining the confidence of the result of GRR analysis for different values of parameters of this analysis.

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