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Measurement of High-Frequency Sub-Noise Temperature Signal and RMS Current Using a Single-Detector High-Speed IR System

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Abstract: NETD (Noise Equivalent Temperature Difference) parameter of infrared systems is the important parameter that allows determining the limit of temperature measurement of tested objects. Currently, the commercially available devices have the NETD < 20 mK. The infrared (IR) detectors and accompanying electronic circuits generate noise. In consequence, it is difficult to achieve the high level of signal-to-noise ratio (SNR) while measuring temperature. This paper presents a method of measuring the root mean square (RMS) value of alternating current, using a single-detector high-speed IR system for detecting 100 Hz harmonic spectral component of temperature, whose value is certainly below NETD limit.

Keywords: Current measurements, high frequency (HF) sub-noise, temperature, IR detector, NETD, SNR, harmonics

1. Introduction

Nowadays, IR systems based on a single detector, as well as thermal detectors matrix, constantly offer the growing resolution and sensitivity. The NETD of a thermal system allows determining the minimum difference in changes in the temperature value in the area of interest [1, 3, 4]. Modern solutions and materials used for the construction of IR detectors focus on the implementation of HgCdTe, InSb, PbS CQD and InGaAs technologies, since they increase the possibilities and scope of applications of new IR and NIR (near infrared) devices [6]. Current, low-cost IR bolometric systems used in industry have a NETD value of less than 60 mK [2]. The fast cooled IR systems, with NETD < 20 mK, have been used so far mainly in scientific, medical and military sectors. As a result of technological progress, these systems are now increasingly used in industry.

This paper presents a verifying study of the sensitivity of the single pixel detector with detectivity $D^* > 10^{11}$ cmHz$^{0.5}$/W equipped with 4-stage Peltier cooler [9]. The aim is to apply such an IR head for temperature measurement and estimating the RMS value of the alternating current (AC) [5, 11–14]. The obtained experimental results prove that the applied methodology and the implementation of the IR detector allow the determination of the value of the second harmonic of the temperature spectrum for f = 100 Hz (T_{100}) below 1 mK level.

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2. Theory

Modern IR systems have additional computing units that are designed to reduce the influence of noise, especially thermal noise, which is caused by the operation of electronics over time, for high frequency ranges. The noise is known as Johnson-Nyquist noise, and its value significantly affects the NETD parameter, which is represented by (1) [1, 4, 6]:

$$\mathrm{NETD} = (\Delta T_o U_n)/(\Delta U_o) \tag{1}$$

where: ΔT_o – object temperature change, U_n – RMS value of noise (V), ΔU_o – camera output signal change (V).

Assume a pure sinusoidal current of 50 Hz flowing in the power cable (2).

$$i(t) = I_{50}\cos(\omega_{50} t) \tag{2}$$

where I_{50} and ω_{50} denote the amplitude and angular frequency of AC current.

In most of practical cases, the mean temperature is measured, which can be determined using the thermal resistance R_{th} of the cable and the mean power P_{mean}, as given by (3).

$$T_{mean} = R_{th} P_{mean} \tag{3}$$

In fact, the power dissipated in the cable is continuously changing with f = 100 Hz frequency. In order to evaluate temporal variation of temperature, the thermal impedance is required. Finally, temperature is the product of power and thermal impedance spectral components for f = 100 Hz. Determination of the T_{100} spectral component of temperature requires the power amplitude P_{100} and the modulus of thermal impedance Z_{th100}, both for f = 100 Hz, which can be expressed by (4) and (5):

$$T_{100} = Z_{th100} P_{100} \tag{4}$$

$$P_{100} = (I_{50})^2 \rho_e / (2S) \tag{5}$$

where: T_{100} – amplitude value of the temperature spectrum component for f = 100 Hz, Z_{th100} – modulus of the thermal impedance for f = 100 Hz for the length unit, P_{100} – amplitude value of the power for f =100 Hz dissipated in the unit-length cable, ρ_e – electrical resistivity and S – the cross-sectional area of the wire.

The problem is that due to the thermal mass and its thermal inertia, the value of Z_{th100} is very low, typically for a 1 mm diameter steel or cooper wire it is of the order of nK/W [5].

3. Measurement setup and test procedures

For the purpose of verification, the capabilities of measuring such small temperature signal by commercially available IR system, the single MCT MWIR detector was selected for tests [9]. This detector area is 1 × 1 mm², its FOV = ~36° and it captures infrared radiation within 3–5 μm spectral band [9, 15]. The experimental setup presented in Figure 1 and 2 was especially developed for this research.

The study is carried on using a steel wire (1) with a diameter of 1.3 mm which was connected to an electrical circuit with the resistive load (2) R = 1.3 Ω as presented in Figure 1. The sinusoidal current was generated by an isolated AC power supply of alternating current NDN AFC-110 (3). In the presented research, the IR head (4) VIGO PVI-4 TE equipped with the amplifier MIP-DC-1M-F-M4 DC Coupled Preamplifier Integrated with Fan (bandwidth: DC – 1 MHz) [9, 10] placed at a distance of 2 cm is used for recording changes in the temperature value of the tested steel wire (1). The data acquisition system records the signals with a 14-bit resolution at minimum 10 kHz sampling rate (5). The device simultaneously recorded alternating current value changes in real time by using the AC current probe AmpFlex A110 (6). The control, data acquisition, registration and processing are performed using the computer with the dedicated software (7) (Fig. 1).

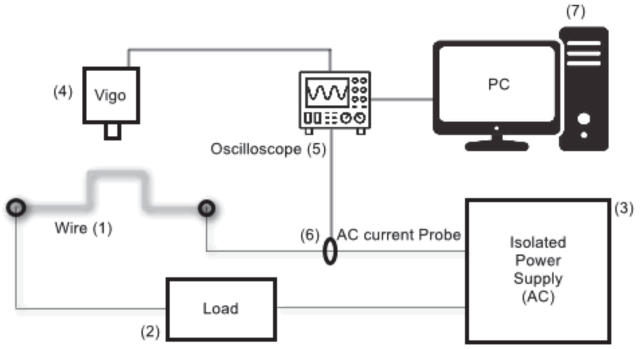

Fig. 1. The diagram of measurement setup
Rys. 1. Schemat układu pomiarowego

The measurement procedure consists of five registrations of the temperature signal using channel CH1 of acquisition system synchronized with changes in alternation current registered by channel CH2. The sampling frequency $f = 10$ kHz and number of $N = 128\ 000$ samples are selected for each measurement. The acquired signals are filtered in order to obtain the T_{100} – RMS value of the temperature spectrum for $f = 100$ Hz using 3-order Butterworth filter. The test is repeated for five different values of alternating current [5, 11–14]. The IR head was not calibrated, hence it measured the radiation power corresponding to the temperature of the object.

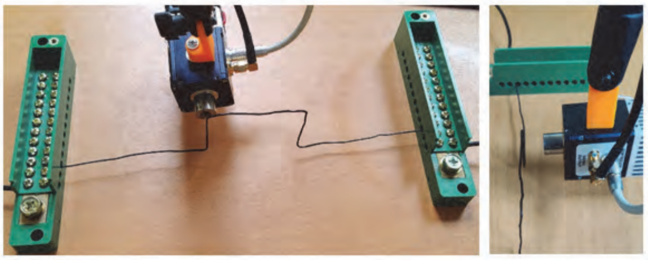

Fig. 2. Measurement setup – IR detector VIGO PVI-4 TE with the amplifier MIP-DC-1M-F-M4 DC and tested wire
Rys. 2. Stanowisko pomiarowe – detektor IR VIGO PVI-4 TE wraz ze wzmacniaczem MIP-DC-1M-F-M4 DC oraz badany drut

4. Results

The obtained results of the measured mean temperature and its 100 Hz spectral component are presented in Table 1. The wire was without the isolation and was covered by the highly emissive black mat paint. Temperature ΔT_{mean} denotes the temperature above the ambient temperature, $U(T_{100})$ is an output voltage corresponding to the radiation power approaching the sensor.

The averaged results from all measurements for each considered RMS current values varying in the range 3.46–6.32 A are subjected to the proprietary filtration method and FFT analysis as shown in Table 1. The implementation of the VIGO PVI-4 TE detector and the processing algorithms allow obtaining the changes in the value of the second harmonic of the temperature signal spectrum T_{100} at the µV level. Changes in the mean value of the wire relative temperature of the tested wire ΔT_{mean} (above ambient temperature) are within the range of 14.11–42.73 °C depending on the RMS value of the alternating current.

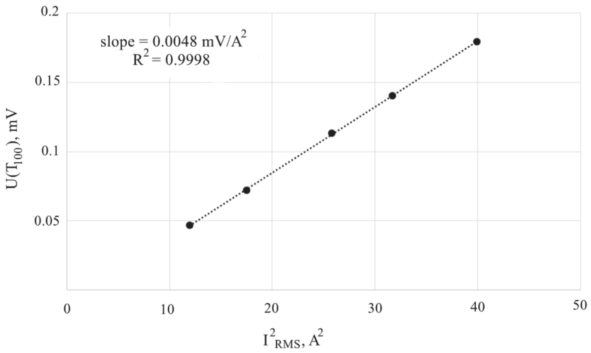

Fig. 3. Calibration curve $U(T_{100}) = f(I^2_{RMS})$ of the tested wire
Rys. 3. Wykres krzywej kalibracji $U(T_{100}) = f(I^2_{RMS})$ badanego drutu

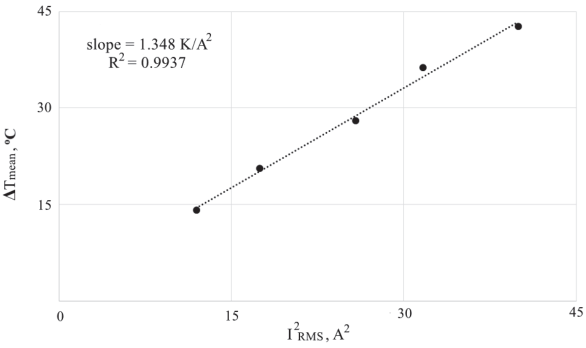

Fig. 4. Diagram of the mean value core temperature ΔT_{mean} of the tested wire as a function of square RMS current values
Rys. 4. Wykres średniej wartości temperatury rdzenia ΔT_{mean} badanego drutu w funkcji kwadratu prądu skutecznego IRMS

Table 1. Measurement results for the selected steel wire

Tabela 1. Wyniki pomiarów badanego drutu stalowego

I_{RMS}, A	I^2_{RMS}, A^2	$U(T_{100})$, V	ΔT_{mean}, °C
3.46	11.97	4.67E-05	14.11
4.18	17.47	7.19E-05	20.60
5.08	25.81	1.14E-04	28.05
5.63	31.70	1.40E-04	36.31
6.32	39.94	1.80E-04	42.73

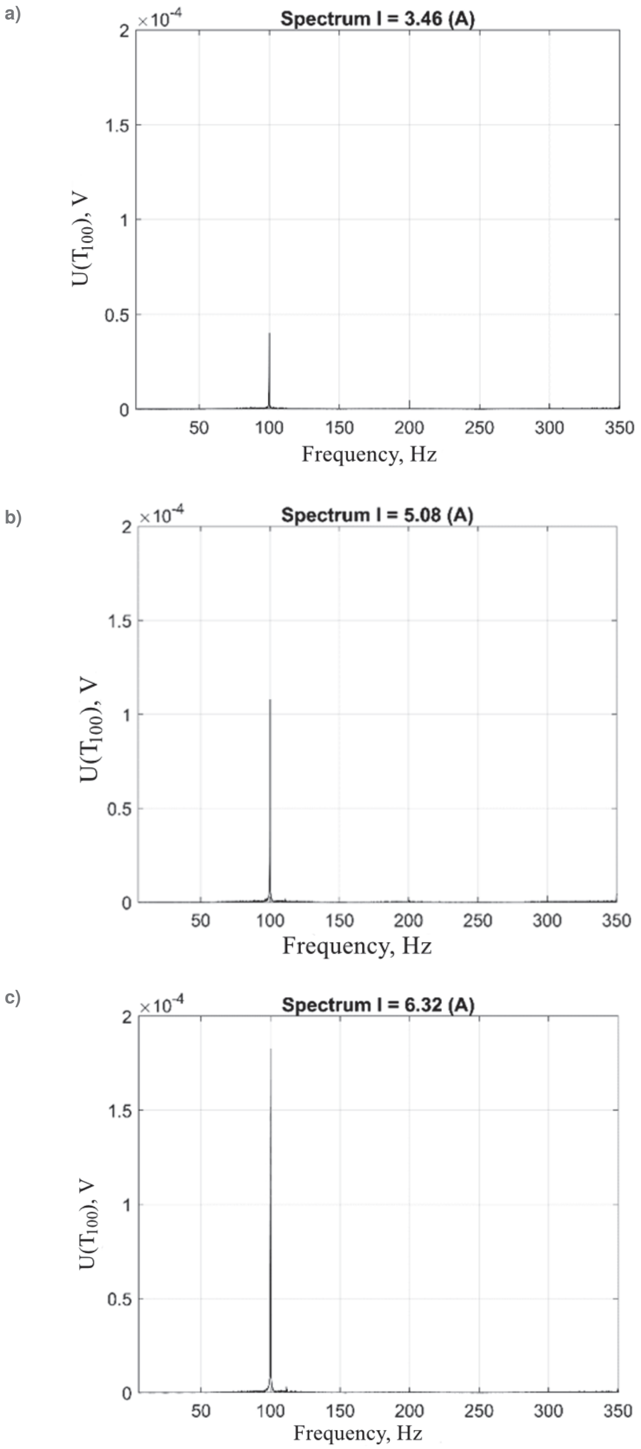

Fig. 5. Examples of temperature spectrum for three different RMS values of AC current: a) 3.48 A, b) 5.08 A, c) 6.32 A

Rys. 5. Przykłady widma temperatury dla trzech różnych wartości skutecznych prądu przemiennego I_{RMS}: a) 3,48 A, b) 5,08 A, c) 6,32 A

Based on the above results, one may obtain the calibration curve $U(T_{100}) = f(I^2_{RMS})$ for the tested wire (Fig. 3) and the characteristics of the temperature change as a function of the square of the current $\Delta T_{mean} = f(I^2_{RMS})$ (Fig. 4).

According to the results presented in Fig. 3 and Fig. 4, one may notice the linear relation of temperature changes with the correlation coefficient $R^2 = 0.9998$ and slope $m = 0.0048$ mV/A², of linear function $T_{100} = f(I^2_{RMS})$. For $\Delta T_{mean} = f(I^2_{RMS})$, the determined parameters of the function are: $R^2 = 0.9937$ and slope $m = 1.0348$ K/A². The obtained results confirm the correctness of the theoretical assumption, as well as the effectiveness of the proposed method.

Additionally, examples of temperature spectrum in the range of 50–350 Hz for current values: $I_{RMS} = 3.46$ A, $I_{RMS} = 5.08$ A and $I_{RMS} = 6.32$ A, are shown in Fig. 5. The mean value of the measured signal was removed by high-pass filter. The only second harmonic of the temperature signal T_{100} (f = 100 Hz) is observed, which amplitude value is below the declared threshold of thermal sensitivity of the used detector [9].

One may ask for the reason of using the 100 Hz harmonic of the temperature T_{100} to measure the RMS current instead of the mean value ΔT_{mean} which is much higher and much easier to measure. The convincing answer is that the high-frequency temperature harmonic is not depend on environmental conditions that can affect the measurement, such as convective and radiative cooling/heating, as well as radiation on a sunny day [5, 11, 14].

5. Conclusions

The conducted tests using a standard, low-cost single pixel IR system for measurement the temperature signals below the NETD limit, were successful. The proper measurement methodology based on the high-pass filtering and Fourier frequency analysis, allows recording radiation power changes at the μV level of the output signal.

The obtained T_{100} spectra, which are responsible for the amplitude change of the second harmonic of the temperature spectrum of the tested steel wire with a cross-section diameter of 1.3 mm, are related to the change in the RMS value of the alternating sinusoidal current. The experiments also allow confirming the effectiveness of the developed „2-ω" methodology [5, 11–14], which is based on measuring the RMS value of alternating current using a low-cost, high-speed single-detector IR head.

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Podszumowy pomiar temperatury do wyznaczania wartości skutecznej prądu przemiennego przy zastosowaniu systemu z pojedynczym detektorem podczerwieni o dużej szybkości działania

Streszczenie: Parametr NETD (ang. Noise Equivalent Temperatura Difference) dla systemów podczerwieni (IR) jest ważnym parametrem pozwalającym określić dolną granicę pomiaru temperatury badanych obiektów. Obecnie dostępne na rynku chłodzone kamery termowizyjne charakteryzuje parametr NETD < 20 mK. Detektory podczerwieni i towarzyszące im obwody elektroniczne generują szum. W konsekwencji trudno jest uzyskać wysoki poziom stosunku sygnału do szumu (SNR) w systemach radiacyjnego pomiaru temperatury. W artykule przedstawiono metodę pomiaru wartości skutecznej prądu przemiennego stosując system IR z pojedynczym detektorem o dużej częstotliwości generacji próbek. Metoda polega na pomiarze składowej harmonicznej widma temperatury o częstotliwości 100 Hz, której wartość jest znacznie mniejsza od poziomu określonego przez parametr NETD.

Słowa kluczowe: pomiar prądu, szumy wysokiej częstotliwości (HF), temperatura, detektor IR, NETD, SNR, harmoniczne

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