Statistical methods for the evaluation of the quality of measurement data on the test benches

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1 Abstract

Test benches for rocket engines are exposed to high thermal and mechanical stress. This applies in particular to the measurement equipment of the test benches. Therefore it is necessary to be able to give a clear statement about the quality of the measured data.

What is the situation on the test benches?

- The best measurement method (TC or Pt100 or Pt1000) was selected.
- The best mathematical model for the sensor was selected.
- The installation of the measurement equipment was performed correctly.
- The transducer was calibrated by the best available procedure.
- All used materials (flange assembly, seals, and external surfaces of the transducer) are fit for purpose.
- The routing of the cabling is such that all mechanical and electrical influences have been minimized.
- All cabling are protected from external high frequency sources.
- The thermal impact on the electronic equipment is minimized.
- The grounding of all components was performed by certificated procedures and standards.
- The operators are well skilled, competent, working with certificated procedures and they are highly motivated.

But for all that, it's impossible to measure the true value.

To appraise the quality of measurements of a test bench, different statistical methods can be used. Two statistical methods are described in this paper, the classical Gaussian error propagation and the general uncertainty method. We will show how these statistical methods can be used to give a reliable indication of the quality of the measurements. We will also show the limits as well as the advantages and drawbacks of the two methods. The statistical results of the two methods indicate measurement problems at an early state and furthermore it is possible with these methods to narrow down the sources of an error. Hence these methods help to identify problems in measurement chains swiftly enabling repairs to be carried out before data loss occurs. Moreover these results can be taken into consideration and lead to criteria for measurement quality standards.

Our results are illustrated with examples of the test bench P5 in Lampoldshausen, Germany.

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2 Introduction

In first and foremost the main object of this presentation is to show two statistical methods for determining the quality of measurements. In addition to this the idea is to initiate further discussion about the quality of measurements making use of modern technology to share experience and ideas.

The two methods, presented here will show a new approach to the problematic of measurement quality. This presentation can be seen as trigger to use advanced statistical functions within this subject.

With mathematics we can achieve objective results. The interpretation of these results depends on experience and predefined definitions (e.g. error limits, spikes, requirements). Eventually these methods will help to locate the sources of error and to see trends. To react to problems in time is essential for the work on test benches.

3 Specific characteristics

- Arithmetical mean
- Variance, even when the expected values (of two independent series of measurement) are the same, the deviance may differ
- Dispersion
- Spikes – thats the group of measured values those violate the 3σ limit of the normal distribution function
- Median – giving an alternative to the arithmetical mean, where the spikes are sorted to the beginning or the end of the list
- Modus
- Normal distribution
- Skewness of the normal distribution
- Kurtosis of the normal distribution

The definition of spikes has to be done with respect to the process we are looking at. It is linked to the arithmetical mean. Spikes are the result of spontaneous signal jumps. Mostly it's the bad connection (temporary connection of the signal wire with the voltage supply or zero wire) within the miniature plugs. The number of passes of a specified limit is counted. The limit is dedicated to the 3σ value of the data.

To capture a 50Hz noise in a signal we measure the signal with 20 points per second. If 50% of it is over the limit, that is 10 points violating it, this indicates a 50 Hz noise signal.

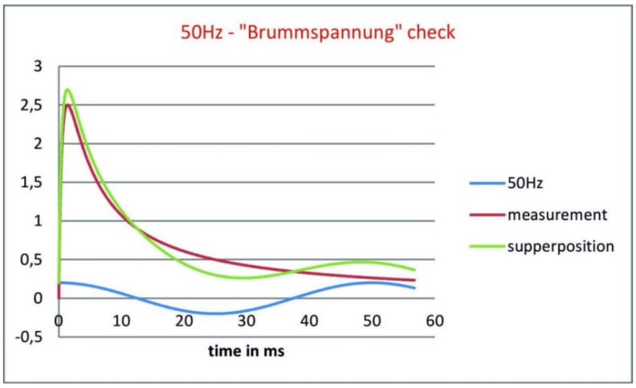

Figure 1: the 50Hz check at a dynamic signal fails; a quasi-static phase is necessary

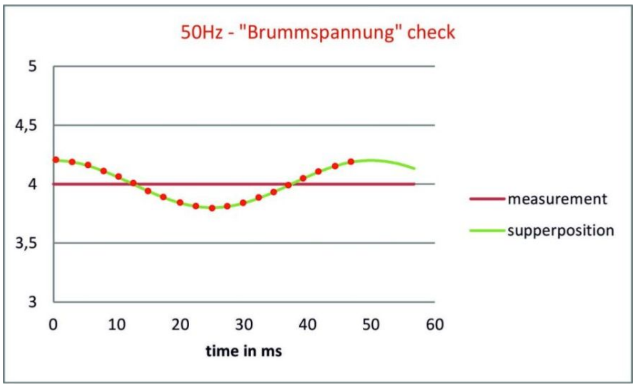

Figure 2: the 50Hz check at a quasi-static signal by 20 samples within 1 second

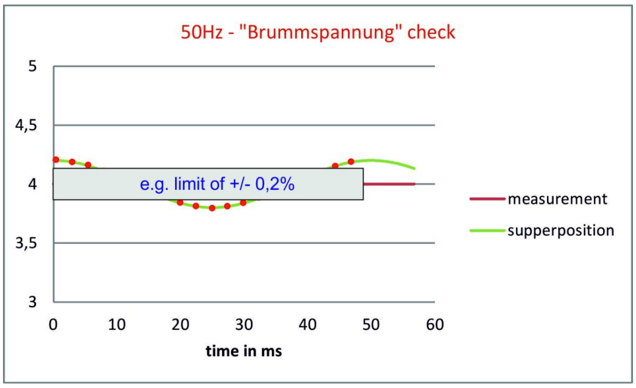

Figure 3: the 50Hz check - 10 points outside the limit

For the Modus the use in measurement and computer technology is limited. The Modus gives the measurement value, which appeared at most. When digitizing the signals with a 16 bit analogue digital converter (ADC) we will have a one bit quantization error. It is not possible for measurements to be digitalized more accurately than this. Hence when we measure signals we always measure it inaccurately.

After measuring the signals the following results are possible for the mean:

- The Modus does not show a characteristic value ⇒ that means all the measurement data was acquired and processed in a sensible electrical and physical range.
- The Modus shows a high characteristic physical value (typical the maximum of the measurement range) ⇒ the measurements show signal saturation. Therefore either the measurement range isn't correctly defined, e.g. with the maximum to small, or the signal was over amplified. The reason for this could be an incorrectly calculated gain factor or a defect amplifier. Hence the amplifier has to be checked and if it is working correctly, the calibration data sheet has to be checked and analyzed.
- The Modus shows a very small characteristic physical value ⇒ the measurement signal is too small so it is overlain by noise. The reason is either the measurement range is too wide or the connection to the sensor is lost. Again we have to check the amplifier. If no problem can be found, the measurement range has to be looked at.
- A short circuit has occurred if the amplifier shows a constant zero value (whereas zero Volt does not correspond to zero bar or zero Kelvin) and in which case the cable, the amplifier and the connectors have to be checked.

4 Frame condition for an analysis

For analyzing measurements a clearly defined time range for all tests is necessary. During this time the following conditions have to be used. The time when the chill down criteria for the engine is reached, that is from $T_{count-down} = -2min15s$ to $T_{count-down} = 0s$. This defined time frame is applicable for the test bench and the engine.

- all preparation procedures for the hot run are finished
- the test bench is ready for hot run, the run tank pressures are constant, the temperatures of the supply lines are constant, no venting activation on tanks and lines
- the engine is ready for hot run
- the requested temperature regarding the bench-engine interface is defined
- constant ambient temperature within the test cell
- constant humidity in test cell and on the test bench
- sampling rate during this time is 10 samples/s, which gives 1350 points for evaluation. If we reduce the time to 60s then we have 600 samples for statistical evaluation. These samples form the statistical population.

5 Definition of Anomalies

5.1 Physical Anomalies

Physical anomalies can be caused by the process, the product under test and/or the test bench. These kind of anomalies are not previously "defined" or expected. Before a test campaign starts, the customer needs all the information about the operational state of the bench. After each maintenance the results must be evaluated by transparent procedures. Between the tests the operating company has to analyze after each test the most important measurement channels and has to fix it in a report. The goal of this method is, if such anomalies occur, to be able to find and identify the cause of them as soon as possible.

The reason for these anomalies could be:

- first sign of fatigue of material
- possible leakage - especially on the interfaces between sensor and the test bench hardware
- tightness problems in pipes - especially untightness on valves, seals or flanges
- unexpected mechanical stress by not exact fixed mechanical elements (unexpected vibrations)
- thermal stress dependent on the operation point (high temperature gradient on one mechanical element)
- parasitic oscillations in tanks and in pressure compensations tanks

- mechanical oscillations in pipes for cryogenic media like LH2 and LOX
- valve velocity problems, if the valve opens or closes to slow

5.2 Electrical anomalies

The reason for these kind of anomalies could be:

- for sensors mounted on surfaces - connecting problems (DMS, RTD, TC, vibration)
- for sensors mounted in closed systems – sealing problems, heat transfer problem
- for sensors mounted in pipes and the sensor body modifys the media stream characteristic
- contact problems on connectors caused by vibrations (spikes)
- insulation problems caused by dampness
- short circuits caused by miniature connectors (only occur with vibrations)
- signal saturation by a wrong amplifier setting
- signal shift by an offset voltage
- superposition of noise and measurement signal
- pre-amplifier with wrong offset
- not exact sensor voltage or current supply - the exact calibration was done but some days before test

6 Data test due to the "Gauss distribution behavior"

The measurement channels THQ1, THQ2, THQ3 and THQ4 were analyzed statistically during the ARTA M253B campaign on the test bench P5. The positions of the four measurement points is on the run tank pipe in the sector of the three flow meters. We can point out that for all tests we have got the same frame conditions. For the statistically evaluation we treated 3050 samples per channel with MS Excel.

On the figure nb. 4 the logical positions of valves, measurement points and flow meters are pictured. It's the synoptic on the operators screens.

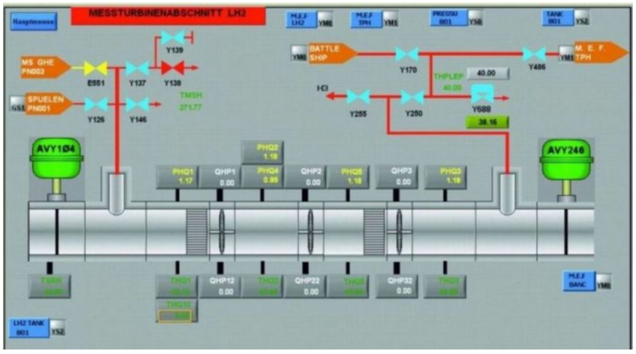

Figure 4: position of measurement points in the section of the flow meter for LH2

Results of a first data evaluation:

	M253B-01	M253B-02	M253B-03	M253B-04
Average	20,8493	21,0012	20,9802	21,0486
Modus	20,8600	20,9992	20,9881	21,0474
Median	20,8512	21,0010	20,9828	21,0491
Variance	0,041592466	0,035345851	0,032987396	0,034861716
Variance^2	0,001729933	0,001249329	0,001088168	0,001215339
Kurtosis	-0,165531822	0,082352291	0,47274839	0,018790116
Skewness	-0,044568849	-0,082269407	-0,397346034	-0,066114404

Figure 5: the first results under attention of a Gauss distribution aspect

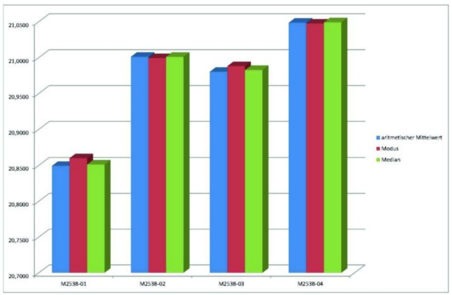

Figure 6: average, modus and median

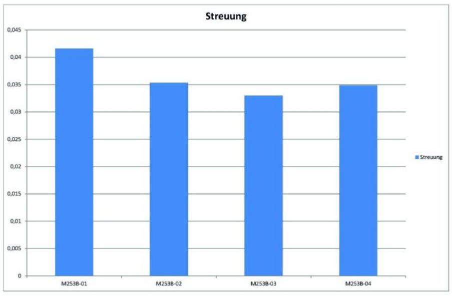

Figure 7: variances in compare

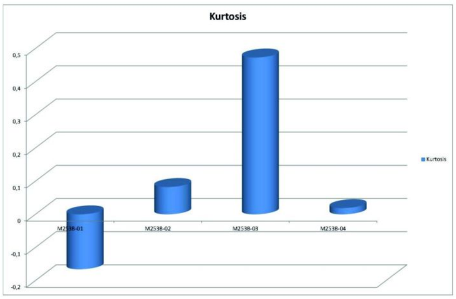

Figure 8: Kurtosis statement

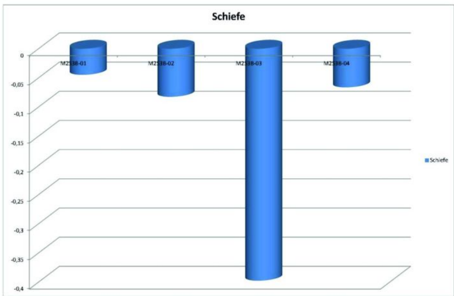

Figure 9: skewness statement

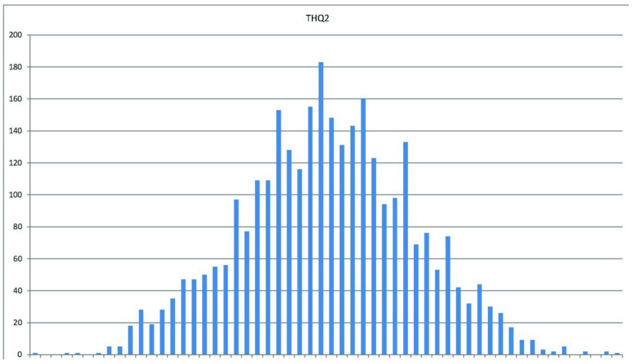

Figure 10: evaluation of the THQ2 histogram

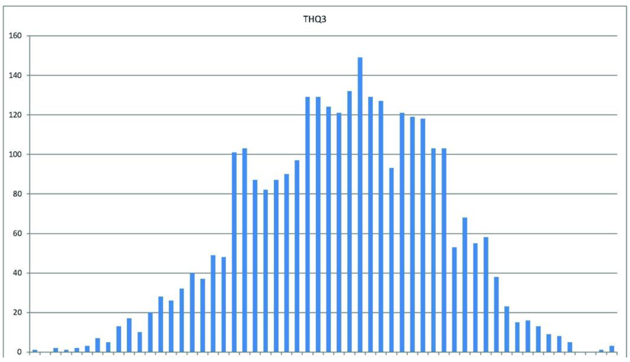

Figure 11: evaluation of the THQ3 histogram

7 Statistical methods

7.1 Classical method

7.1.1 The theory, the variables and the true value

- X - the true value of the parameter with the measured value x
- ε - random error value
- ε and X are unknown
- ε we can only provide an estimated value of Δx but we can point out $|\varepsilon| \leq |\Delta x|$
- Δx is a value in an expected range of:

  $x - |\Delta x| < X < x + |\Delta x|$.

Each measured value has got an error based on the measurement itself. We have to analyze how single measurement errors are modifying the accuracy of the calculated value of our parameter Y. It means: We have to find the answer what is the magnitude for Δy as a rate for the expected discrepancy from the true value of Y.

$Y = y + \Delta y = f(x_1 + \Delta x_1; ...; x_k + \Delta x_k)$

$\Delta y \Rightarrow dy = \frac{\partial y}{\partial x_1}\Delta x_1 + ... + \frac{\partial y}{\partial x_k}\Delta x_k$

absolute maximal measurement error:

$\Delta y_{max} = \pm\left(|\frac{\partial y}{\partial x_1}\Delta x_1| + ... + (|\frac{\partial y}{\partial x_k}\Delta x_k|\right)$

relative maximal measurement error:

$\Delta y_{rel} = \frac{\Delta y_{max}}{y}$

Analysis of a simple example:

We have to calculate a resistor R based on the two measurements of voltage U and current I. We are looking for the maximal measurement of the resistor R.

$U = 10,3mV \pm 0,2mV$

$I = 15mA \pm 0,3mA$

$R = \frac{U}{I} = f(U, I)$

$\Delta R_{max} = \pm\left(|\frac{\partial R}{\partial U}\Delta U| + |\frac{\partial R}{\partial I}\Delta I|\right)$

$\Delta R_{max} = \pm\left(|\frac{\Delta U}{I}| + |\frac{U}{I^2}\Delta I|\right)$

For calculation of the maximal measurement error we have to divide the expression by the value of R and we take for the parameter $U = I \cdot R$:

$\Delta R_{rel} = \frac{\Delta R_{max}}{R} = \pm\left(|\frac{\Delta U}{I \cdot R}| + |\frac{U}{I^2 \cdot R}\Delta I|\right)$

$\Delta R_{rel} = \pm \left(|\frac{\Delta U}{U}| + |\frac{\Delta I}{I}| \right)$

$\Delta R_{rel} = \pm \left[\frac{0,2}{10,3} + \frac{0,3}{15} \right] \approx \pm 0,0394 => 3,94\%$

result: The final maximal error is the addition of both single maximal errors.

calculation rules

- **Addition:** $y = x_1 + x_2 \Rightarrow F_y = F_1 + F_2$
- **Subtraction:** $y = x_1 - x_2 \Rightarrow F_y = F_1 - F_2$
- **Multiplication:** $y = x_1 \cdot x_2 \Rightarrow F_y = F_1 + F_2$
- **Division:** $y = x_1 : x_2 \Rightarrow F_y = F_1 - F_2$

7.1.2 Analysis of a measurement chain

Abstraction:

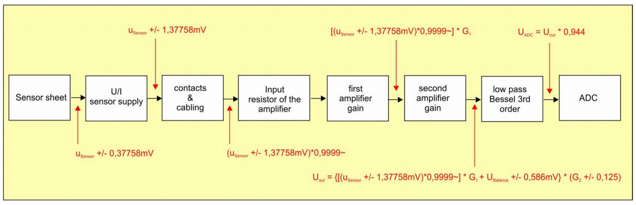

Figure 12: this graphic will be presented in a readable format during the oral presentation

For the current presentation the amplifier type "Laben" was reviewed because the documentation is available in detail. The destination of the P5-MCC system (and the amplifier) is 500m from the test bench P5. It was very interesting to find out how the locally distance impacts the accuracy of the signal.

source	error voltage	factor	digit	remark
sensor	0,377580			from sensor sheet
sensor supply	1,377580			fiction
contacts and cabling		0,999999		calculated
gain 1		1,000000		
gain 2 - 100	0,125000	100,125000		worste case
offset	0,000000			internal alignment
balance	0,586000			worste case
low pass filter (dyn)		0,944000		dynamic part
ADC			2	digital noise
in summa:	0,7477	K		in the range of 20 - 40K

Figure 13: results of all possible components

The results shows an error of more than 0,7K and it's not acceptable for the measurement. The biggest influences are the bad alignment of the sensor supply and the balance setting of the amplifier. The calibration software of the P5 MCC system compensates the possible erroneous settings for the offset and balance. The alignment of the sensor supply voltage is controlled by the a.m. calibration software and is under a daily observation.

source	error voltage	factor	digit	remark
sensor	0,377580			from sensor sheet
sensor supply	0,000000			exact alignment
contacts and cabling		1,000000		calculated
gain 1		1,000000		
gain 2 - 100	0,125000	100,125000		worste case
offset	0,000000			internal alignment
balance	0,000000			internal alignment
low pass filter (dyn)		0,944000		dynamic part
ADC			2	digital noise
in summa:	0,3766	K		in the range of 20 - 40K

Figure 14: result after exact alignment

The correction of the conditioner was done. The sensor supply voltage was set by the technician exactly. At least the final error depends on the sensor data sheet. The dumping of the higher sensor signal in the worst case comes from the low pass filter with the Bessel characteristic of 3rd order.

7.2 The general method based on GUM

This method works not with the single errors but rather with the uncertainness "u" of each arithmetic average. The equation between the uncertainness and the dispersion "s" for a random sample is:

$$u = \frac{1}{\sqrt{N}} \cdot s = \frac{1}{\sqrt{N}} \cdot \sqrt{\frac{1}{N-1} \Sigma_{i=1}^{n} (x_i - x_{average})^2}$$

The second crucial point due to the difference to the classical "Gauss method" is the attention of the specific weight of the kind of the distribution gravity. The parameter "a" stands for the "half of the distribution range".

- the process is based of the nominal distribution $\Rightarrow$ factor for the standard uncertainty u: u = 1
- the process is based of the rectangle distribution $\Rightarrow$ factor for the standard uncertainty u: $u = \frac{1}{\sqrt{3}} \cdot \Delta a$
- the process is based of the triangle distribution $\Rightarrow$ factor for the standard uncertainty u: $u = \frac{1}{\sqrt{6}} \cdot \Delta a$
- the process is based of the "U" distribution $\Rightarrow$ factor for the standard uncertainty u: $u = \frac{1}{\sqrt{2}} \cdot \Delta a$

7.2.1 The concept of GUM

- A measurement delivers never the true value.

- The result of a measurement delivers the best estimated value.

- The uncertainty is a characteristic parameter and is fix linked to the measurement value. The uncertainty characterizes the range were the true value could be with a probability.

Causation and impact of the measure

- Measurement value - in fact it's the converted electrical value from the non-electrical physical parameter; the calibration sheet from the sensor must be available

- Impact of the ambient (can be minimized by a short observation window)

- Impact of the passive electric elements

- Impact of the electronic hardware (it includes the AD conversion)

- Signal resolution (based on the test request)

- Used references (sensor current, TC reference unit, scales)

1st step - the graph

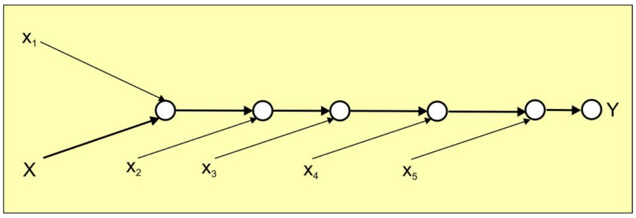

Figure 15: the graph

2nd step - the function:

Tripple „never" . . . .

- Measurement processes can **„never"** be controlled completely

- The influences of a measurement process are **„never"** known 100%

- A measured parameter can **„never"** be characterized by only one value

X – Magnitude of the measured value; includes the "sensor sheet deviation" (selected mathematical model, calculated coefficients)

x_1 - ambient influence

x_2 - cabling and contacts

x_3 - electronic hardware (conditioner and ADC)

x_4 - signal resolution, data evaluation

x_5 - used references

Y - the result under attention of the measured value and the influences of all components

$Y = f(X)$

$X = f(x_1, x_2, x_3, x_4, x_5)$

3rd step - the calculation:

source	uncertainty	remark	factor	distrubution function
sensor	0,1900	see sensor sheet	1,00	normal
sensor supply	0,0100	manual alignment	0,58	rectangle
contacts and cabling	0,0000	no infuence	0,00	
gain 1	0,0000	no infuence	0,00	
gain 2 - 100	0,0000	internal software alignment	0,00	
offset	0,0000	internal software alignment	0,00	
balance	0,0000	internal software alignment	0,00	internal alignment
low pass filter (dyn)	0,0000	no ripple in static range	0,00	
ADC - 2 Bit	0,0977		0,58	rectangle
in summa:	0,1983	K		in the range 20 - 40K

Figure 16: the calculation under attention of the different kinds of distributions

7.2.2 The two specific GUM–methods

Type A: statistical analysis based on repetition of the process

Type B: no-statistical estimation base on well documented basic information (calibration results), experiences or results from already performed tests.

8 Conclusion

Ten points method:

1. Daily logging of all points of measurement (except vibrations and dynamic pressures) before putting the test bench in operation (early bird function)

    - Check the measurement protocol for exceptional values (resulting from locked-in pressures, disconnected sensors, interrupted cabling)

    - Check the measurements with regard to 50Hz noise

2. Control of the reference element for temperature measurements with thermocouples
3. Documentation of the protocols
4. Checking for measurement drifts in a weekly interval
5. Definition of minimum quality levels for individual measurement types (e.g. Thermocouples type E, K, S, Pt-sensors)
6. Regular data-analysis of measurements important for a test, under similar conditions
7. Analysis of a given population (between 100 and 1000 measurements)
    - Test for normal distribution
    - Check for difference between median, mean and mode
8. Documentation of all results
9. Check results for trends
10. Debugging of error possibilities

9 Recomendations

1. Creation of a standard document layout for measurement reports
    - definition of columns [name, type, value average, value RMS, minimum, maximum, abs. deviation, validity check]
    - definition of abbreviations [SG, RTD, QWB, RT]
    - definition of the document type
2. Creation of a document of quality standards
    - definition of criteria
    - definition of the criteria limits
    - explanation of the criteria limits
    - recommendation how the customer can achieve the criteria
    - standard calculation of the failure over all components - guideline and standard procedures
3. Organization of working platforms between the customers and suppliers
    - presentation of results
    - presentation and exchange of experiences
    - presentation of examples and solutions of interests

10 Acronyms

ADC Analogue Digital Converter

ARTA Ariane research and technology accompaniment

DLR Deutsches Zentrum für Luft- und Raumfahrt, location of the test bench P5 for the ARIANE 5 project

DMS Dehnungsmessstreifen, strain gauge element

GUM Guide to the Expression of Uncertainty in Measurement

LH2 Liquid Hydrogen

Laben amplifier/conditioner type in use on the test bench P5 from the Italian company "Laben"

MCC System for measurement, command and control

Pt Pt-sensors are Platin sensors like Pt100, Pt500 and Pt1000

P5 test bench for Vulcain2 tests at the DLR in Lampoldshausen

RMS root mean square value

RT rotation per time

RTD resistor temperature device - sensor will be supplied by a constant current

SG strain gauge bridge measurement device - sensor will be supplied by a constant voltage

TC thermo couple element

TC-E thermocouple element Nickel-Chrom (NiCr) and Kupfer-Nickel (CuNi)

TC-K thermocouple element Nickel-Chrom (NiCr) and Nickel-Aluminium (NiAl)

TC-S thermocouple element Platin-10% Rhodium (Pt10Rh) and Platin (Pt)

THQ temperature hydrogen on the quantity flow sector (volume flow)

VDI Verein der Deutschen Ingenieure

11 Bibliography

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