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Measurement uncertainty analysis for bulk current injection calibration process

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In this article, the setup and calibration process of the BCI test according to ISO 11452-4 and a general evaluation and calculation of the total measurement uncertainty is presented. This sample measurement uncertainty calculations can be used as the measurement uncertainty calculations, which are absent in ISO 11452 standards. After the introduction into the measurement uncertainty calculation, the calibration process is critically examined on many sources of measurement uncertainties and mismatches inside the setup, which have significant impact on the calibration and also on the testing process. Additionally, new sources of uncertainty are evaluated in this paper, which can have a high impact on the calibration and testing process. This sample measurement uncertainty calculations can be used as the measurement uncertainty calculations, which are absent in ISO 11452 standards. With all detected sources of uncertainties, the measurement uncertainty calculation models can be used for other international standards with similar calibration and test processes, which are used for testing devices for different fields of application, and by calibration and testing laboratories, to improve the reproducibility of the calibration and testing process.

Keywords: Bulk Current Injection (BCI) test, calibration process, measurement uncertainty, calibration jig

1 Introduction

Before a new automotive device is mounted into a vehicle, a series of tests for its electromagnetic compatibility (EMC) must be performed to ensure that the device does not cause any damage or disturbances in an existing automotive electronic system. One of the prescribed tests is the conducted susceptibility test according to international standard ISO 11452-4 [1], which is also called the Bulk Current Injection (BCI) test. During this test, disturbance signals are directly induced into the wiring harness via a current injection probe and then it is monitored, if these disturbance signals are causing any adverse effects to the device under test (DUT).

Before the test can be performed, the test setup along with the current injection probe must be calibrated. The current injection probe is mounted into a 100 Ω calibration jig during the calibration process and the forward power is applied into the probe to reach the required injected current level [1].

Although the calibration process is fully automated, there are different aspects, which can have significant influence on the calibration itself [2, 3]. One of the influences is the measurement uncertainty of the whole test setup [2]. Each laboratory, which performs tests on electromagnetic compatibility of DUTs, should have a measurement uncertainty analysis for each accredited test they are performing in their laboratory. This is a requirement of ISO 17025 [4], to which all test and calibration laboratories should be accredited.

To improve the reproducibility of measurement uncertainty calculations, a sample calculation of the total measurement uncertainty of calibration and testing processes is given in the annexes of some international standards such as IEC, EN, ETSI etc. But in the standards for automotive EMC testing ISO 11452, these sample measurement uncertainty calculations are missing. This can lead to different approaches when calculating the total measurement uncertainty of the test. As a result, the test reproducibility may be worse and comparison tests between two EMC laboratories may vary, which can cause problems during the accreditation process.

Since the calibration process can have a significant impact on the test process and on the total measurement uncertainty of the test, the total measurement uncertainty calculation of the calibration process was analyzed and a detailed sample calculation will be given in this article.

2 Calibration setup and process

The calibration of the test setup is usually performed inside an EMC chamber, where the current probe is located inside the calibration jig. For the calibration

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process, the following equipment is used:

- current injection probe
- calibration jig
- signal generator
- power amplifier
- power meter
- voltage/current measurement equipment (e.g., test receiver)
- control system
- 50 Ω termination impedance

The calibration jig is a special calibration fixture, where the current injection probe is mounted in. On one side, the calibration jig is terminated with a 50 Ω impedance (see Fig. 1), and on the other side, the jig is connected to a 50 Ω measurement equipment used to measure the injected current.

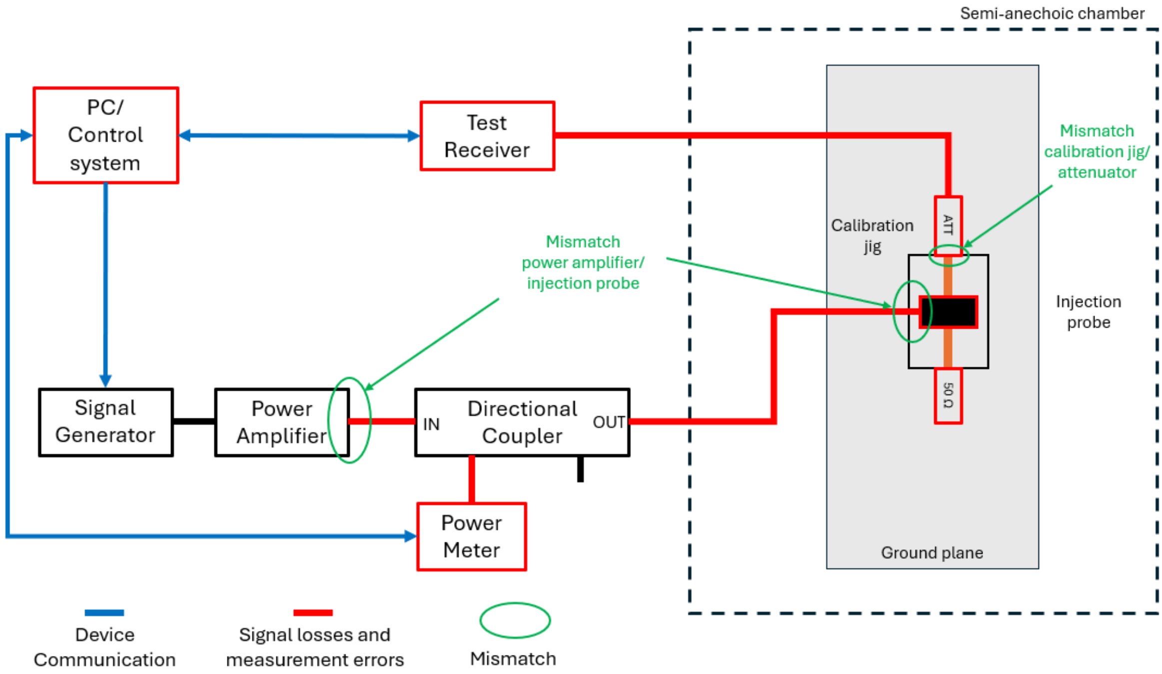


Fig. 1. Calibration setup

Additional 50 Ω attenuators are typically used between the jig and measurement equipment to protect the equipment against high currents, which can cause damage to the measuring device [1].

During calibration, the calibration jig should be placed on the ground plane [1]. When calibrating the specific test level (current), a forward power is applied to the current probe in order to inject a current into the calibration jigs central conductor. This current is measured by the measurement equipment and then the control system regulates the forward power to reach the required test level. The final forward power required to produce the specified current is recorded. This process is repeated for all demanded frequencies in the frequency range [1].

3 Measurement uncertainty calculation

In this chapter, the measurement uncertainty calculation and terminology associated with the uncertainty calculation is in compliance with [5] and [6]. No process of measuring quantities (measurands) with measuring equipment is perfect, which results in an error in themeasurement result. This error consists of two components, a random and a systematic component. Random errors arise from random variations of the measurand during repeated observations, also termed random effects. This effect cannot be compensated, but it can be reduced by increasing the number of observations.

A systematic error cannot also be eliminated, but it can often be reduced. If a systematic effect is recognized, the effect can be quantified and if it is significant in size, relative to the required accuracy of the measurement, a correction or correction factor can be applied to the result of the measurement to compensate the effect.

After applying the correction factor on the measurement results, the result is still an approximation, because of random effects and the imperfection of the correction factor. Therefore, a measurement uncer-tainty must be calculated. The measurement uncertainty is an interval around the measured value, where it is expected with a certain probability, that inside this interval the true value of the measured is located. The measurement uncertainty contains the process of detection and quantification of effects, which affect the measurement.

The result of the measurement is then expressed as

$$Y = \bar{y} \pm U \tag{1}$$

where $\bar{y}$ is the best estimate of the value attributable to the measurand Y and U is the expanded uncertainty, which defines the interval around the measurement result, where the measured is located [7].

In practice, there are many possible sources of uncertainty in a measurement. However, only a small number of uncertainty sources have a significant impact on the measured value (e.g., inadequate knowledge of the effects of environmental conditions on the measurement, etc). That is why it is necessary that all potential sources of uncertainties in the measurement of test method must be analyzed, then the contribution of the analyzed sources of uncertainty numerically quantified to allow final calculation of the standard uncertainty. The standard uncertainty is expressed as the standard deviation of the measured value.

The evaluation of the standard uncertainty can be divided into two categories based on their evaluation method:

- Type A evaluation method: standard uncertainty is obtained from a statistical analysis of a series of measurements/observations
- Type B evaluation method: standard uncertainty is obtained by factors other than statistical analysis of a series of measurements/observations

While type A standard uncertainty is obtained from a probability density function derived from an observed frequency distribution, type B standard uncertainty is obtained from an assumed probability density function based on the degree of belief that an event will occur (this probability is often called subjective probability). Although there are different approaches of evaluation, both employ the recognized interpretation of probability.

3.1 Type A standard uncertainty evaluation

Type A standard uncertainty evaluation is generally used after a series of repeated measurements, where the measurement uncertainty is obtained with statistical methods. For a type A evaluation, an estimate of the standard deviation $s(q_i)$ from a series of n measurements is obtained from:

$$s(q_i) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(q_i - \bar{q})^2} \tag{2}$$

$$\bar{q} = \frac{1}{n}\sum_{i=1}^{n} q_i \tag{3}$$

where q_i is the measured value and $\bar{q}_i$ is the mean value of the n measurements. To reduce the random component of uncertainty, it is necessary to divide the standard deviation $s(q_i)$ by the square root of the number of measurements n. The resulting value represents the standard deviation of the mean $s(\bar{q})$, which is also the standard uncertainty type A u_A

$$u_A = s(\bar{q}) = \frac{s(q_i)}{\sqrt{n}} \tag{4}$$

This means that if a measurement is repeated four times, then by calculating the standard deviation of the mean $s(\bar{q})$, the uncertainty is reduced by half compared to the standard deviation $s(q_i)$.

3.2 Type B standard uncertainty evaluation

Standard uncertainty evaluation type B is based on scientific knowledge on the possible variability of the measurand and is performed by means of non-statistical methods. This knowledge is based on previous measured data, experience from the past and from calibration certificates and datasheets of the devices used during measurement.

For a standard evaluation type B, if the expanded uncertainty is known, then the standard uncertainty type B u_B is calculated via

$$u_B = \frac{U}{k} \tag{5}$$

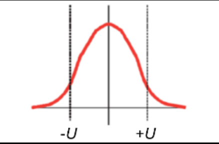
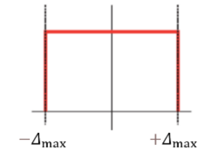
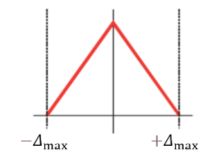
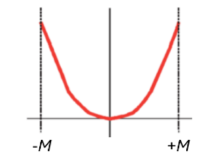
where the coverage factor k depends on the probability distribution. If only the maximum error range $\pm\Delta_{max}$ is known, then the equation

$$u_B = \frac{\Delta_{max}}{\chi} \tag{6}$$

where χ depends on the shape of the error probability in the interval $\pm\Delta_{max}$ [7].

During type B evaluation, it is important to analyze the error probability distribution of each uncertainty source. The probability distribution of errors for the analyzed source of uncertainty describes the probability characteristic of how likely it is that the true value is far from the measured value. The exact probability distribution is usually unknown, which means, that the distribution must be a qualified estimation from measured data, theoretical knowledge, previous experience, etc. After the estimation, the standard uncertainty type B u_B can be calculated [7]. There are four error probability distributions, which are mostly used in EMC testing: normal, rectangular (uniform), triangular and U-shaped distribution (see Tab. 1).

Table 1. Probability distributions for evaluation of type B uncertainty

<table>
<tr><th colspan="2">Normal</th></tr>
<tr><td></td><td>$u_B = \frac{U}{k}$
for $k = 2$ (probability 95.5%)
for $k = 3$ (probability 99.7%)</td></tr>
<tr><th colspan="2">Rectangular (Uniform)</th></tr>
<tr><td></td><td>$u_B = \frac{\Delta_{max}}{\chi}$
for $\chi = \sqrt{3}$</td></tr>
<tr><th colspan="2">Triangular</th></tr>
<tr><td></td><td>$u_B = \frac{\Delta_{max}}{\chi}$
for $\chi = \sqrt{6}$</td></tr>
<tr><th colspan="2">U-shaped</th></tr>
<tr><td></td><td>$u_B = \frac{M}{\chi}$
for $\chi = \sqrt{2}$</td></tr>
</table>

Normal probability distribution is applied when it is expected that only small deviation from the nominal value occur or for uncertainties are derived from multiple contributions (e.g., calibration uncertainties). Standard uncertainties with a normal error probability distribution are calculated using Eqn. (5), where the coverage factor k is dependent on the demanded probability of occurrence of the correct value. For a level of confidence of 95.5%, the coverage factor $k = 2$, and for a level of confidence of 99.7%, the coverage factor $k = 3$.

The rectangular distribution means that there is an equal probability of the true value lying anywhere between to prescribed limits $\pm\Delta_{max}$. This distribution is assigned, where specifications limits obtained from manufacturers are used as the uncertainty. Rectangular distribution is also used, when there is no additional statistical information about the analyzed factor, which means that the distribution is unknown. For rectangular distribution, Eqn. (6) is used, with $\chi = \sqrt{3}$.

The triangular distribution is used, when the probability of the true value is lying at a point between two limits increases uniformly from zero at the prescribed limits $\pm\Delta_{max}$ to the maximum in the center. This distribution is assigned, when the majority of values between the limits lie around the central point. As an example, the triangular distribution is applied, when a parameter is derived from theoretical values, but the actual value may be slightly shifted in the given limits $\pm\Delta_{max}$. For calculating the uncertainty with Eqn. (6) using triangular distribution, $\chi = \sqrt{6}$ is applied.

The U-shaped probability distribution is applicable for cases, where mismatches occur. It is meant for mismatch uncertainties, where the probability of the true value being close to the measured value is low. As an example for applicability of this distribution, the calculation of the standing wave ratio (SWR) between a generator and load is shown. The combination of a forward and reflected wave creates standing waves, which produces a mismatch error M between the generator and the load. This mismatch error M is calculated as

$$M = 20\log(1 \pm \Gamma_G \Gamma_L) \tag{7}$$

where Γ_G and Γ_L are the reflection coefficients of the generator and load. The standard uncertainty type B u_B is then calculated as

$$u_B = \frac{M}{\chi} \tag{8}$$

where $\chi = \sqrt{2}$.

3.3 Calculating the total measurement uncertainty

Before the total measurement uncertainty can be calculated, it is necessary to ensure that the standard measurement uncertainties of both evaluated types A and B have the same physical unit. This can be achieved by multiplying the uncertainty with the sensitivity coefficient A_i [4]. When all uncertainty sources are evaluated and calculated, then all calculated uncertainties must be combined using Gauss's law of propagation of standard deviations, which is calculated by using the formula

$$u_c(y) = \sqrt{\sum_{i=1}^{m} A_i^2 u_i^2(y)} \tag{9}$$

where $u_c(y)$ is the calculated combined uncertainty, m is the number of uncertainties, A_i is the sensitivity coefficient and $u_i(y)$ is the corresponding standard uncertainty type A or B.

If there are two or more sources of uncertainty, which are influencing each other during the testing and calibration process, then the correlation must be mathematically estimated. This degree of correlation is characterized by the estimated correlation coefficient. Taking in account the correlation coefficients, Eqn. (9) changes to

$$u_c(y) = \sqrt{\sum_{i=1}^{m} A_i^2 u_i^2(y) + 2\sum_{\substack{i=2,\\ k<i}}^{m} A_i A_k u_i u_k r_{jk}} \tag{10}$$

where the correlation coefficient r_{jk} is the estimated correlation between the uncertainty sources u_i and u_k.

Finally, the expanded uncertainty U is calculated. In most cases, the true value of $u_c(y)$ is found in the given interval with a probability of 66%. To increase the probability of the true value occurring in a certain interval, it is necessary to expand the analyzed interval. With the expansion coefficient k, it is possible to change the size of the interval and thus determine the probability (in percent) with which the true value is found in a given interval. The expanded uncertainty U is then calculated using

$$U = ku_{\mathrm{c}}(y) \tag{11}$$

The recommended expansion coefficient is $k = 2$.

If the uncertainty estimation is done for a measured value, then the final result can be written into Eqn. (1) with the given expansion coefficient.

4 Measurement uncertainty calculation for the calibration process

Due to the complex setup of the calibration process and to improve the reproducibility of the measurement uncertainty calculations, the calculation of the total measurement uncertainty is divided into different section, which can be later used also for uncertainty calculations of the testing process and its two testing methods. The measurement uncertainty evaluation and calculation is done for a general calibration setup and will not include any special setups, which can be different in each testing and calibration laboratories. Normally, the expanded measurement uncertainty is calculated by combining Eqns. (9) and (11), or Eqns. (10) and (11) if there is any correlation between two sources of uncertainty. In this case, no correlations are considered, therefore the equation for expanded uncertainty calculation is

$$U = k\sqrt{\sum_{\mathrm{i}=1}^{m} A_{\mathrm{i}}^{2} u_{\mathrm{i}}^{2}(y)} \tag{12}$$

In the sequel, this equation will be used to calculate the expanded uncertainty with the recommended expansion coefficient is $k = 2$. The impacts of analyzed measurement uncertainties and the quantification of those uncertainties were also checked at the EMC lab at the Faculty of Electrical Engineering and Information Technology of the Slovak University of Technology in Bratislava.

4.1 Measurement of RF losses inside the calibration setup

The information of power losses in a calibration and test setup is very important not only for the test and calibration processes but also for the calculation of the measurement uncertainty. The measurement method itself consists of measuring the power value of a harmonic signal at the generator output P_G using an RF power meter (for selected frequency values). In the second step, the power value at the output of the measurement chain P_L, whose attenuation L we are interested in, is measured. The attenuation L in dB is expressed as

$$L = P_{\mathrm{G}} - P_{\mathrm{L}} \pm U_{\mathrm{L}} \tag{13}$$

where U_L is the expanded measurement uncertainty of the loss measuring process. This uncertainty is calculated via Eqn. (12), using two uncertainty sources. The measurement uncertainty of the power meter u_{PM} has a normal uncertainty probability distribution (see Tab. 2) because it is expected that only a small deviation will occur during power measurement. The value of this uncertainty can be obtained from the manufacturer's specification (or the calibration certificate). The signal generator level repeatability u_{SG} has a rectangular distribution because this uncertainty arises from the devices imperfection and its value is normally found in the manufacturer's specifications or data sheets of these devices [8].

Fig. 2. Current injection probe inside calibration jig

Table 2. RF losses – estimating measurement uncertainty type B for U_L

u_i	Influence quantity	Probability distribution	Unit	A_i
u_{PM}	power meter measurement uncertainty	normal	dB	1
u_{SG}	signal generator level repeatability	rectangular	dB	1

4.2 Forward power measurement

Forward power measurement is one of the most important processes during calibration. When calibrating the injected current level, the forward power must be measured as accurately as possible to improve the reproducibility of the calibration and testing process. Therefore, every measurement uncertainty source must be evaluated, to reduce any errors during calibration and also to ensure, that the process is as accurate as possible. The forward power applied on the current injection probe P_{FWD} is expressed as

$$P_{FWD} = P_{PM} + L_{Coupler} + L_{FWD} \pm U_{FWD} \quad (14)$$

where P_{PM} is the forward power measured by the power meter, $L_{Coupler}$ is the attenuation on the directional coupler (see Fig. 1), L_{FWD} is the power loss on the cable which is connected from the output of the directional coupler to the injection probe and U_{FWD} is the total expanded uncertainty of the power measuring process via Eqn. (12). This expanded uncertainty contains at least (see Tab. 3): the calibration uncertainty of the power meter u_{CALPM}, measurement uncertainty of the power meter for power measurements u_{ACC}, which depends on the measured RF bandwidth of the signal, measurement uncertainty related to frequency setting u_{FREQ} and the source of uncertainty related to the accuracy of the power meter attenuators u_{ATT} are all uncertainties related to the power meter limitation. Those uncertainties are all documented inside the manufacturer's specifications, but because only a low impact on the measured value by those uncertainties is expected, the normal probability distribution is applied in the calculations [8].

Uncertainty in determining the attenuation of the measuring branch of the direction coupler and the cable connected to the power meter $u_{LCoupler}$ and the source of uncertainty u_{LFWD} when determining the attenuation of the forward branch of the directional coupler and the cable connected to the current injection probe have also assigned a normal probability distribution. This is also due to the low impact of uncertainties on the calibration process [8]. These uncertainties are often quantified on the basis of the previous measured data and loss measurement uncertainty calculation described in the previous section.

Table 3. Power measurement – estimating the measurement uncertainty type B for U_{FWD}

u_i	Influence quantity	Probability distribution	Unit	A_i
u_{CALPM}	calibration uncertainty of the power meter	normal	dB	1
u_{ACC}	measurement uncertainty of the power meter	normal	dB	1
u_{FREQ}	measurement uncertainty related to frequency setting	normal	dB	1
u_{ATT}	accuracy of the power meter attenuators	normal	dB	1
$u_{LCoupler}$	uncertainty of attenuation coupler – power meter	normal	dB	1
u_{LFWD}	uncertainty of attenuation coupler – injection clamp	normal	dB	1

4.3 Current injection probe

Other sources of uncertainty which have a significant impact on the calibration process are the impedance mismatch of the current injection probe and a wrong positioning of the probe inside the calibration jig (see Fig. 2). These errors will lead to different forward power values and therefore will have an impact on the testing process [9]. Therefore, it is necessary to calculate the expanded uncertainty U_{IC} for this part of the calibration (see Tab. 4) by applying Eqn. (12).

U_{IC} must contain the source of uncertainty u_{IMP} caused by the transfer impedance instability during mechanical closure of the magnetic circuit (split core) of the current injection probe. The instability may occur, when there is an incorrect closure of the injection probe or contamination (by hair or grease) of the magnetic core inside the probe. This source of uncertainty is very uncommon, but can affect the injection of current. After testing the impact of this effect, the current injection is affected only when the ferromagnetic core of the injection probe is very contaminated. Therefore, the normal distribution was applied for this calculation and the quantification is based on previous measured data, from experience from the past and on scientific research.

Table 4. Current injection probe influence – estimating the measurement uncertainty type B for U_{IC}

u_i	Influence quantity	Probability distribution	Unit	A_i
u_{IMP}	stability of transfer impedance	normal	dB	1
u_{PIC}	impedance mismatch at input of injection probe	U-shaped	dB	1

The second source of uncertainty is the impedance mismatch between the power amplifier and the current injection probe. Normally, the output impedance of the power amplifier is 50 Ω in the whole tested frequency range, but the transfer impedance Z_T of the injection probe is usually changing in the demanded frequency range, which affects also the insertion losses inside the calibration jig [9]. Because of that, the uncertainty of the impedance mismatch at input of injection probe u_{PIC} must be evaluated and calculated. Due to the fact, that the uncertainty is caused by a mismatch, the U-shaped probability distribution must be applied during calculations. When calculating this uncertainty, data from previous measurement should be used to quantify this uncertainty.

4.4 Injected current measurement

During calibration, the current, which is injected via the current injection probe, must be usually monitored using an EMI test receiver. For better measurement, the measured quantity is the voltage V_{VM} at the output of the calibration jig and the current is than calculated using Ohms law. The current I_{CAL} is obtained using the expression

$$I_{CAL} = V_{VM} + R_{50} + L_{ATT} + L_I \pm U_I \qquad (15)$$

where R_{50} is the value of the 50 Ω impedance in dBΩ, L_{ATT} is the attenuation at the output of the calibration jig, L_I is the cable loss from the calibration jig to the EMI test receiver and U_I is the expanded measurement uncertainty of current measurement process. The expanded measurement uncertainty U_I (see Tab. 5) contains the uncertainty related to the determination of amplitude accuracy u_{ACC}, measurement uncertainty related to frequency setting u_{FREQ}, source of uncertainty related to the accuracy of the power meter attenuators u_{ATT}, measurement uncertainty caused by conversion to a logarithmic scale of the measuring receiver u_{LIN} and uncertainty caused by changing the frequency range of the measuring receiver u_{BAND}. These uncertainties are related to the EMI test receiver and therefore they can be evaluated by using the manufacturer's specifications. Because the deviations of value settings and conversions are very small, the normal probability distribution can be applied for the four sources of uncertainty [10].

Table 5. Injected current measurement – estimating the measurement uncertainty type B for U_I

u_i	Influence quantity	Probability distribution	Unit	A_i
u_{ACC}	measurement uncertainty of EMI test receiver	normal	dB	1
u_{FREQ}	measurement uncertainty related to frequency setting	normal	dB	1
u_{ATT}	accuracy of the EMI test receiver attenuators	normal	dB	1
u_{LIN}	uncertainty due to logarithmic scale conversion	normal	dB	1
u_{BAND}	uncertainty caused by switching the frequency range	normal	dB	1
u_{50}	inaccuracy of 50 Ω termination impedance	rectangular	dB	1
u_{MIS}	impedance mismatch at the output of the calibration jig	U-shaped	dB	1
u_{LEMI}	measurement uncertainty during losses measurement	normal	dB	1

Another source of uncertainty is the measuring error caused by the inaccuracy of the value of the 50 Ω termination impedance u_{50}. This contribution can be obtained from the manufacturer's specification, or by using a circuit analyzer is normally a rectangular probability distribution [10]. The impedance mismatch between calibration fixture and attenuator (see Fig. 1) u_{MIS} has a rectangular uncertainty probability distribution, due to the mismatch. u_{LEMI} is the measurement uncertainty occurring during RF losses measurement between the calibration fixture and the measuring receiver. A normal probability distribution is assigned to this uncertainty because only small deviations are expected.

4.5 Total measurement uncertainty

After evaluating and calculating all important measurement uncertainties in the different measurement and calibration branches, the total measurement uncertainty of the calibration process U_{CAL} should be calculated. Apart from the three measurement uncertainties evaluated in the previous chapters (U_{FWD}, U_{IC} and U_I), two additional measurement uncertainties will be added (see Tab. 6). The first is U_{CS} as the uncertainty of the control system when setting the current, rounding error during level setting on the signal generator and reading values from the measuring devices. This uncertainty can be quantified by evaluating previous calibration data a and experience from previous measurements. From previous calibration, the impact of this uncertainty is as significant as the others, but is constant during measurement. Therefore, the rectangular probability distribution was chosen.

The second uncertainty is the combination of all small deviations and effects related to the calibration setup U_{SETUP}, which were not included in previous calculations. This measurement uncertainty can include: impact of the ground plane on the calibration setup, small deviation in the setup of the calibration jig and uncertainties caused by unidentifiable factors that will be detected during repetitions of the calibration process. Because this uncertainty is the sum of all small uncertainties, which are normally evaluated with a normal probability distribution, the probability distribution of U_{SETUP} will be also a normal distribution.

Table 6. Power measurement – estimating measurement uncertainty type B for U_{FWD}

U_i	Influence quantity	Probability distribution	Unit	A_i
U_{FWD}	power measurement uncertainty	normal	dB	1
U_{IC}	current injection probe influence	normal	dB	1
U_I	injected current measurement uncertainty	normal	dB	1
U_{CS}	uncertainty of the control system	rectangular	dB	1
U_{SETUP}	uncertainty of the calibration setup	normal	dB	1

After evaluating all necessary measurement uncertainties, the total measurement uncertainty is calculated via Eqn. (12) and the expansion coefficient is $k = 2$. The resulting equation

$$U_{CAL} = 2\sqrt{U_{FWD}^2 + U_{IC}^2 + U_I^2 + U_{CS}^2 + U_{SETUP}^2} \quad (16)$$

can be used to calculate the total measurement uncertainty of the calibration process.

5 Conclusion

In this article, the process of evaluation and calculation of measurement uncertainties is presented. Additionally, measurement uncertainties of the calibration process according to ISO 11452-4 (BCI test) were evaluated and a calculation of the total measurement uncertainty of the calibration was presented. The uncertainty determination was performed for a standard calibration laboratory setup, where the calculation can be applied for any laboratory.

This sample measurement uncertainty evaluation for the BCI calibration process can replace the missing measurement calculations, which are absent not only in the ISO 11452 standards, but also other standards (e.g., MIL STD 461 etc.) similar to ISO 11452-4. Additionally, these new calculations include uncertainties (e.g., stability of transfer impedance of the injection probe), which were not considered before in other international standards calculations and are crucial for the calibration and test process.

The evaluation also shows common sources of measurement uncertainties which can be reduced and eliminated during the calibration process, if the test engineer is aware of the topic. This can also improve the reproducibility of the calibration of the BCI test.

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References

[1] ISO (2020). "International Standard ISO 11452-4, Road vehicles - Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 4: Harness excitation methods", *ISO,* 2020-04, Fifth edition, 44 pages

[2] M. Gabrišák, J. Hallon and M. Bittera, "Critical Analysis of Bulk Current Injection (BCI) Testing Methods", In *Applied Electronics 2024*, Pilsen, 2024, pp 31-34, ISBN 979-8-3503-5073-9

[3] M. Gabrišák, J. Hallon, M. Bittera and M. Dzuriš, "Influence of Wire Misalignment in Current Injection Probe on the Bulk Current Injection (BCI) Test", In *Measurement 2025*, Bratislava, 2025, pp. 113-116, ISBN 978-80-69159-00-6

[4] ISO (2017), "General requirements for the competence of testing and calibration laboratories", *ISO*, 2017-11, Third edition, 38 pages

[5] JCGM, "JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement", First Edition, *JCGM*, September 2008, 134 pages

[6] United Kingdom Accreditation Service, "LAB34 - The Expression of Uncertainty in EMC Testing – Edition 1", *UKAS*, August 2002, 36 pages

[7] J.R. Taylor, „An Introduction to Error Analysis, the Study of uncertainties in Physical Measurements, Second Edition", *University Science Books*, 1997, 333 pages, ISBN 978-0-935702-75-0

[8] European co-operation for Accreditation, "Expression of the Uncertainty of Measurement in Calibration", In *EA-4/02*, December 1999

[9] M. F. Sultan, "Modeling of a Bulk Current Injection Setup for Susceptibility Threshold Measurements", In *IEEE International Symposium of Electromagnetic Compatibility*, pp. 188-195, San Diego, CA, 1986

[10] M. Stecher, "Rohde & Schwarz GmbH & Co. KG: A Detailed Analysis of EM1 Test Receiver Measurement Uncertainty", In *Electromagnetic Compatibility Symposium*, February 2001, ISBN 0-7803-6569-0

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