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Analysis of the total random error in simulation systems

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ABSTRACT

The article presents an analytical assessment of error in computer simulation systems for cases of an unknown arbitrary type of symmetric distributions of the total random error of calculations. The study is based on the use of asymptotic properties of a sequence of random variables. The work includes the development of a mathematical framework for predicting a confidence estimate of random error. An innovative approach to selecting the initial approximation is proposed. The proposed approach increases the efficiency of the iterative error calculation process. It has been established that, for any type of symmetric distribution laws, the series contains only integer powers of n. Using the established pattern ensures better convergence and optimizes the calculation of the numerical value of the modeling error. Simplified formulas have been created for calculating confidence intervals at high probability levels. The applicability conditions of the methodology have been determined. It has been experimentally confirmed that for a uniform distribution, acceptable accuracy is achieved with at least two components. At the same time, for a sinusoidal distribution, at least three components are needed to achieve an error below the acceptable limit. For high levels of modeling reliability, the required accuracy is achieved with two components without the need to introduce additional adjustments. The reliability of the obtained results was verified for two cases of input data. In the first case, the results of studies on modelling accuracy using the representation of numbers in the binary-hexadecimal system as arrays were used. In the second case, input data from error calculations of solving linear GPU NVIDIA tasks with floating-point representation were used. The methodology is universal and can be applied to both random and systematic errors that occur in simulation systems.

Keywords: Simulation modelling; forecasting; machine learning; information technologies; high-precision calculations; floating point representation; random error summation; simulation errors; improving accuracy of simulation systems; unequal-sized data; simulation system; representation as arrayslist skills; labour market analysis; unsupervised learning; clustering; academic program; specific subject competences

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INTRODUCTION

Simulation modelling systems are actively used to forecast the development of various processes. However, the euphoria and widespread fascination with trendy technologies increasingly rely on the business interests of developers, while insufficient attention is paid to the accuracy and reliability of the final modelling results. Confirmation of this thesis can be seen in a recent series of publications on news websites and social media analysing the reliability of artificial intelligence outcomes [1].

A study by the Salesforce AI Research team, which revealed shortcomings in the performance of popular artificial intelligence tools, is being actively discussed. Citing the study's author, Pranav Narayanan Venkit, it is noted that systems such as Perplexity, You.com, and Microsoft Bing Chat have been found to be "unreliable, overly confident, and biased". Artificial I ntelligence (AI) is capable of saving time by quickly finding information, but ultimately, AI-generated outputs contain statements that are not supported by reliable sources [1].

It is noted that approximately one-third of the statements made by AI tools lacked confirmation in the sources they cited. For OpenAI's GPT-4.5, this figure reached 47 %. Modern studies of AI applications show that during 'debates,' AI tends to present one-sided arguments, delivering them very confidently. This approach creates an 'echo chamber' effect, where users are exposed only to viewpoints that align with their own, without alternative perspectives [1]. Publications also note: «research showed that a significant portion of the data was fabricated or unverified. Across different systems, citation accuracy ranged from 40% to 80%».

Taking the above into account, it should be emphasized that a significant number of educational materials in Ukrainian universities dedicated to computer modelling do not pay sufficient attention to the issues of model reliability and the assessment of errors in predicted numerical values.

The paper is structured as follows: Section 2 reviews the literature on the requirements of employers in the IT industry; Section 3 describes the research methodology using unsupervised learning in the form of clustering; Section 4 defines the academic program corresponding to the cluster of vacancies; the last section concludes.

As an example, publications [2], [3] can be cited, which, from another perspective, are worthy examples of substantial contemporary Ukrainian educational literature.

Research on the sources of errors and the assessment of error magnitudes in modern scientific publications is either occasional [4], [5] or focused on specific subject areas [6], [7], [8], [9],]10], [11].

Modern computer simulation systems play a key role in various fields of science and technology [4], [6], [9], [12], where the accuracy of calculations and the reliability of results are critically important requirements. The issue of accounting for the magnitude of cumulative random error in such systems is becoming particularly relevant, as the reliability of the obtained simulation results depends on the correct assessment of its impact on the final calculation outcomes.

Among the entire range of simulation modelling systems, the most complex are the simulation systems of sociotechnical processes, such as: combat simulation systems [13], simulation systems of urban infrastructure, and simulation systems as part of aircraft and ship training complexes [14]. In these systems, the software is based on a well-studied set of physical process models and mathematical models that take into account the uncertainty of decision-making, including elements of artificial intelligence. However, it is also necessary to consider the error introduced by computer calculations, which has not received sufficient attention in modern studies. It is clear that large computational errors in these systems can lead to a significant distortion in the human operator's perception of the actual course of events.

Traditional approaches to error estimation often rely on the assumption of normally distributed components, which does not correspond to real modelling conditions. In practice, computer calculations have to deal with various error distribution laws (normal, uniform, arc sinus), their combinations [15], and interactions. This creates the need to develop a universal methodology that would take into account heterogeneous sources of uncertainty and provide a reliable estimate of the total random error.

Attention is drawn to the issues of optimizing computational resources [16] while maintaining the required accuracy of results, which requires the development of efficient algorithms and simplified formulas for practical application. An important aspect is also ensuring the scalability of the methodology for complex modelling systems and its adaptation to different subject areas.

The proposed work is devoted to the development of a universal methodology for calculating the total random error for computer simulation systems, which takes into account different distribution laws of the error components and ensures practical calculation accuracy at various confidence levels. The proposed approach is based on the use of the asymptotic properties of a sequence of random variables and includes the creation of a mathematical framework for predicting the confidence estimate of the random error of a measurement system

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

An analysis of publications devoted to the issues of reducing calculation errors and increasing the reliability of predictive models in computer systems makes it possible to outline the following three main directions of current research.

Works related to the first conditional direction can include attempts to model the quantitative value of the error in indirect measurement of a physical quantity, which is a component of the error in determining the unit of a physical quantity. Essentially, these works are aimed at determining the error of an indirect measurement method. A significant drawback of this approach, from the point of view of creating simulation modelling systems, is the need to construct an accurate physical model of the process while eliminating the uncertainty of factors that affect the quantitative value of the error. Examples of this approach can be found in works [17], [18], [19], [20], [21], [22].

In the work [17], the authors do not specifically present direct methods for calculating the total error, but they offer a comprehensive review of methods for quantitative uncertainty assessment (UQ) in the context of scientific machine learning. The authors propose a unified framework that integrates different approaches to uncertainty modelling, including both traditional methods and new solutions. Special attention is given to the integration of Bayesian

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methods with deep learning, which allows for more accurate assessment and prediction of uncertainties in complex scientific models. The study also highlights the importance of selecting appropriate evaluation metrics and post-processing methods to ensure the reliability of predictions. The study also highlights the importance of properly choosing evaluation metrics and post-processing methods to ensure the reliability of predictions.

The study [18] presents a methodology for calculating the total random error in phantom dosimetry systems through software modelling. A key aspect of the work is the development of an algorithm that takes into account various sources of random errors and combines them into an overall estimate of measurement uncertainty. The authors use the Monte Carlo method to simulate individual error components, and then apply statistical methods to calculate their cumulative effect, which allows them to obtain a comprehensive assessment of the overall random error of the system without conducting numerous practical measurements.

The research results demonstrate the effectiveness of the proposed approach for calculating the total random error, where each error component is modelled separately and then integrated into the overall uncertainty assessment. Special attention is given to validating the method by comparing the calculated total errors with experimental data, confirming the accuracy and reliability of the proposed approach. The method allows not only determining the overall magnitude of random error, but also assessing the contribution of each individual source of uncertainty to the total result, which is critical for optimizing measurement systems and improving their accuracy.

The scientific work [19] presents an innovative approach to analysing motion reliability and modelling errors in parallel mechanisms with multiple degrees of freedom. The researchers developed a hybrid method that combines probabilistic and interval approaches for a more accurate assessment of the total random error. A key feature of the proposed methodology is its ability to account for different sources of uncertainty and their cumulative impact on the system, allowing for an increase in reliability assessment accuracy by 15-20% compared to traditional methods.

The practical verification of the method was carried out on a real mechanism, which confirmed its effectiveness for complex multi-stage systems. The research results demonstrate that the developed approach not only provides more accurate predictions of system behaviour but also allows for the optimization of its parameters to minimize overall error. The method has a wide range of practical applications in robotics, precision mechanisms, and industrial manipulators, where high accuracy in positioning and motion control is critically important.

The study [20] presents a comprehensive approach to analysing and quantitatively assessing the impact of errors in analog quantum simulation systems. The authors developed an innovative methodology based on perturbation theory and numerical methods to determine the sensitivity of quantum systems to various types of errors. A key achievement of the work is the creation of a universal framework that allows for setting quantitative limits on permissible errors and identifying critical parameters that affect the stability of quantum simulation.

The practical significance of the research lies in the development of specific optimization methods to reduce the impact of errors and improve the reliability of quantum computing. The performance metrics and error control methods proposed by the authors demonstrate high efficiency in practical applications within quantum simulators. The results of the work are fundamentally important for the further development of quantum computing, providing quantum system developers with concrete tools to assess and minimize errors that arise during quantum simulations.

In the work [21], the authors demonstrate an innovative approach to simulating open quantum systems using error mitigation methods for deep quantum circuits. The authors developed a comprehensive methodology that combines digital evolution techniques for simulating open systems with new error mitigation methods, allowing for efficient exploration of stationary states and relaxation processes. The key innovation is the development of advanced algorithms that ensure computational accuracy when working with deep quantum circuits.

The practical significance of the work is confirmed by the successful simulation of complex open quantum systems and the accurate calculation of relaxation rates. The proposed methods are widely used in modelling quantum systems with dissipation and in studying quantum dynamics. The research results are of fundamental importance for the development of quantum computing, providing scientists with effective tools for studying complex quantum systems and developing more efficient quantum algorithms.

In the study [22], the authors proposed a comprehensive analysis of the performance of digital-to-analog converters (DACs) with current sources, taking into account three key factors: random matching errors, gradient errors, and finite output impedance. The authors developed a mathematical model that allows accurate prediction of system characteristics and quantitative assessment of the impact of different types of errors on the overall DAC performance. Special attention is given to the analysis of static and dynamic characteristics, as well as the study of temperature dependence and the influence of process variations.

The practical significance of the work lies in creating effective tools for optimizing the design of DACs and improving their conversion accuracy. The research results provide specific recommendations for reducing the impact of parasitic effects and increasing system reliability. The proposed model allows developers to predict and compensate for various types of errors at the design stage, which significantly enhances the efficiency of developing high-precision digital-to-analog converters and optimizing their characteristics.

A significant number of works that can be attributed to this direction is explained by the multitude of research fields in which computer modelling is used, examples of which are the works [4], [6], [8], [10], [11], [12], [15], [17], [19], [20].

The works that can be attributed to the so-called second direction, observed in printed sources, are those that at the architectural level allow the exclusion of certain components of computational errors. The most interesting in this direction are a number of studies dedicated to creating methods for representing numerical values in computer systems and developing high-precision calculation services. The works [23], [24], [25] are of the greatest interest in demonstrating this approach.

In the work [23], it is specifically noted that the results of modelling the motion of planets for astronomical observations revealed serious numerical inaccuracies, even when mathematical models that have proven effective in other studies of the respective field are applied.

The practical significance of the work for the computer industry is determined by the conclusions that, after addressing a number of significant problems, it was found that arithmetic operations with double-length words are necessary to eliminate computational errors in computer modelling results. It has been established that errors are introduced by the computer system itself during calculations in the binary system, even when using the most accurate models of planetary motion.

To completely eliminate the possible contribution of errors by the computer system in the work [24], the authors propose a method of representing numbers in the binary-hexadecimal system as arrays instead of using floating-point representation.

The practical significance of the work lies in creating the prerequisites for eliminating errors in computer calculations associated with the truncation of digits of numerical data of varying sizes when performing complex arithmetic operations in binary-hexadecimal floating-point computing systems in computers of various purposes.

To eliminate the potential contribution of errors by a computer system during software development, J. Gustafson proposed a format for representing numerical values: unums (universal numbers). This is an arithmetic and binary format for representing real numbers, similar to floating-point as an alternative to IEEE 754 arithmetic. The first version of the unum, now officially known as "type I" unum, was presented in his book "The End of Error" [25], [26]. As a development of type I unum, at the end of 2016, two newer versions of the unum format, “type II and type III”, were created.

Modern works that are dedicated to the quantitative assessment of forecast risks and modelling uncertainty, with a rejection of understanding the performance of mathematical models of the physical process, can be attributed to a conditionally third direction.

As examples of this approach, one can cite the works [27], [28], [29], which the authors were kindly pointed to during the review of the paper.

In the mentioned works, an approach is implemented in which it is proposed to practically abandon the quantitative assessment of modelling error. As a corresponding alternative for reconciling simulations with the experiment, a quantitative assessment of uncertainty in modelling is proposed.

The work [29] offers an assessment of approaches to validation, calibration, and prediction of models when there is uncertainty in simulation or experiment.

However, research in the mentioned area is not a complete alternative to modern simulation modelling systems and high-precision computations when a quantitative assessment of modelling error as indirect measurements of a unit of physical quantity is required.

It is worth noting separately some studies devoted specifically to the study and minimization of errors in computer calculations.

In the scientific paper [30], a systematic review of error estimation methods in computational science is presented, focusing on three main categories: a priori error estimates, a posteriori estimates, and adaptive methods. The authors examine in detail the mathematical foundations of each approach, including classical methods such as Richardson's method and its modifications, as well as modern techniques based on hierarchical models and machine learning. Special attention is paid to the interrelationship between various sources of errors: discretization, rounding, iterative processes, and modelling, as well as methods for their combined assessment. A comparative analysis of the effectiveness of different error estimation methods is presented using typical computational mathematics problems as examples. The authors propose a structured approach to selecting an error estimation method depending on the nature of the problem, accuracy requirements, and computational resources. An important contribution is the consideration of modern challenges in error estimation, including scaling issues for large systems, real-time error estimation, and integration with machine learning methods. However, the methodology for calculating errors during long-term simulations and for computing the total random error is not addressed.

In the work [31], an innovative approach to structural identification is presented, based on the substructure decoupling technique considering the error of the dynamic model. The authors developed a comprehensive methodology that effectively combines uncertainty processing methods with optimization algorithms for parameter identification. The key innovation is the creation of an enhanced substructure decoupling technique, which significantly reduces modelling errors and, consequently, improves the accuracy of determining the structural parameters of the system.

The practical significance of the work is confirmed by the successful experimental verification of the proposed approach and its effective application in real engineering tasks. The research results have widespread practical use in structural monitoring, technical condition diagnostics of structures, and reliability assessment of engineering systems. The proposed method allows for more accurate consideration of uncertainties in dynamic models, which is critically important for optimizing the design and operation of complex structural systems.

Thus, based on the analysis of a number of works dedicated to modern research aimed at determining the total random error in computerized simulation systems, the absence of a universal method for calculating the total random error has been identified. The requirement for the methodology is the need to take into account heterogeneous sources of errors caused by uncertainty regarding the error distribution law across the tolerance field. Existing approaches presented in works on quantum computing, phantom dosimetry, parallel mechanisms, and digital-to-analog converters demonstrate fragmentation and limited applicability, highlighting the need to develop a comprehensive methodology that would provide: a standardized approach to assessing different types of errors, scalability for complex and high-precision systems, efficient algorithms for result validation and optimization of computational resources, while maintaining versatility in simulation modelling and other subject areas, ensuring increased accuracy and reliability of results compared to existing methods.

PROBLEM STATEMENT

Based on the analysis of recent studies and publications, the current goal of the scientific research is to develop a universal methodology for calculating the total random error for computer simulation systems, which takes into account different distribution laws of error components and ensures practical computational accuracy at various levels of confidence probability.

Based on the research objective, tasks arise related to the development of a mathematical framework for predicting the confidence estimate of the random error of a measurement system using probabilistic methods, as well as the creation of a methodology for summing errors with different distribution laws (normal, uniform, arcsine). The work considers the estimation of error values for a class of symmetric distribution laws across the tolerance field, which is a limitation of the study.

THE PURPOSE AND THE OBJECTIVES OF THE STUDY

In computerized simulation systems, forecasting confidence estimates of random errors presents an interesting mathematical problem, which resonates with the calculation of errors in indirect measurements. Although traditional approaches rely on probability theory, the randomization of systematic errors has opened new possibilities for computation during long-term simulations.

The study aims to develop a methodology for predicting the confidence estimate of random error in simulation modelling systems with high-precision computations. The work should establish initial approximations to increase the speed of the iterative process. Conditions for better convergence of calculations for symmetric distributions should be determined. A separate objective of the study is to derive expressions for calculating confidence intervals at probability levels of 0.95 and 0.99.

Experimental verification is subject to checking the conditions for achieving a calculation error of less than 1.5 % for uniform and sinusoidal distribution laws with a confidence probability of 0.95, without the need for additional corrections. It is proposed to use reference data from the Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine, developed for establishing the performance of computer models of genetic algorithms, as the initial data for assessing the methodology's functionality.

DEVELOPMENT OF METHODS FOR DETERMINING TOTAL RANDOM ERROR IN SIMULATION SYSTEMS FOR CASES OF SYMMETRIC DISTRIBUTIONS

Let us consider a measurement system where the readings almost linearly depend on n parameters of individual components of the simulation system. The overall error Y can be represented as $Y = \sum_{j=1}^{n} X_j$. Xj reflects the individual components of the error. Although this formulation seems simple, its practical application becomes more complicated when we go beyond the assumptions of a normal distribution.

In the reality of simulation modelling, one often has to deal with dominant errors that follow non-normal distributions.

This complexity [32] has led to the development of innovative approaches, In particular, the following were obtained:

– methodologies for summing errors represented as sinusoids with randomly uniformly distributed phases;

– solutions for combining components with uniform distributions or their convolutions;

– the use of Gram-Charlier series and asymptotic expansions for approximation [33].

Interestingly, when there are several types of distributions (uniform, normal, and arcsine), the overall error distribution tends to become normal as the number of components increases. Even with a smaller number of components, it is often possible to achieve a satisfactory approximation using a normal distribution with correction terms.

The key innovation lies in the use of the asymptotic properties of sequences of random variables, which differs from traditional approaches. This method is particularly valuable for metrological applications, where the distribution functions Fj(x) exhibit characteristic moments of the k-th order.

The approach proposed by the authors allows not only for more accurate estimation of errors in complex systems but also for optimizing quality control processes in the production of computer equipment.

In the context of error analysis, it is important to consider their mathematical representation through k-th order moments:

$$\alpha_{kj} = \int_{-\infty}^{\infty} x^k dF_j(x). \quad (1)$$

Assuming zero mean values of random variables, the variance of the total error is determined as: $\sigma^2 = \sum_{j=1}^{n} \alpha_{2j}$.

The innovative approach to analysis involves representing the distribution function F(x) of the normalized sum: $Z = \sigma^{-1} \sum_{j=1}^{n} X_j$ through an asymptotic series in powers of $n^{-\frac{1}{2}}$ which has the form:

$$F(x) = \Phi(x) + \sum_{j=1}^{n} \frac{Q_{jn}(x)}{n^{\frac{j}{2}}},$$

where $\Phi(x)$ represents the normal distribution function: $-\frac{1}{\sqrt{2n}} \int_{-\infty}^{x} e^{-\frac{\xi^2}{2}}$.

Of particular interest is the case of symmetric probability distributions, where the odd moments are zero. In this case, the first terms of series (1) take the form:

$$\frac{Q_{1n}(x)}{n^{\frac{1}{2}}} = \frac{Q_{3n}(x)}{n^{\frac{3}{2}}} = 0; \ \frac{Q_{2n}(x)}{n} = -\frac{1}{\sqrt{2n}} \frac{H_3(x)}{24\sigma^4} \sum_{j=1}^{n} K_{4j};$$

$$\frac{Q_{2n}(x)}{n} = -\frac{1}{\sqrt{2n}} e^{-x^{\frac{2}{2}}} \left[\frac{H_5(x)}{720\sigma^6} \sum_{j=1}^{n} K_{6j} + \frac{H_7(x)}{1152\sigma^8} \left(\sum_{j=1}^{n} K_{4j} \right)^2 \right].$$

An important aspect is the use of Hermite polynomials $\mathrm{H}m(\mathrm{x}) = \frac{(-1)^m e^{x^{\frac{2}{2}}} d^m (e^{-x^{\frac{2}{2}}})}{dx^m}$ of degree m and semi-invariants, which allow for simplifying calculations. Semi-invariants have an additive property, which allows representing the general semi-invariant as the sum of individual components:

$$K_2 = \sigma^2 = \sum_{j=1}^{n} \sigma_j^2;\ K_4 = \sum_{j=1}^{n} K_{4j};\ K_6 = \sum_{j=1}^{n} K_{6j}.$$

This mathematical model has special practical significance, since for symmetric distribution functions the series contains only integer powers of n, which ensures better convergence and computational accuracy.

The proposed approach differs from traditional methods in its efficiency and simplicity of calculating expansion coefficients, making it particularly valuable for practical applications in computer modelling systems and error analysis.

In the practical analysis of measurement system errors, the key role is played by the relationship between semi-invariants and the extreme values of the error components δ_j.

This relationship can be expressed by the following relation:

$$\sigma_j^2 = \beta_{2j}\delta_j^2;\ K_{4j} = \beta_{4j}\delta_j^4;\ K_{6j} = \beta_{6j}\delta_j^6. \tag{2}$$

Of particular interest are the proportionality coefficients β_2, β_4, β_6, which characterize different types of distributions encountered in measurement practice: normal (N), uniform (U), and arcsine (A). For the normal distribution, the value of β_2 is calculated for a confidence probability of 0.99.

Important characteristics of the distribution shape are the coefficients: $\gamma = \frac{K_4}{\sigma^4}$ (kurtosis coefficient), $\xi = \frac{K_6}{\sigma^6}$ (sixth-order shape coefficient). These coefficients demonstrate an interesting property: they decrease as the number of components increases according to the laws n^{-1} and n^{-2}, respectively.

Using these coefficients, one can obtain the compact form of the Gram-Charlier series:

$$F(x) = \Phi(x) - \frac{e^{-x^{\frac{2}{2}}}}{\sqrt{2n}}\left[\gamma\frac{H_3(x)}{24} + \xi\frac{H_5(x)}{720} + \gamma\frac{H_7(x)}{1152} + \cdots\right]. \tag{3}$$

The corresponding probability density function takes the form:

$$f(x) = \frac{e^{-x^{\frac{2}{2}}}}{\sqrt{2n}}\left[1 + \gamma\frac{H_4(x)}{24} + \xi\frac{H_6(x)}{720} + \gamma^2\frac{H_8(x)}{1152} + \cdots\right].$$

An interesting observation is that among all symmetric distributions used in metrology, the sum of sinusoids with a random phase demonstrates the slowest convergence to the normal law.

This mathematical model has significant practical value for assessing the accuracy of measurement systems and predicting errors in complex simulation systems (Table 1). Let's consider the practical aspect of approximating distribution functions (Fig. 1) using the example of the sum of three sinusoids of equal amplitude. Comparative analysis demonstrates the highest effectiveness of the proposed approximation approach in the following cases:

– normal distribution (basic approximation) - N;

– refined model with correction terms of order n^{-1} - P;

– trigonometric expansion of distribution functions – T [34].

Table 1. **Asymptotic expansion coefficients according to the distribution laws under consideration**

Coefficient	Distribution law		
	N	P	T
β_2	0,1507	1/3	1/2
β_4	0	-2/15	-3/8
β_6	0	16/63	5/4
γ	0	-1,2	-1,5
ξ	0	6,86	10

Source: **compiled by the authors**

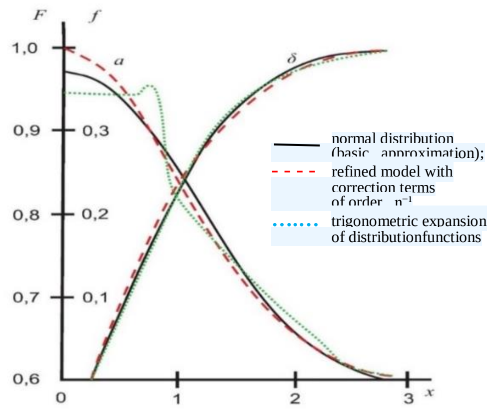

Fig. 1. **Approximation of the curves of the considered distribution laws by asymptotic expansion**
Source: **compiled by the authors**

It is interesting to note that adding the next two terms of the asymptotic expansion practically does not affect the accuracy of the approximation, indicating that the first approximation is sufficient for most practical applications.

A key step in the analysis is determining the confidence intervals of the error. Due to the symmetry of the distribution function, the problem is simplified to finding a single bound (for example, the upper bound) by solving the following equation:

$$F(x)\text{-}0{,}5(1+P) = 0. \quad (4)$$

For the effective solution of equation (4), it is proposed to use the second-order Chebyshev method, which provides rapid convergence through the iterative formula:

$$t^{[j+1]} = t^{[j]} - \frac{F(t^j)-0.5(1+P)}{f(t^j)}\left\{1 + 0.5\frac{f'(t^{[j]})[F(t^j)-0.5(1+P)]}{f^2(t^{[j]})}\right\}, \quad (5)$$

where t[j], t[j+1] represent successive approximations to the value of the root of equation (4).

The efficiency of the iterative process increases significantly with the optimal choice of the initial approximation. The innovative approach involves using the root of the simplified equation Φ(x) - 0.5(1 + P) = 0 as the initial approximation t[0]. For the most common confidence probabilities P = 0.99 and P = 0.95, the roots are 2.5758 and 1.9600, respectively.

The expanded representation of the root after the first iteration can be written as:

$$t^{[j]} = t^{[0]} + \frac{\gamma}{24}H_3\left(t^{[0]}\right) + \frac{\xi}{720}H_5(t^{[0]}) - \frac{\gamma^2}{128}G(t^{[0]}), \quad (6)$$

where $G(t) = H_5(t) + 2H_3(t) + \frac{2}{3}H_j(t) = t^5 - 8t^3 + 9\frac{2}{3}t.$

The structure of this expression reveals the general procedure for obtaining approximations:

– the basic approximation (normal law);
– asymptotic correction of order n^{-1};
– corrections of order n^{-2} (the last two terms).

The structure of this expression reveals the general procedure for obtaining approximations:

– the basic approximation (normal law);
– asymptotic correction of order n^{-1};
– corrections of order n^{-2} (the last two terms).

It is especially important to understand the factors that affect the accuracy of approximation:

– the number of error components;
– the types of component distributions;
– the ratio of error magnitudes.

An interesting fact is that the presence of even one normally distributed component significantly improves the approximation to a normal distribution by reducing the kurtosis coefficient.

For practical application, equation (6) is particularly useful in its simplified form, limited to the first two terms:

$$t = t^{[0]} + \frac{\gamma H_3\left(t^{[0]}\right)}{24}. \quad (7)$$

In asymptotic accuracy assessment in the analysis of confidence intervals during the evaluation of measuring systems' accuracy, particular attention is drawn to the estimation of calculation errors of confidence intervals (4). Let's consider an innovative approach to this problem.

A key element of the methodology is the asymptotic accuracy assessment, which consists of two components: the approximation error of the distribution (caused by the limitation in the number of series terms) and the error of the numerical solution of the basic equation.

Mathematically, this is expressed through the sum of the third and fourth terms of the expansion (6) in the series, which gives us a comprehensive assessment of the accuracy of the calculations (7).

Of particular interest is the proportionality coefficient t, which links the confidence estimate with the root mean square error of the mistake.

This coefficient has a nonlinear nature and depends on several key parameters:

– confidence probability (P);
– distribution shape coefficients (γ, ξ);
– additional distribution characteristics.

Mathematically, this can be represented as a functional dependence: t = t(P, γ, ξ, ...)

The practical significance of approach (7) is especially evident when calculating confidence intervals with high probability (for example, P=0.99), which is often required in high-precision systems.

$$t_{0.99} = 2.576 + 0.390\gamma. \quad (8)$$

with asymptotic error:

$$\Delta t_{0.99} = -0.0262\xi - 0.0123\gamma^2. \quad (9)$$

For P=0.95:

$$t_{0.95} = 1.960 + 0.069\gamma. \quad (10)$$

with asymptotic error:

$$\Delta t_{0.95} = -0.024\xi - 0.097\gamma^2. \quad (11)$$

The graphical analysis of the dependence of the t coefficient on the kurtosis coefficient (Fig. 2) reveals important patterns in the behaviour of confidence intervals.

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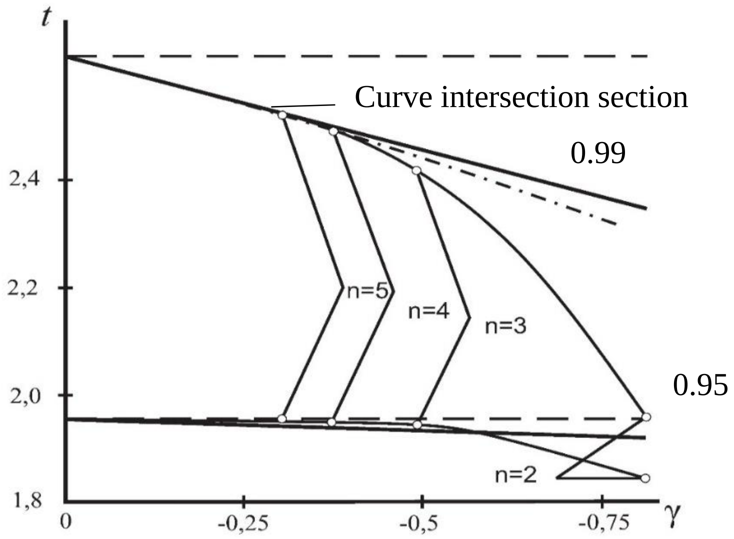

Fig. 2. **Dependence of the coefficient t on the kurtosis coefficient γ for different degrees n of the model in the class of symmetric error distribution laws of modelling across the tolerance field**
Source: **compiled by the authors**

Let us consider the key aspects of the study in comparison with the results presented in well-known works for specific physical processes [35]:

– normal distribution (dashed curves);

– approximate formulas (8) and (10) (solid curves);

– refined calculations with corrections (9) and (11) (dash-dotted curves).

Features for different confidence levels:

– P = 0.99: a marked dependence on the number of components, which has not been previously studied and requires further research;

– P = 0.95: almost complete coincidence of the curves.

For the case of identically distributed sinusoidal components: $\gamma = -1.5n^{-1}$, $\xi = 10n^{-2}$, $\Delta t_{0.99} = 0.29n^{-2}$.

Practical recommendations for the accuracy of calculations for sinusoidal components:

– optimal approximation accuracy with the number of terms in the approximation series is achieved when $n \geq 4$ (approximation error 0.8%);

– acceptable approximation accuracy with the number of terms in the approximation series is achieved when $n \geq 3$ (approximation error 1.5 %).

Sufficient accuracy (with an error of 1-2 %) in calculations for uniform distributions: $\gamma = -1.2n^{-1}$; $\xi = 6.86n^{-2}$, is achieved with an approximation of the distribution $n \geq 2$.

Important constraints on the kurtosis coefficient are: $|\gamma| \leq 0.5$ at P = 0.99.

The features of determining numerical values of errors include the indeterminate behaviour of calculated values at P = 0.95:

– weak dependence on the type of distribution;

– high accuracy even with a small number of components.

Practical recommendations for determining modelling error when approximating distributions:

– for P = 0.95, corrections for deviations from the normal distribution may not be applied when $n \geq 2$;

– the tested calculation procedure for 3 cases of specific symmetric distributions can be applied in future work to any case of a symmetric modelling error distribution. This is what achieves the universality of the tested procedure for calculating error;

–the accuracy of calculations is controllable and predictable by assigning a confidence interval.

RESEARCH RESULTS AND THEIR VERIFICATION

As a result of the scientific research, theoretical and practical results were obtained. The theoretical component includes the development of a mathematical framework for calculating the total random error based on the asymptotic properties of a sequence of random variables, simplifying formulas for calculating confidence intervals at different probability levels (0.95 and 0.99), and it was established that for symmetric distributions, the series contains only whole powers of n, which provides higher convergence. The practical result is the development of a methodology for summing errors with different distribution laws (normal, uniform, arcsine), simple formulas for machine calculations have been derived while maintaining sufficient accuracy of results, and the conditions for the applicability of the methodology have been determined: for a confidence probability of 0.99, the absolute value of the excess coefficient should not exceed 0.5.

The calculations show:

– for a uniform distribution, acceptable accuracy is achieved with at least two components;

– for a sinusoidal distribution, at least three components are needed to achieve an error of less than 1.5 %;

– at a confidence level of 0.95, sufficient accuracy is already achieved with two components without the need for additional corrections.

The proposed procedure for assessing error values can be applied to both random and systematic errors that arise in simulation modelling systems. The key innovation lies in the use of asymptotic properties of sequences of random variables, which differs from traditional approaches. This method is particularly valuable for metrological applications, where the distribution functions Fj(x) exhibit characteristic moments of the k-th order.

Prospects for the development of the proposed approach:

– further research to extend the results to other types of symmetric distributions;

– development of simplified computational algorithms.

The verification of the reliability of the obtained results was carried out for two cases of research results. In the first case, the results of studies on the accuracy of modelling with the representation of numbers in the binary-hexadecimal system were used, representing them as arrays. In the second case, the input data for calculating the errors of solving linear GPU NVIDIA problems using floating-point numerical values were used. Tabular reference data from the Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine, developed to verify the performance of computer models of genetic algorithms of the group argument evaluation method, were used as input data to establish the functionality of the method.

Table 2 presents the results of the calculations of polynomial coefficients using the results of works [24], [25], [36] and using the error estimation of calculations by the proposed method. Work [36] is dedicated to determining the performance of LU factorization in GFlop/s for different types of processors, providing numerical values in single (real) and double precision formats. An additional result of the research is the obtaining of numerical coefficients of polynomials for systems of algebraic equations.

The convergence of the numerical values of polynomial coefficients in known studies, under the condition of representing numbers in various formats and evaluating calculation errors using the proposed methodology, confirms the effectiveness of the developed method.

The conducted study demonstrates a comprehensive approach to addressing the problem of calculating the total random error, which has both theoretical and practical significance. The theoretical significance of the work lies in the development of a mathematical framework based on the asymptotic properties of a sequence of random variables. An important achievement is the establishment that for symmetric distribution laws, the series contains only integer powers of n, which ensures better convergence and simplifies calculations. The obtained simplified formulas for calculating confidence intervals at probability levels of 0.95 and 0.99 make the methodology accessible for practical application.

The practical value of the results is confirmed by the development of a methodology for summing errors with different distribution laws. It is particularly important that the created simple formulas for engineering calculations maintain sufficient accuracy of the results. Established quantitative accuracy indicators provide clear criteria for the applicability of the methodology: for a uniform distribution law, two components are sufficient, for a sinusoidal distribution – three components are needed to achieve acceptable accuracy.

Table 2. **Summary of the calculations of polynomial coefficients in known studies and using the error estimation of calculations proposed by the method with a 0.95 confidence interval**

Dimensionality of the system of simulation modelling equations	Presentation of numerical values			
	real	double	array	unum тип II
	Calculated modelling error value using different methods			
1920	0.42502	0.41311	0.34183	0.33643
3072	0.38071	0.36183	0.31264	0.33041

Source: **compiled by the authors**

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The universality of the developed approach is confirmed by its applicability both to random and systematic errors in mass production, as well as its potential extension to other types of symmetric distributions. An important limitation of the method is the requirement regarding the kurtosis coefficient, which, at a confidence level of 0.99, should not exceed 0.5 in absolute value.

The obtained results provide a basis for the further development of measurement error assessment methods and can be used in the development of new measuring systems and instruments.

CONCLUSIONS AND PRACTICAL SIGNIFICANCE OF THE STUDY

Computer modeling is considered in the work as an indirect measurement for evaluating the value of any physical quantity, where a measurement error accordingly exists. The error is present in computer calculations even without studying the entire set of deterministic or stochastic factors, the combined effects of which ultimately form the value of the error. The method of calculation or a specific type of dependence and how this dependence was obtained are not important. For the work being proposed, what matters is the error that the simulation system introduces into the calculations when the exact and ideal model, developed and studied by mathematicians, is handed over to programmers. During programming, there are limitations on implementing ideal models when even the number representation system cannot reflect all numerical values of an infinite and continuous series of numbers.

To address the defined problem, the authors combined well-known elements of analytical statistics – asymptotic expansions, Gram-Charlier series, moments, and semi-invariants – in the form of a formal methodology for calculating the total random error. The work was carried out to assess the calculation errors in any computer simulation systems without relying on a specific type of model dependence underlying the simulation system.

The procedure for calculating modelling error proposed in the article has been tested for three specific cases of symmetric distributions and can be extended in future work to any case of a symmetric distribution of modelling error. This is precisely what achieves the universality of the tested calculation procedure for error.

Based on the conducted research, a universal method for calculating the total random error for computer simulation systems has been developed, which is based on the asymptotic properties of a sequence of random variables. The theoretical achievements include the development of a mathematical framework for predicting the confidence estimate of random errors, the creation of simplified formulas for calculating confidence intervals at probability levels of 0.95 and 0.99, and establishing that for symmetric distribution laws, the series contains only integer powers of n, which ensures better convergence and optimizes calculations in computerized systems.

The practical testing of the proposed procedure for determining the error demonstrates the effectiveness of the method for various distribution laws (normal, uniform, arcsine) with clear application criteria: for the uniform distribution, two components are sufficient; for the sinusoidal distribution, three components are needed (error less than 1.5 %); at a confidence probability of 0.95, two components are sufficient without additional adjustments. The methodology is universal for computer simulation systems and can be used for both random and systematic errors, providing controlled and predictable computational accuracy while maintaining ease of practical application.

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Аналіз сумарної випадкової похибки в системах імітаційного моделювання

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АНОТАЦІЯ

У статті представлено аналітичну оцінку похибки в комп'ютерних системах імітаційного моделювання для випадків невідомого довільного виду симетричних розподілів сумарної випадкової похибки розрахунків. Дослідження базується на використанні асимптотичних властивостей послідовності випадкових величин. Робота включає створення математичного апарату для прогнозування довірчої оцінки випадкової похибки. Запропоновано інноваційний підхід до вибору початкового наближення. Запропонований підхід підвищує ефективність ітераційного процесу розрахунків похибки. Встановлено, що для будь-якого виду симетричних законів розподілу ряд містить лише цілі степені n. Використання встановленої закономірності забезпечує кращу збіжність і оптимізує обчислення чисельного значення похибки моделювання. Створено спрощені формули для обчислення довірчих інтервалів при високих рівнях ймовірності. Визначено умови застосовності методики. Експериментально підтверджено, що для рівномірного закону розподілу прийнятна точність досягається при наявності не менше двох складових. В той час для синусоїдального закону необхідно не менше трьох складових для досягнення похибки менше прийнятного значення похибки. Для високих значень достовірності моделювання необхідна точність досягається при двох складових без необхідності введення додаткових поправок. Апробація отриманих результатів здійснено для двох випадків вихідних даних. В першому випадку використано результати досліджень точності моделювання з представлення чисел в двійково-шістнадцятирічної системі обчислення їх подання в вигляді масивів. В другому випадку використано вихідні дані розрахунків похибок розв’язку задач лінійної GPU NVIDIA з поданням чисельних значень з плаваючою комою. Методика універсальна та може бути застосована як для випадкових, так і для систематичних похибок, що виникають в системах імітаційного моделювання.

Ключові слова: імітаційне моделювання, прогнозування, машинне навчання, інформаційні технології, високоточні обчислення, представлення з плаваючою комою, підсумування випадкової похибки, похибки моделювання, підвищення точності систем імітаційного моделювання, різнорозмірні данні, комп’ютерні системи, представлення чисел в вигляді масивів

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