ISSN 2522-9818 (print)
Сучасний стан наукових досліджень та технологій в промисловості. 2022. № 1 (19) ISSN 2524-2296 (online)

UDC 621.396 DOI: https://doi.org/10.30837/ITSSI.2022.19.085

A. ZUEV, A. IVASHKO, D. LUNIN

ESTIMATION OF SOFTWARE COMPLEXITY OF CALCULATION OF AUTOREGRESSION COEFFICIENTS AT DIGITAL SPECTRAL ANALYSIS

The **subject** of research in the article are algorithms for fast calculation of autoregression coefficients in digital spectral analysis and estimation of the number of arithmetic operations required for their implementation. The **aim** of the article – comparative analysis of the speed of different algorithms for calculating the coefficients of autoregression as part of the algorithms of spectral analysis, including analysis of the complexity of their microcontroller implementation. **Tasks** to be solved: selection of spectral analysis methods suitable for diagnostics of technological equipment, analysis of methods for calculating autoregression coefficients and derivation of relations for estimating software complexity of algorithms and calculation of numerical estimates of addition and multiplication for some algorithms, adaptation of developed methods and estimates to microcontrollers. spectrum Applied **methods**: algorithm theory, Fourier transform, natural series, microcontroller programming. The **results** obtained: it is shown that spectral estimation methods based on Yul-Walker equations, which require the calculation of autoaggression coefficients, combine sufficient resolution and resistance to interference with acceptable implementation complexity. Estimates of the number of additions and multiplications for the Levinson, Durbin, and Trench algorithms are obtained, and their comparative analysis is performed. The calculation times for microcontroller arithmetic with fixed and floating points were count upon. **Conclusions**: When constructing spectrum analyzers for the diagnosis of technological equipment, it is advisable to use the Yul-Walker method. A comparison of Levinson, Durbin, and Trench algorithms for calculating autoregression coefficients showed that the Trench method requires a minimum number of additions, and the Durbin method requires a minimum number of multiplications. At microcontroller realization of spectrum analyzers, it is necessary to consider features of the arithmetic used by the controller. The Trench method is the fastest in the case of floating-point arithmetic and small-scale modeling. In other cases, Durbin's method is more effective.

Keywords: spectral analysis; autoregression; Levinson; Durbin; Trench algorithms; computational complexity; computer arithmetic; microcontrollers.

Introduction

Monitoring of spectra of mechanical oscillations and signals of energy objects is widely used in solving some problems in the fields of technical and medical diagnostics. By analyzing the amplitudes and locations of the spectral density peaks, we can conclude about the state of the object under study. In particular, changes in the pattern of mechanical vibrations caused by malfunctions of mechanical systems, including turbines and generators, can be quickly detected. On the other hand, the analysis of the spectrum of energy signals allows to assess the quality of electricity and take measures to improve it.

There are a number of spectral estimation algorithms that differ in resolution, resistance to interference, complexity of software and hardware implementation. At the same time, the development of microprocessor technology has made it possible to create portable devices with built-in microcontrollers that provide operational spectral analysis of technical objects in real time. The spectral analysis algorithms used in such devices must ensure acceptable separation and suppression of noise and at the same time a minimum number of addition and multiplication operations.

Sufficient accuracy in combination with acceptable computational complexity is provided by spectral analysis algorithms based on parametric models, in particular Berg's algorithm, covariance algorithm, MUSIC method. The most widespread due to the combination of satisfactory technical characteristics and ease of implementation was the method of Yul-Walker [1]. Its practical application, however, is somewhat complicated by the lack of estimates of the number of computational operations that may be required for a reasonable choice of a microcontroller. Therefore, it is important to obtain the relations that determine the computational complexity of both the algorithm for spectral estimation in general and its individual components.

Review of existing methods of spectral analysis and estimates of their labor content

Automated diagnostic systems for technological equipment are increasingly used in the creation of the industrial Internet of Things and eventually in the construction of "smart industries". Rhythmic work of modern automated industries is impossible without timely detection and replacement of failed elements. At the same time, the development of modern computer equipment allows the use of complex but effective diagnostic algorithms.

Thus, [1] solves the problem of classification of aircraft engine operating modes based on neural network technologies in real time, and selects the most efficient network architecture. In the article [2] to solve this problem uses the apparatus of fuzzy sets. In this case, the proposed logical inference mechanism eliminates the use of the product rule base, which ensures the practical independence of the computational procedure from the size of the problem. A feature of the methods used in [1, 2] is the use of complex computational algorithms that require significant computing power.

Many papers recommend the use of digital signal processing in technical diagnostic tasks, including analysis of frequency characteristics. Thus, in [3] a method of increasing the stability of estimates of parameters of energy systems, including spectral characteristics, is proposed. However, the main attention in the article is paid to modifications of algorithms for calculation of autocorrelation functions, while methods of calculation of

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ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2022. No. 1 (19)

autoregression coefficients and estimation of their complexity are practically not considered.

Similar issues are studied in [4, 5], where the stability of energy systems is analyzed by monitoring electromechanical oscillations. As diagnostic information in the work it is offered to consider frequencies and attenuation coefficients of the main harmonics of energy signals. The efficiency of the multi-channel Yule-Walker estimation of a multidimensional autoregressive model for determining the parameters of power systems is investigated, and in [4] the model is introduced, and in [5] its decomposition by eigenvectors is considered. Unfortunately, the methods proposed in the works require a significant amount of calculations and are unsuitable for use at local measuring instruments.

Algorithms for solving systems of linear equations with Hankel matrices [6] and Toeplitz [7], which arise in spectral analysis problems, are considered in [6, 7], however, the methods proposed in these works are not always suitable for solving Yul-Walker equation systems. The Levinson-Durbin algorithm for studying autoregression processes is used in [8]. The authors modified the algorithm, providing on the one hand its recursive execution, on the other - the ability to calculate derivatives and the Hesse matrix. However, there is no comparison of the Levinson-Durbin algorithm with other algorithms, in particular, the Trench algorithm.

Issues of speed of spectral analysis algorithms are considered in [9, 10]. The main idea of the article [9] is to estimate the spectral peaks by the method of maximum likelihood. The method developed by the authors significantly reduces the computational complexity of spectral estimation, providing sufficient resolution. In [10], it is proposed to estimate the frequency spectrum by interpolating the discrete Fourier transform coefficients, which allows to detect spectral peaks and adjacent frequencies. In this case, the performance estimates given in [9, 10] are not tied to a specific technical base, which complicates the design of spectrum analyzers.

A number of works consider the possibility of using a modern element base for signal processing. Thus, in [11] the implementation of the method of measuring the parameters of signals and paths on FPGA with increasing the accuracy of optimal information processing is considered, but the work does not provide data on the speed of the proposed technical solutions. The microcontroller implementation of spectrum analyzers is considered in [12, 13].

The aim of the article is a comparative analysis of the speed of different algorithms for calculating the autoregression coefficients as part of the algorithms of spectral analysis, including the microcontroller implementation of some algorithms.

Theoretical analysis of autoregressive algorithms

A group of spectral analysis algorithms based on signal representation as a result of white noise passing through a digital filter has become widespread. In this case, the spectrum *X(ω)* coincides with the frequency response of the filter *H(ω)* up to a constant multiplier. Then, restoring the structure and coefficients of the filter, you can calculate its frequency response and the spectrum of the signal *X(ω)*. If the supposed filter has HIX – the structure containing only the return branch, i.e. in its transfer characteristic there are only poles

$$H(z)=\frac{1}{1-b_1\cdot z^{-1}-b_2\cdot z^{-2}-...-b_{M-1}\cdot z^{-(M-1)}-b_M\cdot z^{-M}},\quad (1)$$

where M is a model order,

b_i – filter coefficients (autoregression coefficients),

then there is an autoregression model (AR model). Determining the spectrum estimate in the case of using the autoregression model occurs in three stages:

1. Calculation of estimates of autocorrelation functions (ACF),

$$R(k)=\frac{1}{N}\sum_{i=0}^{N-1}x_i\cdot x_{i+k}\ ,\quad (2)$$

where x_i - samples of the discrete signal, N is the number of samples, $R(k)$ is the ACF value.

2. Compilation and solution of the so-called Yul-Walker equations

$$\begin{bmatrix} R(0) & R(-1) & \dots & R(-M) \\ R(1) & R(-0) & \dots & R(-M+1) \\ \dots & \dots & \dots & \dots \\ R(M-1) & R(M-2) & \dots & R(1) \\ R(M) & R(M-1) & \dots & R(0) \end{bmatrix}\cdot\begin{bmatrix} 1 \\ -b_1 \\ \dots \\ -b_{M-1} \\ -b_M \end{bmatrix}=\begin{bmatrix} D_\varepsilon \\ 0 \\ \dots \\ 0 \\ 0 \end{bmatrix},\quad (3)$$

where M is a model order,

b_i – filter coefficients (autoregression coefficients) in (1),

D_ε – noise dispersion.

3. Calculation of power spectral density S(ω),

$$S(\omega)=\frac{D_\varepsilon}{\left(1-\sum_{k=1}^{M}b_k\cos(\omega k)\right)^2+\left(\sum_{k=1}^{M}b_k\sin(\omega k)\right)^2},\quad (4)$$

and the amplitude spectrum X(ω)= $\sqrt{S(\omega)}$,

where *ω* is the dimensionless cyclic frequency,

$S(\omega)$ is the spectral power density,

$X(\omega)$ is the amplitude spectrum.

The most labor content stage of calculations is the solution of the system of Yul-Walker equations (3). The application of the traditional Gaussian method requires approximately $\frac{M^3}{3}+\frac{3}{2}M^2-\frac{5}{6}M$ arithmetic operations. However, it should be borne in mind that the matrices of coefficients of systems of linear equations have a special form - they have all the elements located on any diagonal, identical, i.e. $a_{i,j}=a_{i+k,j+k}$. Such matrices are called greenhouse (named after the German mathematician O. Toeplitz), and a number of methods have been developed to solve systems with greenhouse matrices of coefficients

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Сучасний стан наукових досліджень та технологій в промисловості. 2022. № 1 (19) ISSN 2524-2296 (online)

– algorithms of Levinson, Durbin, Trench [14]. The use of such algorithms can significantly reduce the number of operations and the amount of memory when solving systems of linear equations and, thus, simplify the process of finding model coefficients and spectral estimates.

Calculation of the number of arithmetic operations

To solve the system of Yul-Walker equations using the Levinson algorithm, it is necessary to make (*M* – 1) iterations, where M is the order of the model. At each iteration, the scalar variables *α*, *β*, and *μ*, as well as the auxiliary vectors ν and *z*, are calculated. When calculating the scalar variable β by the formula

$$\beta_k = \beta_{k-1}(1-\alpha_{k-1}^2)$$

it is necessary to perform two multiplication operations and one addition operation. When calculating the scalar variable μ by the formula

$$\mu_k = \frac{b_{k+1} - r^T \cdot E_k x^*}{\beta_k}$$

k additions and *k* + 1 multiplications are performed, where k is the number of the current iteration. To find the vector by the formula

$$\upsilon = x + \mu y^*$$

it is necessary to perform *k* additions and *k* multiplications. To calculate the scalar variable α by the formula

$$\alpha_k = -\frac{r_{k+1} + r^{(k)T} \cdot y^*}{\beta_k}$$

k additions and *k* + 1 multiplications are spent, and finding the auxiliary vector z by the formula

$$z = y + \alpha y^*$$

k additions and *k* multiplications are performed. Summarizing all arithmetic operations, we obtain the number of additions and multiplications in the algorithm. For the first part of the algorithm, when k changes in the range 1: *M* – 1:

Number of additions $S_{k1} = 1 + k + k = 2k + 1$;

Number of multiplications $P_{k1} = 2 + k + 1 + k = 2k + 3$.

For the second part of the algorithm, when *k* = 1:*M* – 2:

$S_{k2} = k + k = 2k$;

$P_{k2} = k + 1 + k = 2k + 1$.

Calculate the total number of additions and multiplications for each of the stages, using the formula to calculate the sum of the arithmetic progression.

$$S_1 = \sum_{k=1}^{M-1} S_{k1} = \sum_{k=1}^{M-1}(2k+1) = M^2 - 1,$$

$$P_1 = \sum_{k=1}^{M-1} P_{k1} = \sum_{k=1}^{M-1}(2k+3) = M^2 + 2M - 3,$$

$$S_2 = \sum_{k=1}^{M-2} S_{k2} = \sum_{k=1}^{M-2} 2k = M^2 - 3M + 2,$$

$$P_2 = \sum_{k=1}^{M-2} P_{k2} = \sum_{k=1}^{M-2}(2k+1) = M^2 - 2M.$$

Combining these two sums, we finally get the number of additions:

$$S = S_1 + S_2 = 2M^2 - 3M + 1. \quad (5)$$

And the number of multiplications:

$$P = P_1 + P_2 = 2M^2 - 3. \quad (6)$$

When solving the system of Yul-Walker equations based on the Durbin algorithm at each step, the calculation of two scalar variables *α*, *β* and the auxiliary vector *z* is performed, which can be written by such recursive relations

$$\alpha_k = -\frac{r_{k+1} + r^{(k)T} \cdot y^*}{\beta_k},$$

where $\beta_k = \beta_{k-1}(1-\alpha_{k-1}^2)$.

The number of iterations of the main cycle in the algorithm is equal to *M* – 1. When calculating the scalar variable *β* it is necessary to perform two multiplication operations and one addition operation. When calculating the scalar variable *α*, *k* additions and *k* + 1 multiplications are performed, where *k* is the number of the current iteration. To calculate the auxiliary vector *z* by the formula:

$$z_i = y_i + \alpha y_{k+1-i}, \text{ where } i = 1:k.$$

k additions and *k* multiplications are performed (*k* is the number of the current iteration). Summarizing the arithmetic operations for one iteration, we obtain: the number of additions at each step $S_k = 1 + k + k = 2k + 1$; the number of multiplications $P_k = 2 + k + 1 + k = 2k + 3$.

Since k depends on the number of iterations, and the number of required iterations is *M* – 1, the total number of additions and multiplications is equal to:

$$S = \sum_{k=1}^{M-1} S_k = \sum_{k=1}^{M-1}(2k+1) = M^2 - 1, \quad (7)$$

$$P = \sum_{k=1}^{M-1} P_k = \sum_{k=1}^{M-1}(2k+3) = M^2 + 2M - 3. \quad (8)$$

To solve the system of Yul-Walker equations, using the Trench algorithm, the first step is to calculate the scalar variable *γ*, as well as the auxiliary vector ν by formulas:

$$\gamma = \frac{1}{1 + r^T y^*},$$

$$\nu = \gamma y^*.$$

Counting the number of transactions, we obtain:

Number of additions $S_1 = M - 1$;

ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2022. No. 1 (19)

Number of multiplications $P_1 = M + M - 1 = 2M - 1$.

In the second stage, a nested cycle is used, which calculates the matrix $B = T^{-1}$. The number of iterations of the inner cycle depends on the current step of iteration of the outer cycle and is equal to: for the outer cycle i = 2:((M – 1)/2 + 1), for the inner cycle j = i:(M – i + 1). When calculating the elements of the matrix B by the formula:

$$b_{i,j} = b_{n-j,n-i} + \frac{\upsilon_i \upsilon_j - \upsilon_{n-j}\upsilon_{n-i}}{\gamma}$$

it is necessary to perform two addition operations and three multiplication operations at each stage of the internal and external cycles. Thus, the number of additions and multiplications in the second stage will be equal:

$$S_2 = \sum_{k=2}^{\frac{M-1}{2}+1} \sum_{i=2}^{M-i+1} S_{k2} = \sum_{k=2}^{\frac{M-1}{2}+1} \sum_{i=2}^{M-i+1} 2 = 2 \cdot \sum_{k=2}^{\frac{M-1}{2}+1} (M - 2k + 2) = 2 \cdot \frac{M^2 - 2M + 1}{2} = M^2 - 2M + 1$$

$$P_2 = \sum_{k=2}^{\frac{M-1}{2}+1} \sum_{i=2}^{M-i+1} P_{k2} = \sum_{k=2}^{\frac{M-1}{2}+1} \sum_{i=2}^{M-i+1} 3 = 3 \cdot \sum_{k=2}^{\frac{M-1}{2}+1} (M - 2k + 2) = 3 \cdot \frac{M^2 - 2M + 1}{2} = \frac{3}{2} \cdot (M^2 - 2M + 1).$$

Combining the two sums, we finally get the number of additions and multiplications:

$$S = S_1 + S_2 = M - 1 + M^2 - 2M + 1 = M^2 - M\ ; \tag{9}$$

$$P = P_1 + P_2 = 2M - 1 + \frac{3}{2}(M^2 - 2M + 1) = \frac{3}{2}M^2 - M + \frac{1}{2}. \tag{10}$$

According to formulas (5-10), graphs of the dependences of the number of additions S and multiplications P required to solve the Yul-Walker equations on the order of the autoregression model M were constructed.

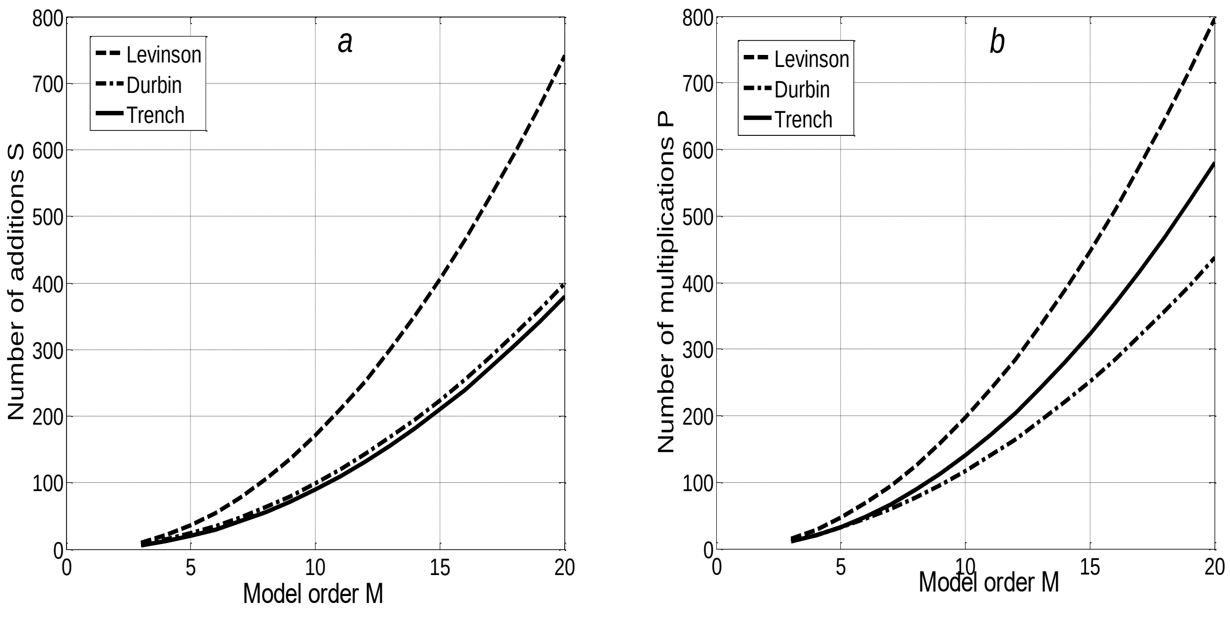

Fig 1. Dependence of the number of additions *(a)* and multiplications *(b)* on the order of the autoregression model

From the figures it is obvious that the number of additions is minimal for the Trench algorithm, the number of multiplications – for the Durbin algorithm. A more accurate comparison of the performance of algorithms can be performed taking into account the specific element base used.

Estimation of complexity of microcontroller realization of the solution of Yul-Walker equations

When creating portable spectrum analyzers for diagnostics of energy facilities and other technological equipment, it is advisable to use hardware and software based on microcontrollers [12, 13]. For a reasonable choice of parameters of the microprocessor spectrum analyzer can be useful to calculate the approximate time of solving Yule-Walker equations on a microcontroller base, taking into account the previously obtained relations (5-10) and information about the time of arithmetic operations, given, for example, in [15].

Thus, the Mega 2560 microcontroller requires 12 microseconds for 64-bit integer addition and 60 microseconds for integer multiplication. For floating-point arithmetic operations, 13 and 15 microseconds,

ISSN 2522-9818 (print)
Сучасний стан наукових досліджень та технологій в промисловості. 2022. № 1 (19) ISSN 2524-2296 (online)

respectively. As a result, the dependences of the time of solving the Yul-Walker equations on the order of the model were constructed (fig. 2). The obtained time characteristics are, of course, evaluative, as they do not take into account the delay and branching commands, but can be the basis for a reasoned choice of technical means.

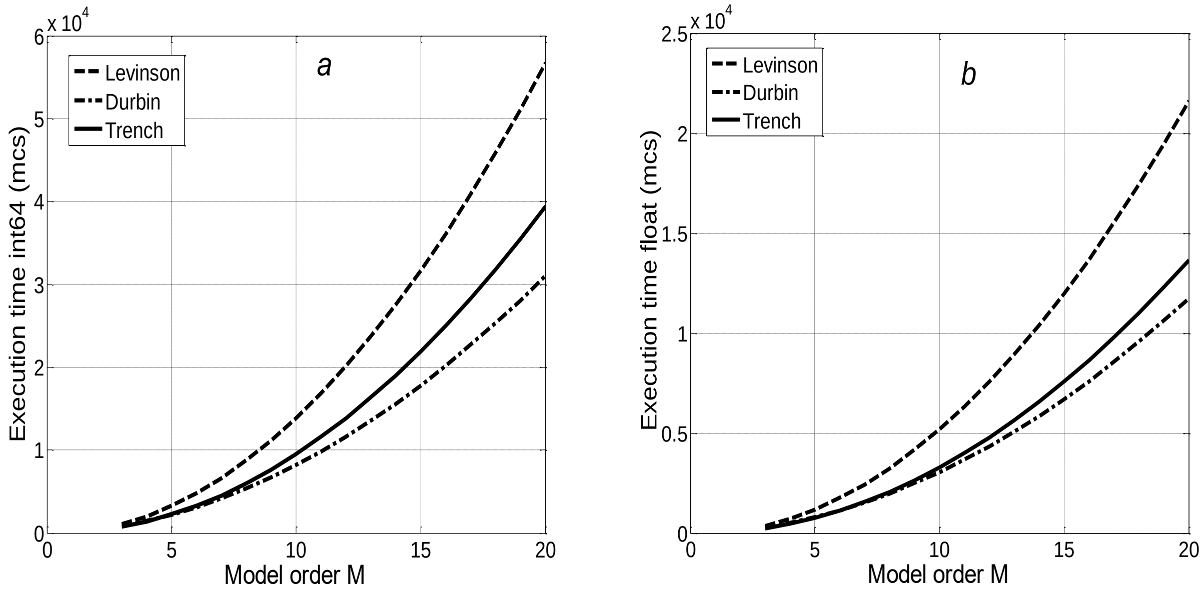

Fig. 2. Dependence of the time of solving the Yul-Walker equations on the model order (*a*-integer arithmetic, *b*-floating-point arithmetic)

It follows from the figures that the Durbin algorithm has the highest speed for fixed-point arithmetic. For floating-point arithmetic at small values of the model order ($M \leq 6$), the Trench algorithm is more efficient. Thus, for $M=5$ the calculation time according to the algorithm of the Trench algorithm is 755 µs, according to the Durbin algorithm - 792 µs. At values of $M > 6$ the performance of the Durbin algorithm is higher. Naturally, in the presence of data on the time of arithmetic operations, similar calculations can be performed on other platforms.

Conclusions

1. The spectral estimation method based on the Yul-Walker equations, which require the calculation of autoregression coefficients, combines sufficient resolution and noise immunity with acceptable implementation complexity.

2. Comparison of Levinson, Durbin and Trench algorithms for calculating autoregression coefficients showed that the Trench method requires a minimum number of additions, and the Durbin method – a minimum number of multiplications.

3. In the microcontroller implementation of spectrum analyzers should take into account the features of the arithmetic used by the controller. The Trench method is the fastest in the case of floating-point arithmetic and small-scale modeling. In other cases, Durbin's method is more effective.

4. In the future it would be actual to obtain estimates of the execution time of other components of spectral estimation algorithms – ACF calculation, solving Yul-Walker equations and Fourier transform calculation, which would allow a comprehensive assessment of software and hardware complexity of spectrum analyzers.

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Received 23.03.2022

Відомості про авторів / Сведения об авторах / About the Authors

Зуєв Андрій Олександрович – кандидат технічних наук, доцент, завідуючий кафедри автоматики та управління в технічних системах, Національний технічний університет "Харківський політехнічний інститут", вул. Кирпичова, 2, Харків, Україна; e-mail: dakarton@gmail.com; ORCID: http://orcid.org/0000-0001-8206-4304

Зуев Андрей Александрович – кандидат технических наук, доцент, заведующий кафедрой автоматики и управления в технических системах, Национальный технический университет "Харьковский политехнический институт", ул. Кирпичева, 2, Харьков, Украина.

Zuev Andrey – PhD, Associate Professor, Department of automation and control in technical systems, head of the department, National Technical University "Kharkiv Polytechnic Institute" Kyrpychova str., Kharkov, Ukraine.

Івашко Андрій Володимирович – кандидат технічних наук, доцент кафедри автоматики та управління в технічних системах, Національний технічний університет "Харківський політехнічний інститут", вул. Кирпичова, 2, Харків, Україна; e-mail: ivashkoauts@gmail.com; ORCID: https://orcid.org/0000-0002-4012-1697

Ивашко Андрей Владимирович – кандидат технических наук, доцент кафедры автоматики и управления в технических системах, Национальный технический университет "Харьковский политехнический институт", ул. Кирпичева, 2, Харьков, Украина.

Ivashko Andrey – PhD, Associate Professor, Department of automation and control in technical systems, National Technical University "Kharkiv Polytechnic Institute", Kyrpychova str., 2, Kharkov, Ukraine.

Лунін Денис Олександрович – старший викладач кафедри автоматики та управління в технічних системах, Національний технічний університет "Харківський політехнічний інститут", вул. Кирпичова, 2, м. Харків, Україна, 61002; e-mail: lunindenis77@gmail.com; ORCID: http://orcid.org/0000-0002-9418-0000

Лунин Денис Александрович – старший преподаватель кафедры автоматики и управления в технических системах, Национальный технический университет «Харьковский политехнический институт», ул. Кирпичева, 2, Харьков, Украина.

Lunin Denis – Senior Lecturer Department of Automation and Control in Technical Systems National Technical University «Kharkiv Polytechnic Institute», Kyrpychova str., 2, Kharkiv, Ukraine.

ОЦІНКА ПРОГРАМНОЇ СКЛАДНОСТІ ОБЧИСЛЕННЯ КОЕФІЦІЄНТІВ АВТОРЕГРЕСІЇ ПРИ ЦИФРОВОМУ СПЕКТРАЛЬНОМУ АНАЛІЗІ

Предметом дослідження у статті є алгоритми швидкого обчислення коефіцієнтів авторегресії при цифровому спектральному аналізі та оцінки кількості арифметичних операцій, необхідних для їх реалізації. **Мета** статті – порівняльний аналіз швидкодії різних алгоритмів обчислення коефіцієнтів авторегресії як складової частини алгоритмів спектрального аналізу, у тому числі аналіз складності їхньої мікроконтролерної реалізації. **Завдання**, що вирішуються: виділення методів спектрального аналізу, придатних для діагностики технологічного обладнання, аналіз методів обчислення коефіцієнтів авторегресії та виведення співвідношень для оцінювання програмної складності алгоритмів та розрахунок числових оцінок числа додавань та множень для деяких алгоритмів, адаптація розроблених методів та оцінок до мікроконтролерної реалізації аналізаторів спектру Застосовувані **методи**: теорія алгоритмів, перетворення Фур'є, натуральні ряди, програмування мікроконтролерів. Отримані **результати**: показано, що методи спектрального оцінювання на основі рівнянь Юла-Уолкера, що вимагають обчислення коефіцієнтів авторегресії, поєднує достатню роздільну здатність і стійкість до перешкод з прийнятною складністю реалізації. Отримано оцінки числа додавань та множень для алгоритмів Левінсона, Дурбіна та Тренча, виконано їх порівняльний аналіз. Розраховані часи обчислення для мікроконтролерної арифметики з фіксованою та плаваючою точкою. **Висновки**: При побудові аналізаторів спектра для діагностики технологічного обладнання доцільно застосовувати метод Юла-Уолкера. Порівняння алгоритмів Левінсона, Дурбіна та Тренча для обчислення коефіцієнтів авторегресії показало, що метод Тренча потребує мінімальної кількості додавань, а метод Дурбіна – мінімальної кількості множень. При мікроконтролерній реалізації аналізаторів спектра слід враховувати особливості використовуваної контролером арифметики. Метод Тренча є найбільш швидкодіючим у разі застосування арифметики з плаваючою точкою та невеликого порядку моделі. В інших випадках ефективніший метод Дурбіна.

Ключові слова: спектральний аналіз; авторегресія; алгоритми Левінсона; Дурбіна; Тренча; обчислювальна складність; комп'ютерна арифметика; мікроконтролери.

ОЦЕНКА ПРОГРАММНОЙ СЛОЖНОСТИ ВЫЧИСЛЕНИЯ КОЭФФИЦИЕНТОВ АВТОРЕГРЕССИИ ПРИ ЦИФРОВОМ СПЕКТРАЛЬНОМ АНАЛИЗЕ

Предметом исследования в статье являются алгоритмы быстрого вычисления коэффициентов авторегрессии при цифровом спектральном анализе и оценки числа арифметических операций, необходимых для их выполнения. **Цель** статьи - сравнительный анализ быстродействия различных алгоритмов вычисления коэффициентов авторегрессии как составной части алгоритмов спектрального анализа, в том числе анализ сложности их микроконтроллерной реализации. Решаемые **задачи**: выделение методов спектрального анализа, пригодных для диагностики технологического оборудования, вывод соотношений для оценивания программной сложности алгоритмов и расчет числовых оценок вычислительной сложности, адаптация разработанных методов и оценок к микроконтроллерной реализации анализаторов спектра. Применяемые **методы**: теория алгоритмов, преобразование Фурье, линейная алгебра, натуральные ряды, программирование микроконтроллеров. Полученные **результаты**: показано, что метод спектрального оценивания на основе уравнений Юла-Уолкера, требующих вычисления коэффициентов авторегрессии, сочетает достаточную разрешающую способность и помехоустойчивость с приемлемой сложностью реализации. Получены оценки числа сложений и умножений для алгоритмов Левинсона, Дурбина и Тренча и выполнен их сравнительный анализ. Рассчитаны времена вычисления для микроконтроллерной арифметики с фиксированной и плавающей запятой. **Выводы**: сравнение алгоритмов Левинсона, Дурбина и Тренча для вычисления коэффициентов авторегресси показало, что метод Тренча требует минимального количества сложений, а метод Дурбина – минимального количества умножений. При микроконтроллерной реализации анализаторов спектра следует учитывать особенности используемой контроллером арифметики. Метод Тренча является наиболее быстродействующим в случае применения арифметики с плавающей точкой и небольшого порядка модели. В остальных случаях более эффективен метод Дурбина.

Ключевые слова: спектральный анализ; авторегрессия; алгоритмы Левинсона; Дурбина; Тренча; вычислительная сложность; компьютерная арифметика; микроконтроллеры.

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