# Experimental demonstration of Measurement System Analysis

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**Abstract:** This work presents the application of Measurement System Analysis (MSA) and the advantages of the Six Sigma approach in the validation of a servo-hydraulic tester. The diagnosis of repeatability and reproducibility by using repeatability (R) and reproducibility (R) gage analysis (so called Gage R&R Type II tool) which shows the correct operation of the measuring system including uncertainty of staff and measuring instrumentation. The Gage R&R Type II tool is based on the analysis of variance, called ANOVA. The structural approach to the subject has also provided knowledge of the error of the measurement system.

**Keywords:** measurement system analysis, MSA, variance analysis ANOVA, validation, servo-hydraulic tester

## 1. Introduction

The measurement system is a key aspect for each research and development work. Usually, measurements from advanced computerized systems are treated as a perfect source of data with a zero measurement system. This thinking can lead to the acceptance of measurement data without any critical look at the measurement system, and making conclusions based on incorrect data. There are very well-known measurement system analysis methods, but classically many of them concentrate on the calibration process. The automotive industry has developed the best practice method to perform measurement system analysis and asses the measurement error.

The main concept of MSA divides measurement error components into the following groups [2]:

– Accuracy:
  - Calibration/Bias
  - Linearity
  - Stability
– Precision:
  - Repeatability
  - Reproducibility

In fact, the Accuracy part represents the calibration process because calibration/bias is meant to calibrate a given measurement system in line with the master system in order to give correct read out, and therefore to have zero read out at a zero point, which is called bias. The next component, linearity, is the calibration made over the whole range of interest. The last aspect within accuracy is stability of the measurement system over a period of time or other parameter related to time or environment, such us temperature or pressure.

The precision component of measurement error takes into account not only the complete measurement system, but also the measurement method, operators and measured specimen. Repeatability shows the difference between the two extreme measured values repeated for the same part per the same operator. Reproducibility is the difference between the average values of measurement carried out for the same part for different operators. There is a statistical tool called Gage R&R, used by Six Sigma methodology, to assess the precision of the measurement system [2]. It needs to be stressed that Gage R&R will show how precise the measurement can be, but this tool will not ensure calibration and other accuracy related aspects.

## 2. Measurement System Accuracy

The measurement system being evaluated is a servo-hydraulic system designed to measure force – velocity characteristics of components targeted to provide damping functions. The servo-hydraulic machine consists of a hydraulic actuator, and the system is equipped with sensors measuring displacement and force [1]. The performance of the machine executing a given displacement signal over time is kept by means of a controller with a closed control loop. This machine set -up ensures stable behavior and theoretically correct measurements performed on this measurement system. However, as described above, complete measurement system analysis also requires an operator, measurement method and the investigated parts to be included into the measurement evaluation experience. It has been agreed to perform the following steps in order to understand measurement systems [2]:

Calibration of sensors used in the system is treated as being correctly performed by an external laboratory. The reason to skip this step is that it requires special equipment, and additionally this activity has recently been performed. The mentioned calibrations cover two of the three accuracy aspects: (i) accuracy/bias, (ii) linearity – as the calibration was performed over a complete range of interest.

The next step is to check the stability of the machine with these experiments:

The stability of machine performance, which is the achieved velocity based on the requested signal. The requested signal is sin wave, velocity is measured as the maximum for two stroke directions, named rebound and compression. To assess

**Tab. 1.** Standard deviation values velocity for compression
**Tab. 1.** Odchylenie standardowe wartości prędkości kompresji

| Variable | Velocity1 | Velocity2 | Velocity3 | Velocity4 | Velocity5 |
|---|---|---|---|---|---|
| Standard Deviation | 0.000341 | 0.000352 | 0.000728 | 0.000705 | 0.000849 |

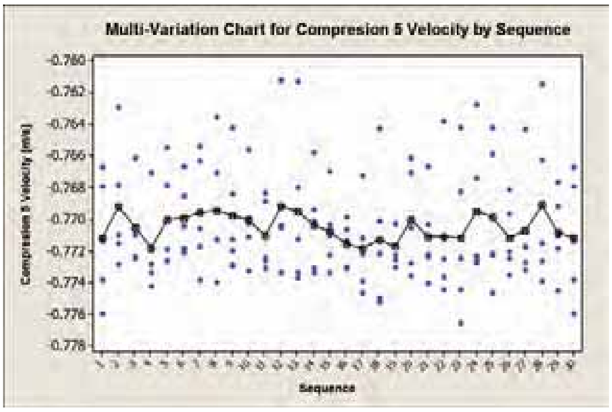


**Fig. 1.** Stability for velocity at compression stage
**Rys.1.** Stabilność prędkości kompresji

the stability of the machine, 30 measurements were performed on a consolidated sin wave signal with 5 velocities. As a result, we gained an evaluation of 5 achieved velocities for 2 directions of actuator movement. For the compression movement we have the following standard deviation values of the achieved velocities [m/s] (tab. 1).

The relative standard deviation, calculated as a standard deviation divided by the mean value of speed, is around 0.1 %, which provides a very good and acceptable result. The graph in fig. 1 presents 30 repetitions of the same signal for the highest velocity. The black points show the average values for each repetition based on individual values from 5 loops for each velocity.

**Tab. 2.** Standard deviation values velocity for rebound
**Tab. 2.** Odchylenie standardowe wartości prędkości rozprężania

| Variable | Velocity1 | Velocity2 | Velocity3 | Velocity4 | Velocity5 |
|---|---|---|---|---|---|
| Standard Deviation | 0.000493 | 0.000250 | 0.000679 | 0.000768 | 0.000773 |

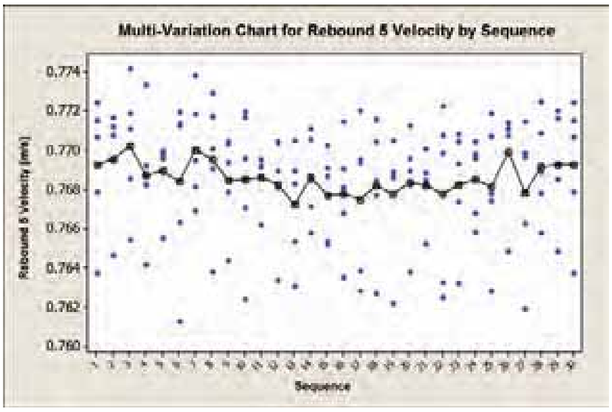


**Fig. 2.** Stability for velocity at rebound stage
**Rys. 2.** Stabilność prędkości rozprężania

The same approach for analysis was used during the rebound (extension) stage, where the standard deviations for all velocities are the following (tab. 2).

The graphical representation of the maximum velocity for the rebound stage is shown in fig. 2.

Stability for the master piece, which is the mono-tube based damper known as stable damping components. The test was performed with the mentioned sin wave signal with 5 increasing velocities. In this case the measured output is not the velocity but the force measured at maximum speed. The graph in fig. 3 shows 30 repetitions of measurement for maximum speed during the compression stage.

The graph clearly shows an issue with the stability of the damping forces of the measured unit. There are multiple potential results of damper instability, however this is not the aim of this paper. The instability is presented in tab. 3 as standard deviation per each velocity.

**Tab. 3.** Standard deviation values force for compression
**Tab. 3.** Odchylenie standardowe wartości sił kompresji

| Variable | Compression1 | Compression2 | Compression3 | Compresion4 |
|---|---|---|---|---|
| Standard Deviation | 9.31 | 9.19 | 13.75 | 18.0 |

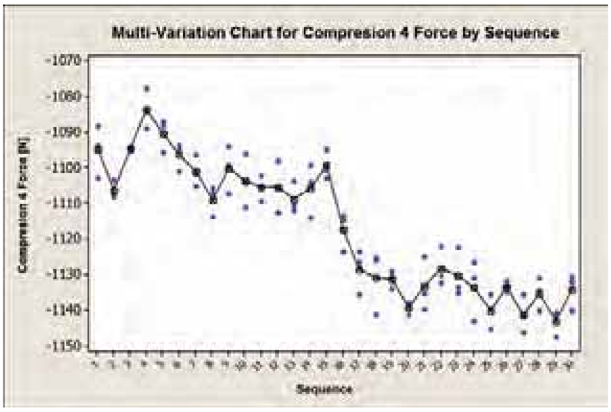


**Fig. 3.** Force stability for compression
**Rys. 3.** Stabilność siły kompresji

The standard deviation is very often used to present the confidence interval around mean values. In this case, the Confidence Interval (CI 95 %) for compression force at max speed would be ±36 N. As the variation of the force is not the same over 30 repetitions it can be allowed to assess the common variation of measured force over 1 repetition by means of – the Pooled Standard Deviation (PSD) calculated for each velocity are presented in tab. 4.

**Tab. 4.** Pooled standard deviation values velocity for compression
**Tab. 4.** Łączne odchylenie standardowe wartości prędkości kompresji

| Variable | Compression1 | Compression2 | Compression3 | Compresion4 |
|---|---|---|---|---|
| PSD | 2.15 | 2.66 | 3.85 | 5.51 |

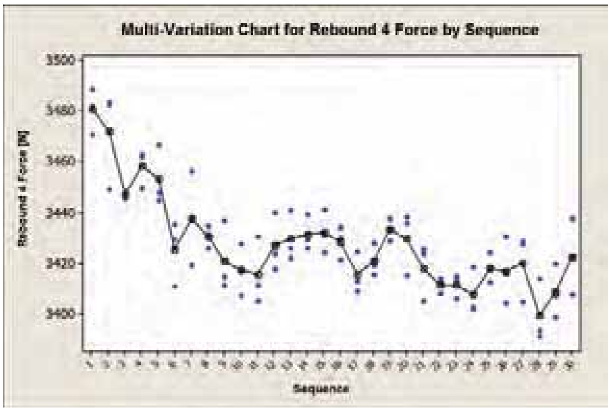


**Fig. 4.** Force stability for rebound at maximum speed

**Rys. 4.** Stabilność siły rozprężania przy maksymalnej prędkości

Based on the pooled standard deviation for maximum speed we can say that CI 95 % is equal to ±11 N, which means that 95 % of single measurement is within the range of ±11 N. This value is much better, however it is valid only for 1 single measurement case.

The situation for rebound force at maximum speed is presented in fig. 4.

The standard deviations and pooled standard deviations are the following in tab. 5.

**Tab. 5.** Standard and pooled standard deviation values force for rebound

**Tab. 5.** Odchylenie standardowe i łączne odchylenie standardowe wartości sił rozprężania

| Variable | R1 | R2 | R3 | R4 |
|---|---|---|---|---|
| Standard Deviation | 55.3 | 32.7 | 15.6 | 18.4 |
| Pooled Standard Deviation | 14.1 | 8.15 | 10.4 | 10.7 |

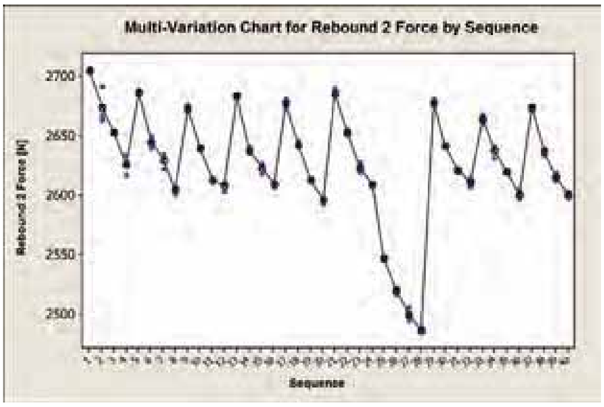


**Fig. 5.** Damping forces measured over a period of time

**Rys. 5.** Zmierzone siły tłumienia w okresie czasu

Here the situation for the rebound stage is very similar to compression. Even though we can observe better stabilization of damper performance over time, the pooled standard deviations are similar over the velocities.

The stability over time exercise was meant to show the influence of different factors related to the time domain. There are 30 tests performed over a certain period of time with usually 4 repetitions in a row. The graph in fig. 5 shows damping forces for the rebound stage.

The pattern of decreasing forces in groups of 4 (in one case, 8) repetitions is easily explained because measurements were performed in rows of 4 tests, increasing the temperature, which leads to a damping force decrease due to lower viscosity of the oil. This experiment clearly showed the issue with stability of the damper and the strong influence of temperature as a noise factor. This means that the measurement system analysis performed based on a damper must be carried out with the elimination of all noise factors influencing the final measurement.

## 3. Measurement System Precision

In order to understand the measurement error components called repeatability and reproducibility, we need to use the Gage R&R statistical tool, which is based on the analysis of variance – ANOVA [4]. The standard approach for this experiment is to measure a minimum of 10 parts measured by 2 operators, each operator has to measure at least 2 times. In the presented case, there are 2 operators testing the same specimen 30 times over the complete test sequence, consisting of 4 test velocities, creating full force over the velocity characteristic for rebound and compression movement [2]. Nested Gage R&R was used to analyze the obtained results, and the statistical and graphical

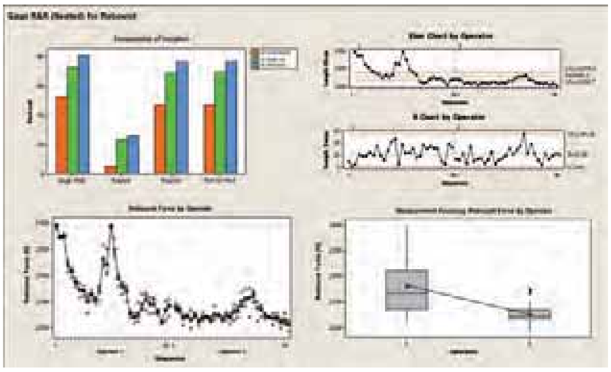

**Fig. 6.** Gage R&R results for rebound, first velocity, tolerance band is 300 N

**Rys. 6.** Wyniki Gage R&R rozprężania, pierwsza prędkość, tolerancja 300 N

**Tab. 6.** Contribution percent rate

**Tab. 6.** Udział procentowy

| Source | Variation Compression | Contribution [%] |
|---|---|---|
| Total Gage R&R | 1629.46 | 52.56 |
| Repeatability | 167.26 | 5.40 |
| Reproducibility | 1462.20 | 47.16 |
| Part-To-Part | 1470.81 | 47.44 |
| Total Variation | 3100.27 | 100.00 |

results for the first velocity for the rebound stage are presented in fig. 6. If the measurement system was perfect, we should see 30 identical values obtained for each of the operators, additionally, with no difference between operators. This would lead to a standard deviation equal to zero, when in our case we see that standard deviation coming from the measurement system is above 40 [N]. The six standard deviations show that almost 100 % of the measurement system is equal to 52.56 % of the tolerance band (tab. 6). This result is unacceptable as a marginally acceptable measurement system should not give a value above 30 %, according to the AIAG MSA manual. The huge difference arises from the different ways used for measurement between Operator 1 and Operator 2 (lower – right fig. 6).

Standard proces tolerance of study variation is classificate at value 300 N (tab. 7).

**Tab. 7.** Percent rate for tolerance elements of Gage R&R

**Tab. 7.** Wskaźnik procentowy tolerancji elementów Gage R&R

| Source | Standard Deviation | Study Variation | Study Variation [%] | Tolerance [%] |
|---|---|---|---|---|
| Total Gage R&R | 40.3666 | 242.200 | 72.50 | 80.73 |
| Repeatability | 12.9330 | 77.598 | 23.23 | 25.87 |
| Reproducibility | 38.2387 | 229.432 | 68.68 | 76.48 |
| Part-To-Part | 38.3511 | 230.107 | 68.88 | 76.70 |
| Total Variation | 55.6801 | 334.080 | 100.00 | 111.36 |

As Operator 1 was the root cause of the weak measurement system analysis results, it was decided to perform proper re-training of this operator. Additionally, analysis was repeated for the data obtained only by Operator 2. The improvement is visible on the following table – where the percentage of tolerance decreased to a level of 23.88 % (tab. 8).

**Tab. 8.** Values of elements included in the Gage R&R for Operator 2

**Tab. 8.** Wartości elementów wchodzących w skład Gage R&R dla Operatora 2

| Source | Standard Deviation | Study Variation | Study Variation [%] | Tolerance [%] |
|---|---|---|---|---|
| Total Gage R&R | 11.9408 | 71.645 | 68.92 | 23.88 |
| Repeatability | 11.9408 | 71.645 | 68.92 | 23.88 |
| Reproducibility | 0.0000 | 0.000 | 0.00 | 0.00 |
| Part-To-Part | 12.5526 | 75.316 | 72.45 | 25.11 |
| Total Variation | 17.3249 | 103.949 | 100.00 | 34.65 |

Gage R&R results for rebound, first velocity, tolerance band is 300 N, based only on the second operator.

The difference between the operators is even bigger. Additionally, Tolerance achieved values of 243.86 % where the maximum allowed value is 30 % (tab. 9). This result confirms the problem with Operator 1.

**Tab. 9.** Values of elements included in the Gage R&R for Operator 1

**Tab. 9.** Wartości elementów wchodzących w skład Gage R&R dla Operatora 1

| Source | Standard Deviation | Study Variation | Study Variation [%] | Tolerance [%] |
|---|---|---|---|---|
| Total Gage R&R | 81.288 | 487.728 | 75.13 | 243.86 |
| Repeatability | 6.129 | 36.774 | 5.66 | 18.39 |
| Reproducibility | 81.057 | 486.340 | 74.91 | 243.17 |
| Part-To-Part | 71.412 | 428.474 | 66.00 | 214.24 |
| Total Variation | 108.201 | 649.206 | 100.00 | 324.60 |

## 4. Conclusions

The classic approach for measurement system acceptance would finish with the statistical calibration of sensors used by the testing rig. Additionally, the stability of achieved velocities during test sequences would further check the acceptance for the machine. It needs to be stressed that the measurement system, besides measuring equipment, also includes operators, the test method and measured parts and their characteristic behavior. The presented statistical approach utilizes the basic concepts of automotive MSA and investigates the instability of measured units over factors in the time domain, and measurement error caused by unequally trained operators.


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## Dekompozycja oraz analiza składników błędu systemu pomiarowego z zastosowaniem metodologii Six Sigma

**Streszczenie:** W artykule zaprezentowano zastosowanie analizy systemu pomiarowego (MSA) oraz zalety Six Sigma w podejściu walidacji testera serwohydraulicznego. Ustalenie stopnia powtarzalności i odtwarzalności przez użycie analizy powtarzalności (repeatability – R) i odtwarzalności (reproducibility – R) zwanej Gage R&R Type II, która pokazuje prawidłową pracę systemu pomiarowego, w tym niepewność pracowników oraz narzędzi pomiarowych. Narzędzie Gage R&R Type II bazuje na analizie wariancji zwanej ANOVA. Podstawowym podejściem do wiedzy na temat badanego obiektu jest poznanie błędu samego systemu pomiarowego.

**Słowa kluczowe:** analiza systemu pomiarowego, MSA, analiza ANOVA, walidacja, tester serwohydrauliczny

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