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Identification of parameters of measuring modules based on pyroelectric materials

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Abstract

This paper addresses the topical issues in using pyrodetectors within measurement modules of modern monitoring systems. A major issue is the optimal selection of detectors, hindered by incomplete or missing parameter specifications in technical documentation, limiting effective mathematical modelling. The study proposes a method to identify critical pyrodetector parameters – thermal τ_T and electrical τ_E time constants – using experimental data from their key characteristics. It is demonstrated that these parameters can be determined by approximating experimental dependencies in both frequency (amplitude responses) and time domains (transient responses). The experimental setup and procedure for recording pyroresponses to step changes in IR radiation are detailed. Approximation of transient responses using a dual time-constant model enables precise parameter estimation. Validation involves comparing model calculations with experimental measurements across commercial IR pyrodetectors, revealing response durations from 30 s to 7 min. The challenge of distinguishing τ_T from τ_E via approximation is discussed. The method improves metrological support for pyroelectric measurements and can be used to select detectors and design complex pyroelectric systems.

Keywords: pyroelectric detectors; pyroelectric modules; amplitude-frequency response; transient response; transient process.

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Introduction

Modern pyrodetectors and pyroelectric modules based on them have found wide application in various fields of human activity [1]. The noticeable interest in primary converters based on pyroelectric materials is confirmed by the studies described in numerous scientific papers published annually on this topic. According to the estimates made for the period from 2000 to 2024, there are more than 500 such papers. Accordingly, there is a wide range of requirements for the characteristics of pyroelectric detectors due to their functional purpose [2–4] and operating conditions. The choice of primary pyroelectric transducers when used as part of a control or measuring module is usually determined by certain optimization criteria. At the same time, all existing methods used to select a pyroelectric detector for a particular implementation are confined to rational or optimal approaches. The rational approach accounts for expert estimates, while the optimization approach is based on the use of a mathematical model of the detector, which allows predicting its characteristics that are most critical for its specialized application. Unfortunately, to address this problem in practice, in many cases, the rational approach is used, since for commercial pyroelectric detectors, for some reason, many of their critical parameters remain unknown, which makes it impossible to use their mathematical descriptions that include these parameters. The construction of adequate models of any primary transducers is crucial not only to optimise the design of detector structures and subsequently develop them, but also to determine their metrological characteristics [5, 6]. Finding the parameters of pyroelectric generators from approximation dependences of their experimentally available characteristics is used as an alternative to costly physical measurements of the relevant problematic parameters [7, 8]. Thus, in one of the recent works [9], an approximation of the amplitude-frequency characteristic of a pyroelectric generator was used to find its thermal and electrical time constants, which made it possible to further calculate the response to a single radiation pulse, which is crucial for the appropriate application of such a pyroelectric generator. However, the identification of pyroelectric detector parameters can be performed using the approximation of not only frequency characteristics, but also of time characteristics, which is essential, for example, for detectors used in pyroelectric modules without modulators, and which respond exclusively to a step change in the radiation flux. For such applications of pyroelectric detectors, their transient characteristics are most significant. The implementation of this approach is associated with the approximation of dynamic processes.

This study was carried out to facilitate the solution of urgent scientific and practical problems related to the identification of primary pyroelectric transducers and their characteristics.

The purpose of this study is to develop metrological support for pyroelectric measurements by improving the method that allows finding the hard-to-measure parameters of pyroelectric detectors. The method also makes it possible to obtain technical and metrological characteristics of a wide range of modules based on pyroelectric converters. This will make it possible to evaluate the characteristics and make an optimal choice of pyroelectric detectors for measuring equipment and information and measurement systems.

In recent years, pyroelectric detectors have been increasingly used as measuring modules in various monitoring systems, including environmental monitoring systems. The interest in pyroelectric detectors in this area is primarily because many modules and devices are based on them and can monitor and/or measure critical environmental parameters, such as temperature, presence and concentration of various gases, the presence of radiation of the corresponding ranges, the occurrence of fires in forests for remote detection and prevention of forest fires, etc.

The pyroelectric properties of polar dielectrics are a consequence of the peculiarities of their crystal structure, as well as the presence of ionic and polarization types of bonds between positively and negatively charged ions that form an elementary crystal unit cell. The presence of a polarization component of the bond between cations shifts them from charge-neutral positions, which leads to spontaneous polarization on the crystal surface perpendicular to the polar axis. According to the zone theory, the displacement of cations from their charge-neutral positions indicates that they are in an asymmetric potential well. When the temperature rises under the influence of absorbed radiation or in the case of a rapid increase in ambient temperature, the thermal vibrations of all ions increase and cations shift towards charge-neutral positions. This leads to a change in charges on the crystal surface, which is the pyroelectric effect. Thus, this effect is manifested only when the temperature changes and is characterized by a pyroelectric coefficient equal to the ratio of the charge change to the temperature change.

Their most common use is in the infrared (IR) range. The first IR pyroelectric detectors were developed in the 30s of the 20^{th} century [10]. Currently, pyroelectric converters occupy more than 10% of the infrared detector market, which exceeds 50 million US dollars per year [11]. Demand for pyroelectric detectors continues to grow in a variety of areas. In most cases, pyroelectric cells are used as control sensors. But they are also used as primary measuring transducers, providing high metrological characteristics. Common examples of their use in this capacity are infrared spectrometers, laser energy meters and power meters of peak power of pulsed microwave radiation, gas analysers, thermal imagers, etc [12—14]. A wide range of requirements for the characteristics and operating conditions of even only the listed implementations, as well as the further expansion of the application areas of transducers based on the pyroelectric effect in the measuring modules of monitoring systems, renders the task of critical assessment of the current state of the study of both their characteristics in general and of pyroelectric materials used for their manufacture, in particular, urgent. Each individual application area requires the use of transducers with optimal characteristics.

In this case, the primary pyroelectric converter (PEC) shall be understood as a sensitive element that is included in the electrical matching circuit and the means of its matching with the environment or radiation transmission channel. In turn, a measuring module shall be understood as a structurally complete product, which, in addition to the PEC, includes the means of its integration into the measuring equipment or data acquisition network (for example, a radiation source, ADC, data processing, storage, transmission devices, etc.).

Study of the characteristics of pyroelectric detectors and modules based on them

Estimates to determine the characteristics of pyroelectric detectors for various purposes and operating conditions and the optimal characteristics of pyromaterials for them are possible only based on building mathematical models of the corresponding implementations of primary pyroelectric converters. Usually, a mathematical model of a PEC is used, which consists of a mathematical description using linear differential equations and a corresponding equivalent thermoelectric circuit. Such a model is called the basic model (Fig. 1) [15], but there are other approaches to modelling, for example, based on the use of the Green's cell function, etc.

In this case, there are actually two common options to implement electrical matching circuits. The first one is using a repeater (gain is less than one) on a field-effect transistor with a large input impedance. An example of such a matching option is transistors such as 2N4117 [16], 2N4339 [17], or their modern equivalents. The second is using an operational amplifier similar to AD549 or OPA128 with characteristic values of the input resistance R_{in} of the order of 10 terraohms and the input capacitance C_{in} of the order of 1 pF [18]. Such standard amplifiers are produced by Analog Devices and Texas Instruments, respectively. The availability of data on the electrical parameters of the input circuits of the matching circuits is critical for analytical estimation

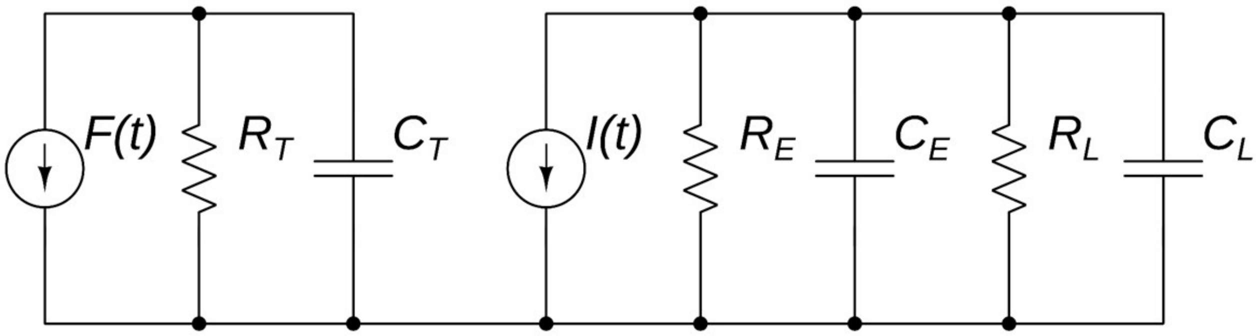

Fig. 1. Basic model of a pyroelectric converter: $F(t)$ is the heat flux; $I(t)$ is the pyroelectric current; $V(t)$ is the output voltage; R_T is the total thermal resistance of the sensing element; C_T is the thermal capacitance of the sensing element; R_E is the electrical resistance of the sensing element; C_E is the electrical capacitance of the sensing element; R_L is the electrical resistance of the input stage; C_L is the electrical capacitance of the input stage

of the value of the electric time constant of PEC. The main catalog characteristic of commercial pyroelectric detectors, which is usually provided by manufacturers in their data sheets, is the voltage sensitivity *RV* [V/W], which describes the dependence of the voltage *V* on the power *P* of the radiation absorbed by the pyroelectric sensing element at a certain modulation frequency (10 Hz, or 1 Hz by standard for motion sensors). However, there are numerous realizations of pyroelectric modules in which there is no mechanical modulator and for which time characteristics are crucial in addition to frequency characteristics. Such implementations include, for example, motion sensors in which the modulator function is performed by multisegment Fresnel lenses. In this case, the operation of such a sensor is a consequence of a transient process in it. The sensitivity and noise of the voltage amplifier in the frequency range of greatest interest for infrared detectors (0.1–100 Hz) are usually considered as criteria for optimal selection of pyroelectric materials. Among more than a thousand known pyromaterials, about a dozen have been commonly used for many years, including lithium tantalate (LTO – $LiTaO_3$), lithium niobate ($LiNbO_3$), lead zirconate titanate (PZT) ferroelectric ceramics, deuterated triglycine sulfate (DTGS), barium titanate ($BaTiO_3$), polyvinylidene fluoride (PVDF), strontium titanate ($SrTiO_3$), hexagonal zinc oxide (ZnO), potassium niobate ($KNbO_3$), barium-strontium titanate (BST), etc. These materials are most commonly used in real commercial infrared detectors, for which reliable data on dielectric properties over a fairly wide frequency range are more or less available. Nevertheless, it should be noted that for most pyromaterials and pyrodetectors, there are no data in open sources that would allow modelling the operation of these detectors, which is necessary for predicting the characteristics of, for example, information and measurement modules for various purposes developed on their basis.

The uncertainty is due, on the one hand, to incomplete data from manufacturers on their commercial detectors, which may be due to numerous circumstances, including competitive ones. On the other hand, some parameters of detectors and the materials used in them are practically impossible to measure or are associated with unreasonably high costs. For example, the thermal time constant of a sensitive element in many cases is a value that can only be estimated theoretically. The dielectric constant and loss tangent at low frequencies (0.1–100 Hz), at which IR sensors are used in most cases, are not known for many materials or are found with a significant error. Until now, standard measurements of these parameters are carried out at a frequency of 1 kHz, and for most pyromaterials they change significantly when the frequency of modulation of the incident radiation flux changes. However, in cases of using reliable data, coincidence of the chosen model with the actual configuration of the detector circuit, and in the presence of reliable data on the parameters of pyromaterials in a given frequency range, this approach allows calculations of sufficient reliability to make engineering decisions in the development of pyroelectric detectors and predict their characteristics. At the same time, it should also be recognized that the very existence of hundreds of pyromaterials on the market indicates that in many implementations, many other criteria come to the fore, including the depolarization temperature of T_D, which shall be accounted for not only during operation but also during the manufacture of detectors. For example, when using modern manufacturing technologies for commercial products, the T_D should not be lower than the group soldering temperature of the components. When integrating pyroelectric detectors into CMOS semiconductor mass production technology, pyroelectric materials shall withstand the temperatures typical of such technological processes. It is crucial to make sure that the selected material is stable and reproducible in mass production. During long-term operation, some materials have problems associated with prolonged use. The environmental impact of lead-based materials shall also be considered.

For successful modelling, it is essential to have full-frequency data based on dielectric properties of pyroelectric materials and the thermal parameters of the detectors. For example, there is very little data on the low-frequency dependence of thermal losses. Improving the reliability of such data reduces the inconsistency between model calculations and the characteristics of real commercial detectors.

The problem of parameter uncertainty does not disappear when developing projects using structurally complete measuring modules based on pyroelectric detectors, of which there is already a fairly large assortment. However, due to the lack of many critical parameters for commercial detectors in open sources (sometimes even the pyromaterial of the sensing element remains unknown), the tasks of using methods that allow the identification of pyroelectric detector parameters, without which further modelling of those characteristics of PECs that are most essential for their use in projects developed on their basis, become relevant.

In general, the problem of identifying the parameters of a particular detector can be solved by conducting experiments available to the researcher (first stage), which result in dependence data, the approximation of which (second stage) can be represented by a characteristic whose mathematical formula includes the desired parameters. That is, the approximation curve of the experimental dependence shall have coefficients that are the uncertain parameters of the detector (opposite to the coefficients of polynomials, which cannot be detector parameters). For pyroelectric transducers, one of the characteristics that can be studied experimentally is, for example, the amplitude-frequency response. This approach allowed us to find the thermal and electrical time constants with sufficient accuracy for a commercial single-element detector sample with a metal absorber PE10-S-Q from Ophir. The amplitude-frequency response was approximated using a least-squares regression procedure implemented in the Solver software environment. As a result of the best match between the data calculated based on the regression equation and the experimental data set, Solver calculated the values of the thermal and electrical time constants, which were used for further analytical calculation of the pyroelectric response to a single pulse of IR radiation. Comparison of the modelled response with the dependence of the pyroelectric voltage on the energy of the LED radiation pulse obtained experimentally proved the correctness of the detector model and the obtained values of the thermal and electrical time constants for the experimental conditions.

The radiation source used in the experimental studies was a high-power LED of the LED660-66-16100 model manufactured by Roithner Lasertechnik GMBH. To obtain a sinusoidal radiation waveform from the LED, a voltage-to-current converter controlled by an accurate functional oscillator was used as its power supply. The output signal of the detector was measured using a digital oscilloscope (model TPS2024) [9].

However, this approach can be implemented using other characteristics of pyroelectric converters. For many of them, under the conditions of their application, the most critical are the time characteristics, which are described, first of all, by the transient process, which is essentially the reaction of the PEC to a step change in the level of radiation absorbed by the sensitive element of the converter. The analysis of the transient response of the PEC allows us to estimate the real relaxation time of the transducer, i.e., the time it takes to return to its initial state. The canonical equation for the output voltage, which describes the dynamic characteristics of the PEC, is a well-known dependence that includes the thermal and electrical time constants [13]:

$$U_s(\omega) = \frac{\alpha \Phi_s \, p \, A_s \, R_E \, \omega}{G_T \sqrt{(\tau_T^2 \omega^2 + 1)(\tau_E^2 \omega^2 + 1)}}, \quad (1)$$

where τ_T and τ_E are the thermal and electrical time constants, respectively;

G_T and R_E are the total heat loss and electrical resistance, respectively;

Φ_S and A_S are the heat flux to the sensing element and its plane;

p is the pyroelectric coefficient;

α is the average bandwidth of the input window in a given wavelength range;

$\omega=2\pi f$ is the circular frequency.

When using commercial pyroelectric detectors, unfortunately, in most cases these parameters remain unknown, and sometimes, as well as the pyroelectric material of the sensitive element itself.

At the first stage, to obtain the experimental dependence of the pyroelectric response to incident radiation, an installation that included an infrared heat source (EMIRS200 manufactured by Axetris, AG, CaF2 window [19]) was used, which was controlled by a driver based on the MCP601 operational amplifier (there are also versions based on CMOS transistors). The pyroelectric response was recorded by a 12-bit ADC with a resolution of 1.5 mV and a sampling step of 10 ms, the data of which were stored in text files and, after appropriate mathematical processing, were used to obtain approximation dependencies. Experimental studies were conducted for several types of detectors from different manufacturers. The block diagram of the experimental setup is shown in Fig. 2.

The characteristic response of the pyroelectric voltage to the approximate equivalent of the stepwise switching on the above-mentioned IR source for one of the detectors (model Z55 manufactured by Eltec Instruments, not available in the company's main catalog) is shown in Fig. 3.

One of the essential characteristics of the PEC is the duration of the transient process, which is equal to the time during which the detector, after turning on the radiation source, transitions from its initial state to a new steady state. As can be seen from

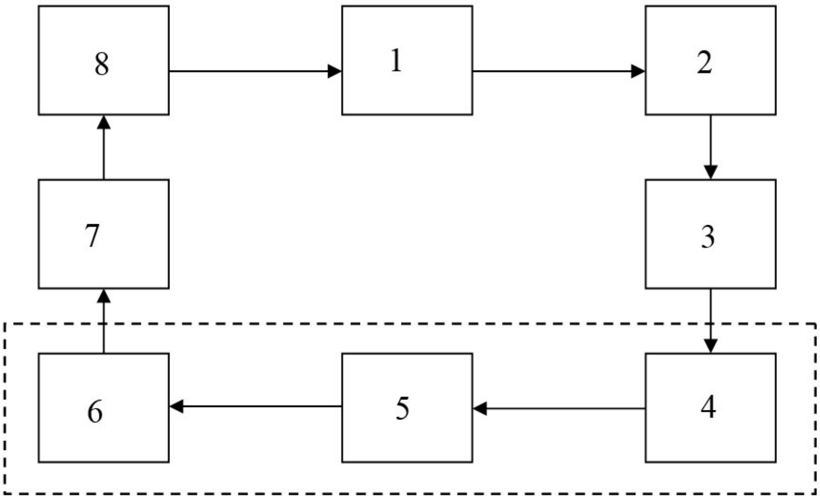

Fig. 2. Block diagram of the experimental setup for recording the output voltage of pyroelectric converters: 1 – personal computer (PC); 2 – DAC; 3 – radiation source driver; 4 – IR emitter; 5 – optical matching device; 6 – pyroelectric detector; 7 – pyroelectric detector driver; 8 – ADC

the usual oscillogram shown in Fig. 3, the duration of the detector transient is approximately 0.8 min. Measurements of the characteristics of a Z55 detector on a setup shown in Fig. 2, showed that at a signal-to-noise ratio of ≈1, the duration of the transient process for this detector is estimated at 7 min. Control of the heating and cooling processes for different detector samples indicates that for commercial devices in the voltage mode, the typical transient duration varies from 30 seconds to 7 minutes (Table 1).

The range of changes in this parameter (by more than an order of magnitude) indicates significant differences in the size of the sensing elements, their mounting structures, parameters of the electrical matching circuits, etc. In the studied pyroelectric detectors, this is confirmed by significant differences in the values of their time constants.

The experimental data of transient processes for each of the studied pyroelectric detectors were obtained as a series of 100 measurements of the pyroelectric voltage, each of which was performed in increments of 10 ms both during heating and cooling of the pyroelectric detector. Such a number of parallel measurements (100 for heating and 100 for cooling) for each of the detectors makes it possible to perform preliminary statistical processing of the data at each time point and thereby to reduce the influence of physical noise, ADC quantization noise, and the resulting uncertainty of the measured experimental data in general [20].

At the second stage, the generalized experimental dependencies obtained were approximated by means of Google Sheets or LibreOffice spreadsheets using a well-known transient equation (2), which is obtained

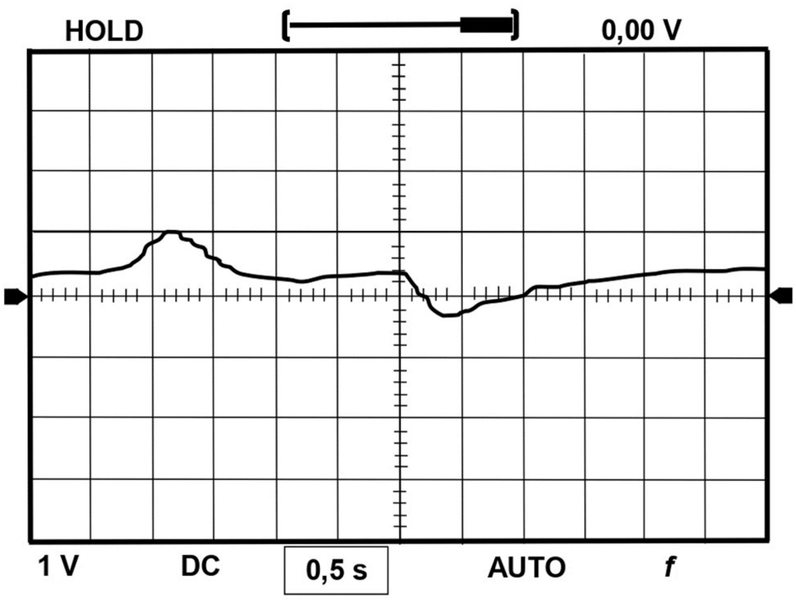

Fig. 3. Oscillogram of the pyroelectric response of a Z55 detector to the stepwise switching on the IR source

Table 1

Transient time for some commercial pyrodetectors in voltage mode

Pyrodetector model	LHI Series: 954, 958, 874, 884	WP21/5192, DP1102/5192, 421	D203B, D204B, E-700, PD1001F	LME-302, LTAG2
Manufacturer	Excelitas Technologies (US)	Eltec Instruments (US)	Hunan Infrared (China)	InfraTec, DIAS Infrared (Germany)
The duration of the transient response, less than, s	30	50	50	420

by applying the inverse Laplace transform to the transfer function (1):

$$U_{\downarrow}s(t) = K\left(e^{\uparrow}(-t/\tau_{\downarrow}T) - e^{\uparrow}(-t/\tau_{\downarrow}E)\right), \quad (2)$$

where

$$K = \frac{\alpha \Phi_s \rho A_s R_E}{G_T(\tau_T - \tau_E)[V]}.$$

The criterion for the optimality of the obtained approximated curve was to achieve the best visual match with the experimental dependence. At the same time, a "manual" correction of the coefficient values was used, which, provided there is an appropriate experience, leads to a better match of the curves. A typical result of such modelling for one of the studied detectors, approximated by the transient equation with two time constants, is shown in Fig. 4.

Thus, the approximate transient equation for the LHI958 pyrodetector is as follows (3):

$$U(t) = 0.055\left(e^{-\frac{t}{0.6}} - e^{-\frac{t}{1.3}}\right)[V]. \quad (3)$$

As can be seen from the graph in Fig. 4, we can observe an almost complete coincidence of the experimental and model curves, which indicates the effectiveness of the presented method and suggests that the characteristic coefficients of the model dependencies obtained in this way are adequate values of the thermal and electrical time constants of the studied commercial detectors. However, it should be noted that the approximation process does not identify which of the found time constants is the thermal τ_T and which is the electrical τ_E [21]. To unambiguously assign the found smaller or larger time constant to the

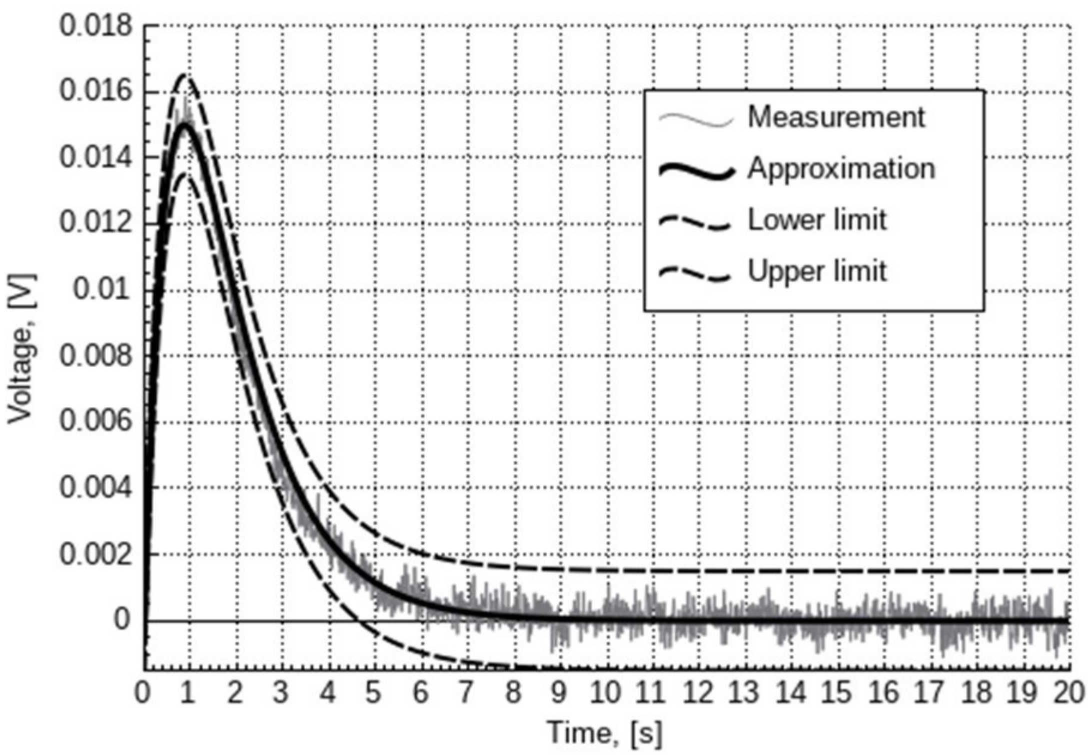

Fig. 4. Experimental (noisy) and normalized model (solid) time dependencies of the pyroelectric detector LHI958 with approximation parameters: smaller time constant 0.6 s, larger time constant 1.3 s, normalizing coefficient of the amplitude of the approximation curve $K = 0.054$ V

electrical time constant, it is necessary to compare them with the value of τ_E calculated accounting for the electrical parameters of the matching schemes provided by the manufacturers of transistors or operational amplifiers used in a particular case. The found values of τ_T, τ_E can be used to predict the characteristics of these detectors under appropriate operating conditions and to optimize the characteristics of measuring modules based on them. Simulation studies of pyroelectric converters using the parameters found for them by the method of approximation identification can also be carried out on the developed simulator [22].

Summary

The coincidence of the experimental data of transient processes with the analytical dependencies obtained based on the basic model of a pyroelectric converter is observed for all studied single-cell and two-cell PECs.

It is established that for pyroelectric converters with a significant duration of the transient process, the deviation of the model dependence from the experimental data increases. The increase in the duration of the transient process is caused by the design features of pyroelectric converters, which are associated with an increase in the size of the sensing elements, the use of compensation circuits with two sensing elements, and the use of complex electrical matching circuits.

Identification of the parameters of pyroelectric functional modules, which are more complex in structure (since they may include two or more sensing elements, more functional signal processing circuits, etc.), requires the correction of approximation models, in which a larger number of characteristic coefficients can be introduced.

Modules on pyroelectric detectors are more complex devices than individual sensors. Modules can consist of many sensing elements, signal processing units, etc. Identification of modules requires more complex mathematical models with numerous coefficients.

The method of the approximation identification of transducer parameters can be extended to other objects, the functioning processes of which are modelled using incomplete data.

Ідентифікація параметрів вимірювальних модулів на основі піроелектричних матеріалів

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Анотація

Розглядаються актуальні питання використання піродетекторів, які знаходять дедалі ширше застосування у складі вимірювальних модулів сучасних систем моніторингу, зокрема екологічного. Наголошується на проблемі оптимального вибору первинних піроелектричних перетворювачів, яка ускладнюється через неповноту або відсутність ключових параметрів у технічній документації комерційних зразків. Ця невизначеність ускладнює використання математичних моделей для прогнозування характеристик детекторів та вимірювальних модулів на їхній основі.

Запропоновано та детально описано методику ідентифікації важливих параметрів піроелектричних детекторів, таких як теплова (τ_T) та електрична (τ_E) сталі часу, за даними експериментальних досліджень їхніх ключових характеристик. Продемонстровано можливість знаходження цих параметрів шляхом апроксимації експериментальних залежностей, отриманих як у частотній області (аналіз амплітудно-частотної характеристики), так і в часовій області (аналіз перехідної характеристики). Детально описано експериментальну установку та процедуру для реєстрації піроелектричного відгуку на східчасту зміну інфрачервоного випромінювання.

Показано, що апроксимація отриманих експериментальних кривих перехідного процесу за допомогою математичної моделі, що враховує дві сталі часу, дозволяє з високою точністю визначити їхні значення. Адекватність отриманих оцінок часових характеристик та знайдених параметрів підтверджується порівнянням модельних розрахунків із даними експериментальних вимірювань тривалості перехідних процесів для декількох комерційних піроелектричних детекторів ІЧ діапазону різних виробників, яка варіюється в широких межах (від 30 с до 7 хв). Обговорюється питання однозначної ідентифікації теплової та електричної сталих часу. Розроблена методика сприяє вдосконаленню метрологічного забезпечення піроелектричних вимірювань та може бути застосована для оптимізації вибору детекторів і проєктування вимірювальних модулів.

Ключові слова: піродетектори; піроелектричні модулі; амплітудно-частотна характеристика; перехідна характеристика; перехідний процес.

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