Measurement Error of Voltage Responsivity of Pyroelectric Detector Induced by Use of Non-Sinusoidal Modulation of Radiation

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Abstract. *For the experimental measurements of pyroelectric detectors voltage responsivity, sinusoidal modulated optical radiation should be used. In practice, optical choppers are commonly used in experimental set-ups to modulate optical source and as a result optical radiation may have a square or trapezoidal waveform. In the paper, the frequency dependence of voltage responsivity of pyroelectric detector for different shapes of waveform of absorbed radiation was studied by use either simulation and experimental method. Simulation studies were carried with the program MATLAB-Simulink and verified experimentally. The results of the studies indicated that the frequency responses of pyroelectric detector show considerable differences for different wave profiles of radiation excited detector.*

Keywords: Pyroelectric Sensor, Responsivity, Optical Modulation

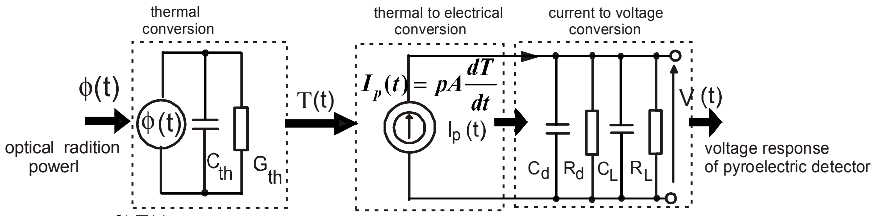
1. Introduction

Theoretical and experimental studies of the frequency dependence of voltage responsivity of a pyroelectric detector should be performed applying sinusoidal modulated optical radiation, which follows from well known formal requirements for determination of the Bode frequency plot. However, in the majority of papers the results concerning the detector voltage responsivity as a function of frequency were obtained for the optical radiation signal of trapezoidal or rectangular shape [1-2] because of the use of an electromechanical modulator of optical radiation. Such results must be charged with error.

The aim of this study was to establish the metrological consequences following from the use of optical signals of trapezoidal or square shape concerning the voltage responsivity R_V of a pyroelectric detector as a function of the frequency of the modulated optical radiation signal. The study was performed by the simulation method with the program MATLAB-Simulink whose results were confronted with experimental data. It should be noted that literature on the subject is scarce, although the problem seems important from the point of view of correct realization of optoelectronic experiments. In fact, only one significant paper devoted to this subject has been found [3]. The results it presents and in particular the final conclusions, are consistent with those obtained in this study. The authors of [3] have applied a completely different method than that used in this work. They have determined the voltage responsivity of the detector as a function of frequency on the basis of a mathematical model of the detector for which they determined a superposition of the voltage responsivities to particular harmonics of the non-sinusoidal optical radiation signal.

2. Subject and Methods

Voltage responsivity of a pyroelectric detector R_v is defined as the ratio of the amplitude of a response signal V_m of a detector to the amplitude Φ_m of a sinusoidal input signal as a function of angular frequency ω or frequency f of this signal. Analytical considerations leading to a mathematical expression for the detector voltage responsivity as a function of angular frequency $R_v = f(\omega)$, are well known [4] and are inferred from the equivalent scheme of a pyroelectric detector [4] shown in Fig. 1.



$$C_{th}\frac{d\Delta T(t)}{dt}+G_{th}\Delta T(t)=\eta\Phi(t) \qquad C\frac{dV(t)}{dt}+\frac{V(t)}{R}=pA\frac{d\Delta T(t)}{dt} \qquad C=C_d||C_L$$

$$C_{th}sT(s)+G_{th}T(s)=\eta\Phi(s) \qquad CsV(s)+\frac{V(s)}{R}=pAsT(s) \qquad R=R_d||R$$

Fig. 1 Equivalent scheme of a pyroelectric detector cooperating with voltage amplifier [4, 5]. Symbols in the figure: C_{th} – thermal capacity of pyroelectric detector, G_{th} - thermal conductance of pyroelectric detector, $\Delta T(t)$ - temperature changes of pyroelectric material, η – absorption coefficient of radiation, p – pyroelectric coefficient, A – surface of pyroelectric detector, C – equivalent capacitance for parallel connected pyroelectric capacitance, C_d and input amplifier capacitance, R - equivalent resistance for parallel connected leakage resistance R_d of pyroelectric detector and input amplifier resistance.

In this study the simulation method was applied using the MATLAB-Simulink environment. Because of the specific way of data implementation in this program package, the voltage responsivity $R_V(s)$ of a pyroelectric detector must be presented in the Laplace domain. After some mathematical transformations of the equations in Laplace domain describing subsequent stages of conversion (described detailed in [5]) the relation for voltage responsivity $R_V(s)$ of a pyroelectric detector is obtained, eq. (1):

$$R_v(s)=\frac{V(s)}{\Phi(s)}=\frac{p\eta\tau_{th}\tau_e s}{c' dC(s\tau_{th}+1)(s\tau_e+1)} \tag{1}$$

where c' is the volume specific heat of the detector, τ_{th} is the thermal time constant defined as $\tau_{th} = C_{th} / G_{th}$, τ_e is the time constant found from the relation $\tau_e = C_d R$, d is the thickness of the pyroelectric plate of detector, .

Equation (1) is in fact transfer function of pyroelectric detector model, which may be used also for simulation study of different type, especially for studies of voltage response signal to excitation with a radiation signal of given wave-form [5].

3. Simulation and experimental results

Simulation investigation of voltage responsivity was performed for the model pyroelectric detector made by the author based on the specific pyroelectric detector type PVDF, of known parameters, using excitations by optical radiation signals of sinusoidal, rectangular and trapezoidal shape of the same amplitudes of radiation power. The results of simulations realised within the MATLAB-Simulink package permitted drawing the voltage responsivity of the pyroelectric detector as a function of frequency $R_V = f(f)$ for the sinusoidal, trapezoidal (of the rise and fall time of 20% of period T) or rectangular modulation of the optical radiation signal (Fig. 2). Fig. 3 presents the relative error δ, in percent, of the voltage responsivity determined for the non-sinusoidal optical radiation signals, i.e. for rectangular one and trapezoid one with the rise and fall times of 20% of period T, with respect to the voltage responsivity obtained for the sinusoidal radiation signal treated as the correct value.

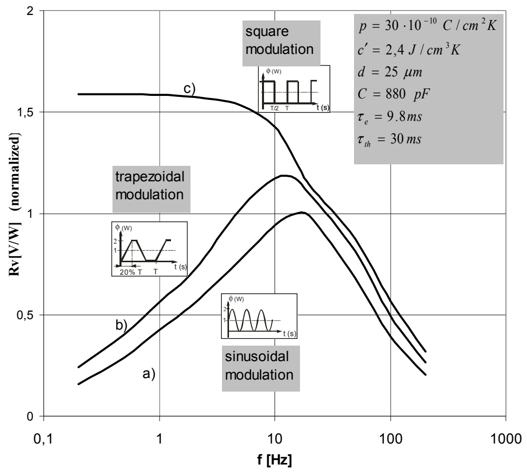


Fig. 2. Frequency dependence of pyroelectric detector responsivity $R_V = f(f)$ with a) sinusoidal modulated radiation, b) trapezoidal modulated radiation with rise and fall times of 20% of period, c) square-wave modulated radiation The studies were performed using computer simulation.

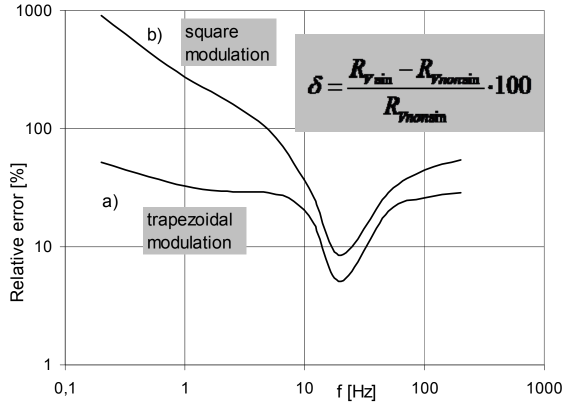


Fig. 3 Relative error δ of frequency dependence of voltage responsivity R_V of pyroelectric detector for non-sinusoidal modulation: a) trapezoidal modulated radiation b) square-wave modulated radiation. The studies were performed using computer simulation.

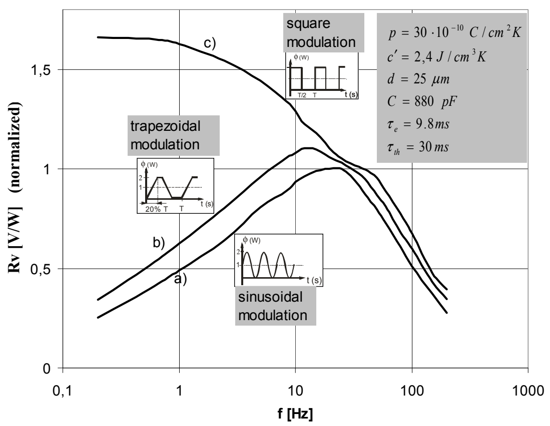


Fig. 4. Experimentally determined frequency dependence of pyroelectric detector responsivity $R_V = f(f)$ with a) sinusoidal modulated radiation, b) trapezoidal modulated radiation with rise and fall times of 20% of period, c) square-wave modulated radiation.

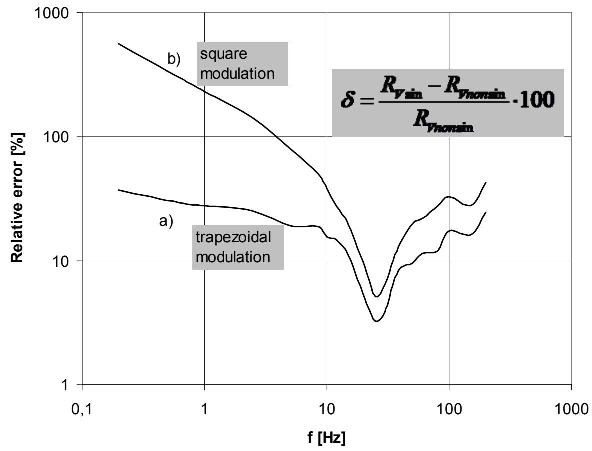


Fig. 5 Relative error δ of experimentally determined dependence of voltage responsivity R_V of pyroelectric detector for non-sinusoidal modulation: a) trapezoidal modulated radiation b) square-wave modulated radiation.

The results of simulation studies of the frequency dependence of voltage responsivity of the pyroelectric detector $R_V = f(f)$, for the sinusoidal, trapezoidal and rectangular modulation of the optical radiation signal are presented in Fig. 2. As shown in these figures, the $R_V = f(f)$ plots obtained for the optical radiation signal of the trapezoidal or rectangular shape can significantly differ from the plot determined for the optical signal of sinusoidal shape, treated as the reference. It should be noted that in particular for low frequencies of optical radiation modulation the voltage responsivity obtained for non-sinusoidal optical radiation signals are charged with considerable error reaching even up to a few hundred percent (Fig. 3). The error is defined as:

$$\delta = \frac{R_{Vnon\sin} - R_{V\sin}}{R_{\sin}} 100 \qquad (2)$$

where: R_{Vnonsin} is voltage responsivity for nonsinusoidal waveform of radiation, R_{Vsin} is voltage responsivity for sinusoidal waveform of radiation.

In the experiment performed to verify the above results, an electronically controlled source of optical radiation, based on a high power light emitting diode, was applied. The voltage responsivity of the PVDF type detector constructed by the author was measured versus the frequency of the optical radiation signal of rectangular and sinusoidal shapes and the same amplitudes. The results are presented in the form of plots of voltage responsivity versus frequency R_V (Fig. 4) and relative error δ versus frequency (Fig. 5). They are in good agreement with the results obtained by simulation study and presented in Figs. 2 and 3.

4. Conclusions

As follows from the results of simulation and experimental studies, the shapes of the plots of voltage responsivity of a pyroelectric detector versus frequency $R_V = f(f)$ obtained for different waveforms of radiation are significantly different and their maximum values occur at different values of frequency. The $R_V = f(f)$ dependence obtained for the optical radiation signal of rectangular shape shows the most pronounced differences from the shape of an analogous dependence for the optical signal of sinusoidal shape. The error related to this difference can reach high values, especially for low frequency of optical radiation modulation.

A general conclusion following from the study is that the use of optical radiation signal of non-sinusoidal shape for experimental investigation of Bode plot of pyroelectric detector is rather unprofessional because brings unreliable results of measurements.

References

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