Analysis of Automated differential Multi-gauging System through Gauge Repeatability and Reproducibility (GRR)

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Abstract
Automated Differential Multi-gauging system is a very complicated and critical tool to measure some casting and machining parts. Hypoid pinion assembly has two taper rollers bearing with assembly play or gap. The differential assembly checking will be on three stages as P is housing and Q is hypoid pinion and the gap between both parts. The differential multi-gauging system needs to evaluate and analyse these critical parameters firmly is very important. So, after manufacturing and assembly of these automated differential multi-gauging system analysis confirmed by Gauge repeatability and reproducibility i.e. GRR. For the GRR method, we can take multiple experiments on the machine as many trials with the different number of parts and operator then that data will be analysed through this method. After analysing the result and accuracy of the measurement system by repeatability trials. The GRR results will be below 10 % is required then and then the only gauging system is Acceptable. The GRR will generate proper graphs and report which shows how multi-gauging system will ready to take thousands of parts checking accurately and precisely in the industry. This research will help anyone to how to analyse and evaluate the multi-gauging system result through GRR.

Key-words: Gauge Repeatability and Reproducibility (GRR), MSA, Multi-gauging System.

1. Introduction

Gauge R&R is used to understand the actual readings in the part, gauge, multi-gauge, and gauging system changes parameter value in measurements. Repeatability shows measurement readings generated by one operator using one gauge. Reproducibility shows the deviation of the parameter due to multiple operators using the same gauge. Part-to-part variation, repeatability, and reproducibility are the 3 different types of source variation. Part-to-part variation is the range of parts by considering manufacturing circumstances. Repeatability has deviation changes because of the
gauge assembly itself, while reproducibility is the inequality because of different workers using the gauge. Repeatability and reproducibility both are known as "Gauging error" and are said as "GAUGE R&R”. A gauge R&R study will let us know that if the gauging system is acceptable for its intended use. Gauge repeatability and reproducibility (GRR) study is a representative measurement system analysis (MSA) tool. Two factors determine the adequacy of a measurement system: accuracy, such as bias, linearity, stability, and correlation, and precision such as repeatability and reproducibility. The main concern of the GRR is that a measurement system has enough precision to measure the variation of the manufactured products or the manufacturing process under consideration. [1]

Statistical Process Control (SPC) is a very powerful collection of problem-solving tools that are widely used for monitoring and improving the process. The purpose of measurements is to track the process. For this reason, SPC methods use a measurement process to control the process. Consequently, the quality of the measurement process influences the quality of the process improvement actions. [2]

DMAIC methodology is used for part quality or process quality improvement in the industry. This process includes dynamic data collection which is primarily based on part dimensional measurements. MSA is a set of techniques that allows us to assess the reliability, repeatability, accuracy of the Measurement System. It is a set of experiments that mainly focuses on identifying the variation and considers the process of obtaining data and the instruments. It evaluates the test process, measuring equipment, and the overall process of obtaining measurements to ensure the reliability of data used for analysis and to understand the effects, and to take the decisions related to the same. The gauge study proves which part of the Measurement System is contributing the most to the instability of the measurements. Measurement Systems have variation from three major sources: The component, the operator taking measurements, and the device used. In a good measurement system, one must expect to calculate almost completely the variation in the products only. If the operators and devices create most of the variation, it shows that the system is not valid. Hence Measurement System Analysis takes into all the critical parameters like linearity, bias, stability, and GRR studies which help in determining the performance of the Measurement System. This research focuses on performing the GRR study on the industry’s measurement system. [3]

The main purpose of a GR&R study is to determine how much of the total observed variability is due to the gauge (or instrument) so that the capability of the gauge can be assessed. The total observed measurement (x) can be defined by Eq.1.

\[ x = x_{\text{Product}} + \varepsilon \] \hspace{1cm} (1)
Where \( X \) product is the true value of the measurement and \( \varepsilon \) is the measurement error. The variance of the total observed measurement (\( \sigma^2 \) Total) is defined by Eq.2 if \( x \) and \( \varepsilon \) are normally and independently distributed random variables with means \( \mu \) and 0 and variances \( \sigma^2 \) Product and \( \sigma^2 \) Gauge, respectively.

\[
\sigma^2 \text{ Total} = \sigma^2 \text{ Product} + \sigma^2 \text{ Gauge}
\]

Total variability includes both product variability and gauge variability. The product variability is the actual variation between parts produced by the process; it is also called the part-to-part variability. The variance of the measurement error (or the deviation of the gauge) is defined by two components, repeatability (deviation due to the gauge itself) and the reproducibility (deviation due to the operators) of the gauge as in Eq.3.

\[
\sigma^2 \text{ Measurement Error} = \sigma^2 \text{ Gauge} = \sigma^2 \text{ Repeatability} + \sigma^2 \text{ Reproducibility}
\]

The experiment used to measure these two components is usually called a GR&R study. [4]

2. Concept, Design and Manufacturing System

The three-stage checking system concept is created. In which Housing, hypoid pinion, and Shim thickness (Gap Measurement) concept is created considering the load and force also the position and orientation of the part by which we will get exact and accurate values. The gear housing is a concept created considering one main locator and sliding plate, sliding plate will move forward and reverse for loading position and gauging position. The main indirect gauging mechanism is used is spring-loaded assembly to measure the distance from one bearing to another bearing as shown in Fig 1a. For hypoid pinion checking concept locator and mechanical clamp used. The indirect spring mechanism is used in hypoid pinion gauging assembly as shown in Fig 1b. The shim station will be measured exact shim size as our gap is generated. Shim station measurement concept consists of one pneumatic cylinder, plunger anvil, and base plate on which shim will be placed as per we will measure the exact size of shim as shown in Fig 1c. After concept creation and concept finalization model design was created. For modelling considered one as to one manufacturing consideration and production requirement also the physical requirement of the system. The main requirement is the production of such a critical system with required tolerances and surface quality as per the application of a multi-gauging system. The overall manufacturing system is shown in Fig 2.
Figure 1(a) - Concept Creation for Gear Housing

Figure 1(b) - Concept Creation for Hypoid Pinion

Figure 1(c) - Concept Creation for Shim Station

Table 1 - Measuring parameter value with tolerance as per component

| Sr. No. | Gauging System                  | Measuring Value  |
|---------|---------------------------------|------------------|
| 1       | Gear Housing - Part 1           | 93.16 ± 0.050    |
|         | Gear Housing – Part 2           | 93.25 ± 0.050    |
| 2       | Hypoid Pinion                  | 89.890 ± 0.050   |
| 3       | Shim Station                   | 3.2, 3.4, 3.6, 3.8, 4.0, 4.2 |
3. Experimentation

Table 2 - Repeatability Trials for P, Q and Shim Station

| Sr. No. | “P” Distance | “Q” Distance | “SHIM” Distance |
|---------|--------------|--------------|-----------------|
| 1       | 93.574       | 89.893       | 3.681           |
| 2       | 93.575       | 89.894       | 3.683           |
| 3       | 93.573       | 89.894       | 3.682           |
| 4       | 93.574       | 89.892       | 3.681           |
| 5       | 93.572       | 89.894       | 3.681           |
| 6       | 93.574       | 89.896       | 3.680           |
| 7       | 93.574       | 89.894       | 3.681           |
| 8       | 93.573       | 89.894       | 3.682           |
| 9       | 93.574       | 89.895       | 3.683           |
| 10      | 93.574       | 89.894       | 3.681           |
| Diff.   | 0.003        | 0.004        | 0.004           |

For the GRR measurement experiment run number of trials on every assembly system stage. For repeatability trials, we generate the number of trial data for understanding the multi-gauging system result. First, take 10 trials of every parameter as shown in Table 2.

For GRR gauge repeatability and reproducibility result as analysed by two methods as 1. Average and Range method and 2. Analysis of Variance (ANOVA). But ANOVA has multiple stages and sub-methods to analysed data as per parameter, level of factor, and requirement of the system.
But in our case, we analysed our result by AIAG method (Average and Range method) for Average and Range method requirement are three operators and 10 number of trials by each operator for every system. As our automated differential multi-gauging system has three stations “P”, “Q”, and “Shim” distance measurement. So, for the “P”, “Q”, and “Shim” system we must take 300 trials as 100 trials for each operator, and one part or component have 3 trials to achieve exact and accurate GRR result. In our differential multi-gauging system has three operators as Prasad, Amit, and Nishant for GRR number of trials. We are taking down every value with tolerance for every operator. As shown in below Table 3.

| OPERATOR: | PRASAD |
|-----------|--------|
| TRIAL 1   | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | AVERAGE |
| 1         | 93.574 | 93.907 | 93.844 | 93.795 | 93.835 | 93.754 | 93.652 | 93.808 | 93.622 | 93.687  |
| 2         | 93.570 | 93.907 | 93.840 | 93.796 | 93.842 | 93.754 | 93.654 | 93.808 | 93.622 | 93.690  |
| 3         | 93.574 | 93.909 | 93.840 | 93.792 | 93.842 | 93.750 | 93.650 | 93.809 | 93.621 | 93.689  |
| Avg.      | 93.573 | 93.908 | 93.841 | 93.794 | 93.840 | 93.753 | 93.652 | 93.808 | 93.622 | 93.689  |
| Range     | 0.004  | 0.002  | 0.004  | 0.004  | 0.007  | 0.004  | 0.004  | 0.001  | 0.001  | 0.003   |
| OPERATOR: | AMIT   |
| TRIAL 1   | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | AVERAGE |
| 1         | 93.574 | 93.907 | 93.844 | 93.792 | 93.835 | 93.754 | 93.650 | 93.808 | 93.622 | 93.689  |
| 2         | 93.574 | 93.909 | 93.844 | 93.796 | 93.842 | 93.750 | 93.654 | 93.808 | 93.621 | 93.690  |
| 3         | 93.570 | 93.909 | 93.840 | 93.795 | 93.840 | 93.750 | 93.654 | 93.809 | 93.621 | 93.689  |
| Avg.      | 93.573 | 93.908 | 93.841 | 93.794 | 93.840 | 93.751 | 93.652 | 93.808 | 93.622 | 93.689  |
| Range     | 0.004  | 0.002  | 0.004  | 0.004  | 0.007  | 0.004  | 0.004  | 0.001  | 0.001  | 0.003   |
| OPERATOR: | NISHANT|
| TRIAL 1   | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | AVERAGE |
| 1         | 93.574 | 93.907 | 93.844 | 93.796 | 93.842 | 93.750 | 93.650 | 93.808 | 93.622 | 93.687  |
| 2         | 93.570 | 93.907 | 93.840 | 93.796 | 93.842 | 93.754 | 93.654 | 93.808 | 93.622 | 93.690  |
| 3         | 93.570 | 93.909 | 93.844 | 93.792 | 93.835 | 93.754 | 93.652 | 93.809 | 93.621 | 93.690  |
| Avg.      | 93.573 | 93.908 | 93.841 | 93.794 | 93.840 | 93.751 | 93.652 | 93.808 | 93.622 | 93.689  |
| Range     | 0.004  | 0.002  | 0.004  | 0.004  | 0.007  | 0.004  | 0.004  | 0.001  | 0.001  | 0.003   |

As the gear, housing end play from 0.1 to 0.5 mm in overall assembly, the Gear housing range for measurement is 93.200 to 92.900. Our least count of tolerance is 0.010 mm or 10 microns. For hypoid pinion measurement, it is a single solid part, so the required measurement range is 89.890 with the tolerance of +0.050- and -0.050 - micron value. As shown in below Table 4.
**Table 4 - Repeatability Trials readings for Station “Q” (Gear Housing)**

| OPERATOR: | PRASAD | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10  | AVERAGE |
|-----------|--------|------|------|------|------|------|------|------|------|------|------|--------|
| TRIAL     |        | 89.894 | 89.914 | 90.049 | 89.873 | 89.877 | 89.814 | 89.860 | 89.855 | 89.869 | 89.850 |
|           | 2      | 89.895 | 89.919 | 90.048 | 89.876 | 89.879 | 89.817 | 89.856 | 89.856 | 89.867 | 89.851 |
|           | 3      | 89.894 | 89.913 | 90.048 | 89.879 | 89.879 | 89.818 | 89.856 | 89.849 | 89.867 | 89.851 |
| Avg.      |        | 89.894 | 89.915 | 90.048 | 89.876 | 89.878 | 89.816 | 89.857 | 89.853 | 89.868 | 89.851 | Xa= 89.886 |
| Range     | 0.001  | 0.006  | 0.001 | 0.006 | 0.002 | 0.004 | 0.004 | 0.007 | 0.002 | 0.001 | Ra= 0.003 |

| OPERATOR: | AMIT | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | AVERAGE |
|-----------|------|----|----|----|----|----|----|----|----|----|----|--------|
| TRIAL     |      | 89.894 | 89.913 | 90.049 | 89.873 | 89.877 | 89.814 | 89.860 | 89.855 | 89.867 | 89.850 |
|           | 2    | 89.895 | 89.919 | 90.048 | 89.876 | 89.879 | 89.817 | 89.856 | 89.856 | 89.867 | 89.851 |
|           | 3    | 89.895 | 89.913 | 90.048 | 89.879 | 89.879 | 89.818 | 89.860 | 89.849 | 89.867 | 89.851 |
| Avg.      |      | 89.894 | 89.915 | 90.048 | 89.876 | 89.878 | 89.816 | 89.857 | 89.853 | 89.868 | 89.851 | Xb= 89.886 |
| Range     | 0.001 | 0.006 | 0.001 | 0.006 | 0.002 | 0.004 | 0.004 | 0.007 | 0.002 | 0.001 | Rb= 0.003 |

| OPERATOR: | NISHANT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | AVERAGE |
|-----------|----------|----|----|----|----|----|----|----|----|----|----|--------|
| TRIAL     |          | 89.894 | 89.913 | 90.049 | 89.873 | 89.879 | 89.814 | 89.860 | 89.855 | 89.867 | 89.850 |
|           | 2        | 89.894 | 89.919 | 90.048 | 89.873 | 89.879 | 89.817 | 89.856 | 89.856 | 89.867 | 89.851 |
|           | 3        | 89.895 | 89.914 | 90.049 | 89.879 | 89.877 | 89.818 | 89.856 | 89.849 | 89.867 | 89.851 |
| Avg.      |          | 89.894 | 89.915 | 90.048 | 89.876 | 89.878 | 89.816 | 89.857 | 89.853 | 89.868 | 89.851 | Xc= 89.886 |
| Range     | 0.001   | 0.006  | 0.001 | 0.006 | 0.002 | 0.004 | 0.004 | 0.007 | 0.002 | 0.001 | Rc= 0.003 |

The formula for the gap or Shim value measurement is,

\[
\text{Gap Measurement} = \text{Gear Housing Value (Station “P”) – Hypoid Pinion Value (Station “Q”)}
\]

For example,

\[
\text{Gap Measurement} = 93.200 – 89.890 = 3.31 \text{ mm}
\]

So, 3.31 mm is the exact gap between gear housing and hypoid pinion, the requirement is to maintain 0.1 to 0.5 end play in the overall differential assembly.

So, Exact Shim required = Exact gap – endplay

Exact Shim required = 3.31 – 0.1 = 3.21 is required shim value.

Now check Shim availability as per range,

So, we have a Shim range from 3.2, 3.4, 3.6, 3.8, 4.0, and 4.2. So, we have the availability of 3.2 Shim near to the exact shim required value. So, we pick 3.2 shims and measure the value of that shim to place that shim in this combination of differential assembly. The exact shim will be displayed on the System screen as per the above calculation and then the operator picks the required shim from the shim rack. Table 5 shows the shim values and repeatability values.
Table 5 - Repeatability Trials readings for Station “Shim” (Spacer Distance)

| TRAIL | OPERATOR | PRASAD |
|-------|----------|--------|
| 1     | 3.481    | 3.810  |
| 2     | 3.482    | 3.806  |
| 3     | 3.481    | 3.805  |
|       | Avg.     | 3.481  |
| Range | 0.002    | 0.002  |
| OPERATOR | AMIT |
| 1     | 3.482    | 3.804  |
| 2     | 3.481    | 3.810  |
| 3     | 3.483    | 3.807  |
|       | Avg.     | 3.482  |
| Range | 0.003    | 0.006  |
| OPERATOR | NISHANT |
| 1     | 3.483    | 3.810  |
| 2     | 3.481    | 3.807  |
| 3     | 3.481    | 3.807  |
|       | Avg.     | 3.481  |
| Range | 0.003    | 0.006  |

4. Results and Discussion

For the GRR result analysis requirement is % GRR is less than 10 %, then the gauging system is acceptable. As shown in below figure 3, component variance method calculation shows Part variation is 100 % and % GRR is 1.9 % as the AIAG method.

Figure 3 - GRR Result Calculation by Component Variance Method and AIAG Method for Gear Housing
Fig 4 shows the system is acceptable as per the GRR result calculation and remarks the measurement system is acceptable for gear housing. The same results we will observe for hypoid pinion and shim station in Fig 7 and Fig 9. Graph and charts show the variation of appraiser bias and consistency, average result, and range results in the measurement system for gear housing as shown in Fig 5. Similar results will be observed for hypoid pinion and shim station in Fig 8 and Fig 11.
As shown in below Fig 6, component variance method calculation shows Part variation is 99.9% and % GRR is 2.7% as AIAG method for hypoid pinion.

Figure 6 - GRR result calculation by Component Variance method and AIAG method for Hypoid Pinion

Figure 7(a) - Component Variance method for hypoid pinion; Figure 7(b) - AIAG method for hypoid pinion

Figure 8(a) - Hypoid Pinion Appraiser Bias; Figure 8(b) - Hypoid Pinion Appraiser consistency
As shown in below Fig 9, component variance method calculation shows Part variation is 100% and % GRR is 1.8% as AIAG method for Shim station.

Figure 9 - GRR result calculation by Component Variance method and AIAG method for shim station

Figure 10(a) - Component Variance method for shim station; Figure 10(b) - AIAG method for shim station
5. Conclusion

Figure 12 - Automated Differential Multi-Gauging System
In this result analysis study, Gauge repeatability and reproducibility i.e. GRR shows us different results at a different level with the different operators for the automated differential multi-gauging system. GRR has multiple calculations done by using a standard excel sheet to give exact and accurate results. In our multi-gaging system has three sub-assemblies that are acceptable and gives accurate measurement reading as per component and their tolerances. Repeatability of gear housing gauge only shows 0.003-micron variation in 10 parts which is required less than 10 microns. As the gear housing gauging system % GRR result shows 1.9 % which is very good as we required % GRR less than 10 %. Also, the gear housing gauging system appraiser bias and appraiser consistency graph are in between upper and lower limit which shows that if operator or component changes do not affect the measurement system. The average chart and range chart for gear housing gauge shows that gear housing gauge results are accurate for multiple and continuous numbers of trials on the measurement system.

Same results will be generated for hypoid pinion and Shim measurement gauging system as repeatability results shows that 0.004 microns for both systems. Also % GRR value is 2.7 % for the gear housing gauging system and the % GRR value is 1.8 % for the hypoid pinion gauging system it shows our manufactured gauging system is very reliable and accurate for results on multiple parts. Also, the appraiser bias and appraiser consistency graph show results between the upper and lower limit for hypoid pinion and shim measurement gauging system. Same for the average chart and range chart results are within limit and acceptable for hypoid pinion and shim distance measurement system. Overall GRR result analysis for the automated differential multi-gauging system will be acceptable and good as a reliable accurate system for measurement.

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