

THE COMBINED METHOD FOR UNCERTAINTY EVALUATION IN ELECTROMAGNETIC RADIATION MEASUREMENT

by

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Scientific paper

DOI: 10.2298/NTRP1404279K

Electromagnetic radiation of all frequencies represents one of the most common and fastest growing environmental influence. All populations are now exposed to varying degrees of electromagnetic radiation and the levels will continue to increase as technology advances. An electronic or electrical product should not generate electromagnetic radiation which may impact the environment. In addition, electromagnetic radiation measurement results need to be accompanied by quantitative statements about their accuracy. This is particularly important when decisions about product specifications are taken. This paper presents an uncertainty budget for disturbance power measurements of the equipment as part of electromagnetic radiation. We propose a model which uses a mixed distribution for uncertainty evaluation. The evaluation of the probability density function for the measurand has been done using the Monte Carlo method and a modified least-squares method (combined method). For illustration, this paper presents mixed distributions of two normal distributions, normal and rectangular, respectively.

Key words: combined method, electromagnetic radiation, disturbance power, mixed distribution, probability density function

INTRODUCTION

Electromagnetic radiation has been around since the birth of the universe. Light is its most familiar form. Electric and magnetic fields are part of the spectrum of electromagnetic radiation which extends from static electric and magnetic fields, through radiofrequency and infrared radiation, to X-rays. RF radiation is electromagnetic radiation in the frequency range of 3 kHz to 300 GHz on the electromagnetic spectrum and it is in the non-ionizing band of the spectrum. Non-ionizing just means there is not enough energy to break chemical bonds between molecules. Unlike ultraviolet light, gamma rays and X-rays are in the ionizing part of the electromagnetic spectrum. The electromagnetic spectrum encompasses both natural and human-made sources of electromagnetic fields. During the 20th century, environmental exposure to man-made electromagnetic fields has been steadily increasing as growing electricity demand, ever-advancing technologies and changes in social behaviour have

created more and more artificial sources. Their presence has affected almost every aspect of living (home, work, travelling, school, etc.).

An electronic or electrical product should not generate electromagnetic radiation which may influence the environment (other products, persons). Directive 2004/108/EC of the European Parliament and EU Council regulates the electromagnetic compatibility of equipment. It aims to ensure the functioning of the internal market by requiring equipment to comply with an adequate level of electromagnetic compatibility (EMC) [1, 2].

EMC measurement results need to be accompanied by quantitative statements about their accuracy. This is particularly important when decisions about product specifications are taken. One of the common problems that we face when examining EMC is an inconsistent approach to adjusting various specified or standardized tests. Consequently, some of the standardized EMC measurements include precisely defined ways of evaluating uncertainty in measurement [3]. For instance, measurement instrumentation uncertainty (MIU), standards compliance uncertainty (SCU) and other types of uncertainties are presented.

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The SCU contains all uncertainties due to MSU, the set up of the equipment under test (EUT) including the lead under test (LUT), and uncertainties due to the measurement procedure and measurement space.

In practice, the uncertainty in the result of a standardized measurement may arise from many possible uncertainty sources. In a measurement standard, each uncertainty source should be specified in a quantitative way by using one or more influence quantities. Consequently, many uncertainty sources in the domain of EMC measurements were not studied enough and need further studying. EMC tests and measurements typically have large uncertainties of at least several decibels [4].

The basic document for evaluating and expressing uncertainty in measurement is the guide to the expression of uncertainty in measurement (GUM) [5]. Consequently, the GUM proposes a standard procedure which is known as GUF (GUM uncertainty framework), which is applied to linear or linearized models [6].

This paper presents a Type B uncertainty budget evaluation for the case of disturbance power measurements in the mains leads of an apparatus according to the standard SRPS EN 55014-1:2010 [7]. The uncertainty budget is limited to Measurement Instrumentation Uncertainty (MIU) [8, 9]. We propose a new model which uses mixed distribution for uncertainty evaluation [10, 11]. The evaluation of the probability density function (PDF) of the output quantity (measurand) has been done using the Monte Carlo method and a modified least-squares method (combined method). In addition, the model equation represents one purely additive linear model whose terms are independent [8]. For illustration, we present mixed distributions of two normal distributions, normal and rectangular, respectively. The results obtained by the Monte Carlo method and the modified least-squares method are compared to corresponding results when applying the standard GUM procedure [10, 11].

MEASUREMENT MODEL

The evaluation of measurement uncertainty is based on the knowledge of the measurement process and input quantities which influence the results of that measurement. The knowledge of the measurement process is expressed by the so-called model equation which reflects the interrelation between the measurand (output quantity) and the input quantities [12]. The knowledge of input quantities is represented by appropriate PDF.

The measurement of disturbance power is performed with an absorbing clamp (in addition to the measurement at the mains leads of the vacuum cleaner), according to the standard SRPS EN 55014-1:2010 [7].

For determining the measurand value, the standardized measurement method is used. Namely, the measurand is the disturbance power. The disturbance power P corresponding to the measured voltage V at each measurement frequency is calculated by using the clamp factor CF obtained from the absorbing clamp calibration procedure described in [13]

$$P = V^2 / CF \quad (1)$$

where P is the disturbance power in dBpW, V – the measured voltage in dBμV, and CF – the clamp factor in dBpW/μV.

In addition, the clamp factor is given in the following equation

$$CF = A + 10 \log_{10}(50 - A) - 17 \quad (2)$$

where, A is the measured insertion loss in dB.

The possibility of variations of obtained measurand values becomes smaller, which reduces the measurement uncertainty that the standardized measurement method is being used.

The basic model of uncertainty includes the following separated sources of uncertainty in a measurement:

- setup of the equipment under test (EUT),
- measurement procedure,
- measurement space, and
- measurement means.

The uncertainty budget for the case of disturbance power measurements (the absorbing clamp test method – ACTM) as described in [8, 9] are not suitable for actual compliance tests in accordance with the CISPR specification given in [14]. Namely, this uncertainty budget is limited to MIU. Uncertainties due to the setup of the EUT, including the LUT, and due to the measurement procedure and measurement space (Faraday cage), are not taken into account.

The used measurement means are various for various EMC measurement methods, but for the case of disturbance power measurements in the mains leads of an apparatus the following general sources of Type B uncertainty in a measurement can be identified:

- receiver reading,
- receiver accuracy,
- frequency step error, and
- mismatch.

Receiver reading will vary for reasons which include measuring system instability, receiver noise, and meter scale interpolation errors (uncertainty determined by the least significant digit fluctuation).

The accuracy can be taken from the manufacturer's specification or calibration report of the receiver. If necessary, the uncertainty for different types of signals/responses may be considered, *i. e.*, CW accuracy, pulse amplitude response accuracy, pulse repetition response accuracy.

The frequency step error should be considered if we use an automated receiver with a programmed step

size. In this case, R&S ESVP, serial number 879691/037, was used as the test receiver and it was used for manual measurement of disturbance power, so that the frequency step error was not considered.

Apart from the given sources of uncertainty in a measurement, uncertainty sources originating from the absorbing clamp should be added to the measurement of disturbance power. It should be mentioned that our measurements were done in the frequency range of 30 MHz to 300 MHz and that an absorbing clamp (MDS 9, Robert Luthi GmbH, serial number 71170) was used. So, when the absorbing clamp (AbC) is used for the measurement of disturbance power, the following sources of uncertainty in the measurement can be identified:

- AbC receiver attenuation,
- AbC insertion loss, and
- AbC receiver mismatch.

The attenuation of the connection between the receiver and the absorbing clamp is obtained from the calibration report or manufacturer's data.

Absorbing clamp insertion loss can be taken from the calibration report. In addition, the loss of the RF cable is included.

For disturbance power measurements, the mismatch is given in the following eq.

$$M = 20 \log_{10}(1 - \Gamma_{ac} \Gamma_r) \quad (3)$$

where Γ_{ac} is the voltage reflection coefficient (VRC) of the absorbing clamp and Γ_r – the VRC of the measurement receiver.

Consequently, Γ is related to voltage standing wave ratio ($VSWR$) by

$$\Gamma = \frac{VSWR - 1}{VSWR + 1} \quad (4)$$

In this case, the measurement receiver specification of $VSWR$ (attenuation 0 dB) and the ab-

sorbing clamp specification of $VSWR$ are assumed. In addition, this can be improved and the associated uncertainty reduced by applying a 6 dB attenuator on the output of the absorbing clamp [8].

The model equation for the evaluation of MIU is given in [8] by the following eq.

$$Y = V_r L_c L_{ac} 10 \log_{10}(50) \quad (5)$$

$$\delta Y_{sw} \quad \delta V_{pa} \quad \delta V_{pr} \quad \delta M$$

Equation (5) represents a purely additive linear model whose terms are independent. Information on the terms of the expression in the model equation is given in tab. 1. Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty, other components by Type B evaluation of measurement uncertainty. Consequently, Type A evaluation is done by calculation from a series of repeated observations using statistical methods and resulting in a probability distribution that is assumed to be normal. Type B evaluation of measurement uncertainty can also be characterized by standard deviations evaluated from probability density functions based on experience or other relevant information.

VALUES OF INPUT QUANTITIES

Table 1 presents an uncertainty budget, a Type B evaluation of the MIU for the case of disturbance power measurements. Namely, the given data are obtained from the manufacturer's specifications, calibration reports, and instrumentation manuals [15, 16], and are used for the evaluation of the MIU, according to the ISO-GUM [5].

The standard uncertainty $u(x_i)$ is calculated by dividing the value of the uncertainty associated with x_i by the coverage factor k_p , whose value depends on the

Table 1. Uncertainty budget of measurement instrumentation uncertainty (MIU) according to the GUM for disturbance power measurements

Input quantity	X_i	Estimate $X_i(x_i)$		Standard uncertainty $u(x_i)$ [dB]	Sensitivity coefficient c_i	Contribution to the standard uncertainty $u_i(y) = c_i u(x_i)$
		Value [dB]	Probability distribution function			
Receiver reading	V_r	0.1	Rectangular $k_p = 1.732$	0.058	1	0.058
AbC-receiver attenuation	L_c	0.1	Normal $k_p = 2.000$	0.050	1	0.050
AbC insertion loss	L_{ac}	+3.0 -0.2	Normal $k_p = 2.000$	0.800	1	0.800
Receiver sine wave voltage	δV_{sw}	1.0	Normal $k_p = 2.000$	0.500	1	0.500
Receiver pulse amplitude response	δV_{pa}	2.0	Rectangular $k_p = 1.732$	1.155	1	1.155
Receiver pulse repetition rate response	δV_{pr}	2.0	Rectangular $k_p = 1.732$	1.155	1	1.155
AbC-receiver mismatch	δM	+1.40 -1.67	U-shaped $k_p = 1.414$	1.086	1	1.086

choice of the probability density function (PDF) and confidence level associated with the given value.

For rectangular or U-shaped probability distribution, where X_i is estimated to lie between $(x_i - a^-)$ and $(x_i + a^+)$, with a level of confidence of 100%, $u(x_i)$ is taken as $a/3^{1/2}$ or $a/2^{1/2}$, respectively [8]. In addition, $a = (a^+ - a^-)/2$ is the half-width (semi-width) of the probability distribution. For a normal probability distribution, the divisor is 2 if the value of the uncertainty associated with x_i has a level of confidence of 95,45% (the value is twice the experimental standard deviation). The estimated value x_i is determined with $x_i = (a^+ + a^-)/2$ [5].

EVALUATION OF MEASUREMENT INSTRUMENTATION UNCERTAINTY

Previous sections present the uncertainty budget of the MIU according to GUM for the case of disturbance power measurement standard SRPS EN 55014-1:2010 [7].

This section presents the application of the combined method to the uncertainty budget of the MIU for disturbance power measurement. Consequently, the model equation for the evaluation of MIU is given with eq. (5). Namely, the Monte Carlo method and the modified least-squares method (combined method) are applied in two cases for two independent input quantities from the given expression. The combined method is used for the evaluation of the probability density function for the output quantity (mixed distribution) according to the probability density function from two independent input quantities, *i. e.*, two independent input quantities assigned by normal distributions, two independent input quantities where the first quantity is assigned a normal distribution and the second is assigned a rectangular distribution. Convolution can be used for the general additive model $Y = X_1 \cdot X_2 \cdots X_N$ by combining X_1 and X_2 , and then combining this result with X_3 , and so forth [17]. The instance of many input variables has not been discussed in this paper.

Monte Carlo simulations for obtaining mixed distributions are done by the procedure described in [10, 11, 18].

The number of classes of histogram k is determined according to eq. (6)

$$k = \sqrt{n} \quad (6)$$

For determining the value of k , other formulas exist in statistics [18]. When determining the empirical formula for k , the basic criterion is that at least one value of the random variable x fits in each class of histograms, providing histogram continuity. On the other hand, k must be greater than 3 in order for the histogram form to indicate the law of distribution of the random variable [19]. It is implied that k is taken as an integer value.

The values for the Monte Carlo simulations are taken from tab. 1. Consequently, the value of N , the total number of trials was 10^6 . The number of data used for the simulation is $n = 10000$. Risk conformity was $\alpha = 0.05$, that is the confidence level $(1 - \alpha)$ was 0.95. One more data that is important for our simulation was the mixed coefficient ε which was 0.5. The results obtained by the combined method are compared to the corresponding results when applying the GUM.

The first example given refers to two independent input quantities, L_{ac} and δV_{sw} , assigned by two normal PDF. Table 1 shows that for the two given input quantities L_{ac} and δV_{sw} estimates are given with a^-/a^+ , *i. e.*, $-0.2/+3.0$ dB and 1 dB, respectively. Then the estimated values are $x_1 = 1.40$ and $x_2 = 0$, and standard uncertainties $u(x_1) = 0.8$ and $u(x_2) = 0.5$, respectively (see tab. 1). After entering the given data into a computer program created in Visual Basic 6.0, the generation of pseudorandom numbers is done (in our case, 10000). For pseudorandom numbers generated in this manner, a histogram is drawn (fig. 1) that represents the empirical curve of a mixed normal-normal distribution. In fig. 1 the empirical curve (histogram) is shown in a white line.

After that, determining point estimates parameters of a mixed normal-normal distribution is done by the combined method [10, 11]. With parameters that are determined like this, the estimated density function of a mixed normal-normal distribution is obtained. The values of these parameters are pseudorandom and with them the fitting of a mixed normal-normal distribution (estimated curve) is tried in a histogram. It should be mentioned that the coming of the curve through the mid-point of each class histogram is considered to be the best fitting.

In fig. 1, the estimated curve is shown in a grey line. Consequently, the theoretical curve is shown by a black line and represents the results obtained according to the GUM (fig. 1). It is noticeable that the fitting of the estimated curve (grey line) in a histogram (empirical curve) is very good, which indicates that the unknown parameters of this distribution are estimated well. Also, it is noticeable that the estimated curve

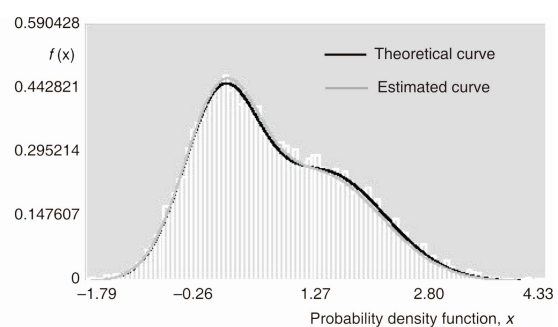


Figure 1. Mixed normal-normal distribution obtained by the combined method and GUM, respectively

(grey line) differs slightly from the theoretical curve (black line). This difference was the result of the evaluation of parameters of the mixed distribution (whose values are pseudorandom) and the number N of iterations (the total number of trials).

The second example which was used refers to two independent input quantities δV_{sw} and δV_{pa} , assigned by normal and rectangular PDF, respectively. Table 1 shows that for the two given input quantities, δV_{sw} and δV_{pa} , estimates are given with 1 dB and 2 dB, respectively. Then the estimated values are $x_1 = x_2 = 0$, and standard uncertainties $u(x_1) = 0.5$ and $u(x_2) = 1.155$, respectively (see tab. 1). As in the previous example, the given data are recorded into the computer program, and then the pseudorandom numbers ($n = 10000$) generating is done. For pseudorandom numbers generated in this manner a histogram is drawn (fig. 2) which represents the empirical curve of a mixed normal-rectangular distribution. In fig. 2, as in the previous example, the empirical curve (histogram), estimated curve, and the theoretical curve are shown by the white line, the grey line and the black line, respectively.

It is noticeable that the fitting of the estimated curve (grey line) in the histogram (the empirical curve)

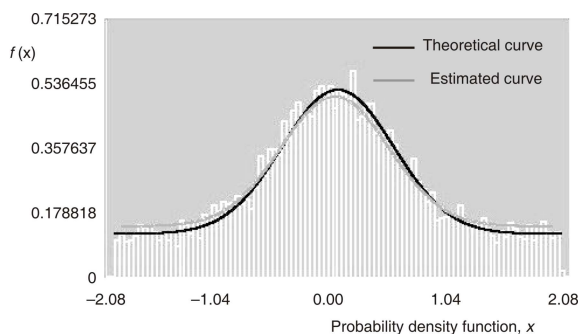


Figure 2. Mixed normal-rectangular distribution obtained by the combined method and GUM, respectively

is very good and does not deviate a lot from the theoretical curve (black line).

This difference was the result of the evaluation of parameters of the mixed distribution (whose values are pseudorandom) and the number N of iterations.

CONCLUSIONS

Electromagnetic radiation has affected almost every aspect of living. In our homes and at work, we are exposed to radiation emanating from electronic or electrical equipment. If you have met the requirements of electromagnetic compatibility for electronic or electrical equipment, you have satisfied the needs of

the people. EMC measurement results need to be accompanied by quantitative statements about their accuracy. This is particularly important when decisions about product specifications are taken. This paper presents a Type B uncertainty budget evaluation for disturbance power measurements. The uncertainty budget is limited to MIU. We propose a new model which uses mixed distribution for uncertainty evaluation. The evaluation of the PDF for the measurand (output quantity) has been done using the Monte Carlo method and a modified least-squares method (combined method). The combined method is applied in two cases for two independent input quantities which were associated to appropriate PDF. It was shown that the combined method can be applied alternatively for the determination of the probability density functions of the output quantity to a satisfactory degree of accuracy. Namely, applying the combined method produces a mixed distribution, *i. e.*, PDF for the output quantity, which fits well (the estimated curve) in histograms and differs slightly from the produced results according to the GUM (theoretical curve).

ACKNOWLEDGEMENT

The Ministry of Education, Science and Technological Development of the Republic of Serbia supported this work under Contracts III 43009 and 171007.

AUTHOR CONTRIBUTIONS

Theoretical analysis and experiments were carried out by A. M. Kovačević. Literature research was carried out by A. M. Kovačević, K. Dj. Stanković, and A. V. Kovačević. The manuscript was written by A. M. Kovačević, with the suggestions of all authors. The figures were prepared by A. M. Kovačević and A. V. Kovačević. All authors analysed and discussed the results.

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Received on May 7, 2014

Accepted on December 13, 2014

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КОМБИНОВАНА МЕТОДА ЗА ПРОЦЕНУ МЕРНЕ НЕСИГУРНОСТИ ПРИ МЕРЕЊУ ЕЛЕКТРОМАГНЕТСКОГ ЗРАЧЕЊА

Електромагнетско зрачење на свим фреквенцијама представља један од најчешћих и најбрже растућих утицаја на животну средину. Све популације изложене су различитим степенима, а нивои ће наставити да расту како технологија буде напредовала. Електронски или електрични производи не смеју генерисати електромагнетско зрачење које може утицати на животну средину, при чему резултати мерења треба да буду праћени квантитативним изјавама о њиховој тачности. Ово је нарочито важно када се доносе одлуке о карактеристикама производа. У овом раду представљен је буџет мерне несигурности при мерењу снаге сметњи код производа као део електромагнетског зрачења. За процену мерне несигурности предложен је један модел који користи мешовиту расподелу. Метода Монте Карло и модификована метода најмањих квадрата (комбинована метода) коришћене су за процену функције густине расподеле мерене величине. Као илустрација, у овом раду је представљена мешовита расподела од две нормалне расподеле, нормалне и правоугаоне расподеле, респективно.

Кључне речи: комбинована метода, електромагнетско зрачење, снага сметњи, мешовита расподела, функција густине расподеле