16th IMEKO TC4 Symposium
Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements
Sept. 22-24, 2008, Florence, Italy

MEASUREMENT ALGORITHMS IN MICROCALORIMETER TECHNIQUES AT MICROWAVE FREQUENCIES

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Abstract- In the paper there are described different algorithms that are possible to be used in the microcalorimeter-based measurements for realizing the broadband high frequency power standards. Besides the equal time-intervals alternating algorithms, able to achieve the effective efficiency of the transfer power standards, it is presented a novel algorithm, based on keeping constant the limits of the microcalorimeter output quantity. The new method should be used for measuring the high frequency losses in magnetic amorphous wires.

I. Introduction

A microcalorimeter is a measurement system considered as a primary power standard. Its practical application is the measurement of the *effective efficiency* for power sensors like thermistor and barretter mounts in transfer standards realizing [1]. A critical part of the microcalorimeter is the feeding path, whose losses give a significant error. Its correction and the contribution to the system uncertainty must be determined in a microcalorimeter calibration step. The perfect dummy load concept and the feeding lines *S*-parameter measurements with the vector network analyzer – VNA – make possible to do this. However, an important part of the system uncertainty arises in this manner from the VNA measurements [2].

The measurement system we are considering is based on a dry adiabatic calorimeter as Figure 1 shows. The calorimetric thermal load consists of twin sensors, perfectly matched from thermal point of view. One of them, the sensor under test – U or SUT –, is alternatively supplied with HF - test power or LF/DC - reference power through two insulating coaxial lines segments [2]. The other sensor, named thermal dummy load – D or TDL –, has no power applied during the calibration process; it works only as a thermal reference mass realizing a differential configuration for rejecting the thermal fluctuations deriving inside of microcalorimeter from its environment, even if the thermal insulation of the system is high. This cold sensor could become SUT without opening the microcalorimeter based on the twin sensors properties. The feeding lines include two thin-wall coaxial parts, fitted with coaxial connectors for an easy characterization based on VNA measurements. The 1-st Section and the 2-nd Section use the property of the skin effect in obtaining the needed high thermal insulation from the external environment and a good HF power propagation in the same time. A such arrangement contributes to better filter the external thermal noise, being more easily conveyed on the thermal ground by the outer-wall of the insulating feeding path. By appropriately combining the output signals of the two-thermojuction arrays, named thermopiles, it obtains a measurement of the temperature difference between SUT and TDL, which is directly depending of the SUT *effective efficiency* [1], [2], [3].

The system shown in Figure 1 can work both with bolometric power sensors and with thermoelectric power sensors. The instrumentation is usually under computer control and the measurement steps require automatic processes.

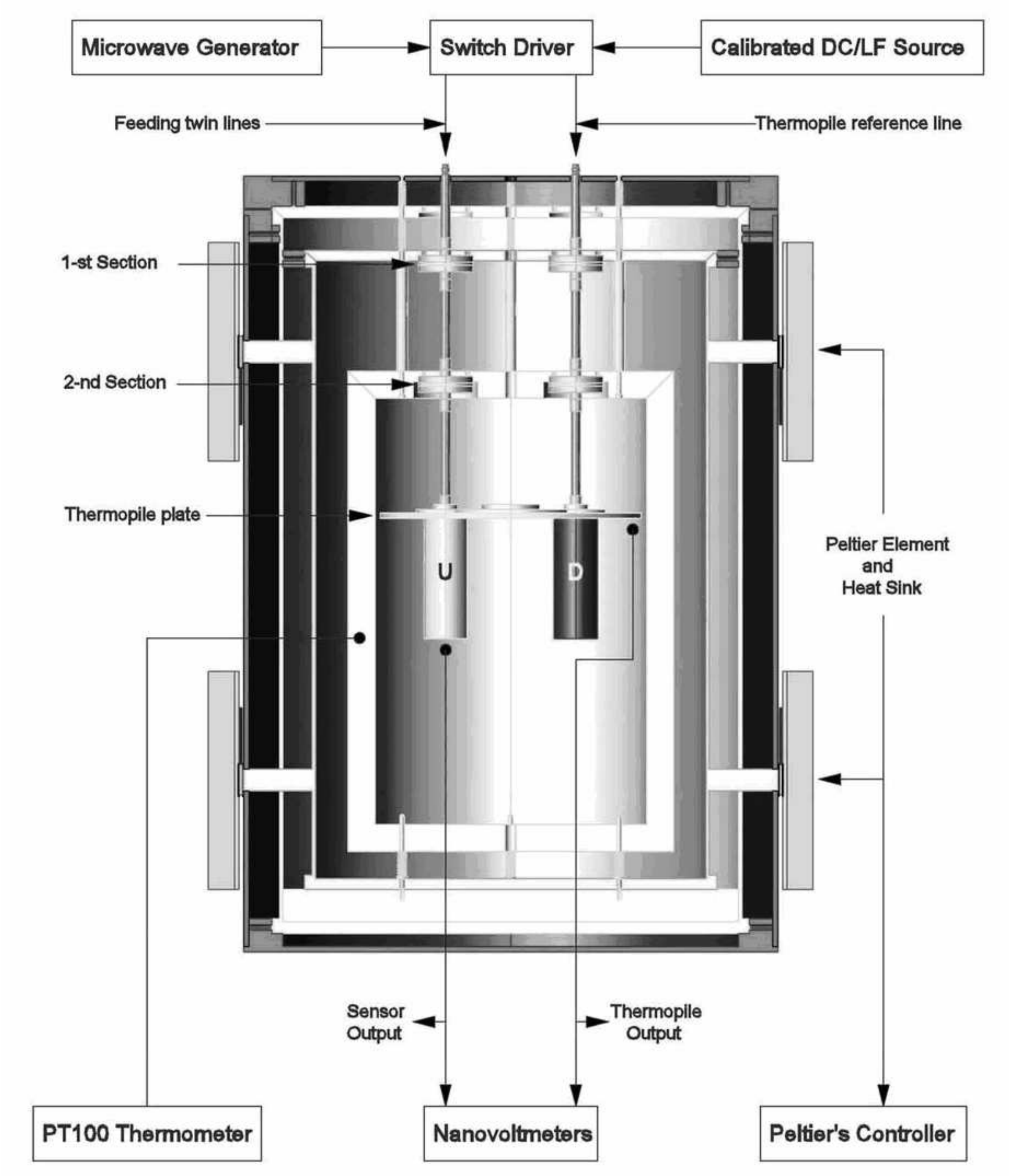

Figure 1: Scaled cross section of a twin coaxial microcalorimeter

II. Long-term measurement and calibration versus medium-term measurements

Only the thermopile output voltage e, measured at the thermal equilibrium, is significantly for our purpose. This value is obtained after 10 time-constants - τ - of the system, at least, and the process is described as long-term measurement. The microcalorimeter thermopile voltage can be considered as resulting from two processes, one related to the power sensor and the other to the feeding line [1]:

$$e = \alpha \Delta T = \alpha R\left(k_1 P_{\mathrm{S}} + k_2 P_{\mathrm{IL}}\right), \qquad (1)$$

where:

α - is the Seebek coefficient of thermopile junctions;
R - a conversion constant depending on thermodynamic parameters of the thermal load;
k_1, k_2 - coefficients that describe the power separation between SUT and feeding line;
P_{S}, P_{IL} - power dissipated in the sensor and in the insulating line respectively.

The thermopile response ratio e_R, when HF-power is applied to the SUT mount and when an equivalent REF-power is substituted in it, for the same effect U, is

$$e_R = \frac{e_2}{e_1} = \left[\left(\frac{P_S|_{REF}}{P_S|_{HF}}\right)\frac{1+k\left(P_{IL}/P_S\right)|_{REF}}{1+k\left(P_{IL}/P_S\right)|_{HF}}\right]_{U_{REF}=U_{HF}} = \frac{\eta_{eff}}{g}, \quad k = \frac{k_2}{k_1}, \tag{2}$$

and includes the power sensor *effective efficiency* η_{eff} and the *microcalorimeter calibration factor* g respectively [2].

For relatively short switching time (T_{SW}) between HF-power and REF-power, the thermopile output does not reach the asymptotic values e_1 and e_2 requested by (2). However, these values can be obtained from the relative maximum and minimum values - e_M and e_m - of the thermopile output signal. The ratio e_R of the thermopile output voltages, equivalent to the long-time measurement as defined in (2), is given by

$$e_R = \frac{e_m}{e_M}\frac{1-\left(e_M/e_m\right)\exp\left(-T_{SW}/\tau\right)}{1-\left(e_m/e_M\right)\exp\left(-T_{SW}/\tau\right)} = e_\tau H_\tau, \tag{3}$$

where e_τ is the ratio of the extreme values of the thermopile output voltage at the switching moments, and H_τ is a correction factor for the limited switching time [2]. The *effective efficiency* of the power sensor will be computed, in this case, with the equation:

$$\eta_{eff} = e_R\, g = e_\tau H_\tau\, g. \tag{4}$$

For a time-constant of 30 minutes, 8 test frequencies and requiring 10 independent results, the overall necessary time is over 800 hours in the long-term measurement case and less than 300 hours in the accelerated case. However, this last method implies mathematical corrections having as result an increasing of the overall uncertainty.

The asymptotic values e_1 and e_2 requested by (2) can be also obtained as extrapolated values by using a nonlinear fitting algorithm as Levenberg-Marquard [4], [5]. Because there are two main parts that contribute to the heat developing, the power sensor and the feeding line, a sum of two exponentials with different time-constants has as result better extrapolated long-term values:

$$\mathit{fittedmodel}\ (x) = a_1 \cdot \exp(-b_1 \cdot x) + a_2 \cdot \exp(-b_2 \cdot x) + c, \tag{5}$$

where a terms are coefficients, b terms - inverse of the time-constants and c – the asymptotic long-term wanted value.

In all cases, the accuracy of the g factor contributes almost completely to the overall accuracy of the system. Therefore, an accurate microcalorimeter calibration step is necessary. We can attempt to measure directly g by reversing (2) for a well-known load. Usually, the microcalorimeter calibration needs both S-parameters and k ratio determination. The last one is a quite critical operation because it requires a change of the microcalorimeter configuration and long-term measurements [1], [2], [6].

The uncertainty budget allows to decide if the measurement method is satisfactory or not. New rules concerning this aspect allow to make the estimation of the uncertainty in every situation [7]. Thus, the long-term method can be used in the microcalorimeter calibration step, and the medium-term method for the repetitive measurements in the required test points.

III. Measurement algorithms and strategies in broadband microcalorimetry

Various states must be reached by the microcalorimeter and it is necessary to be followed by associated measurements: for confirming the state, for acting in various feedback loops and for computing the wanted quantity.

Even for the long-term measurements case, it is necessary to implement an algorithm considered as optimum for a given goal. Thus, the necessary measurement steps, the acquisition time intervals, the power levels, the frequency values, etc., are established according to the aim of the measurement [8], [9]. The applied algorithm is usually complete automatic [8], [10]. Before beginning a measurement/calibration process, the system is run usually for 24 hours in order to reach the steady temperature. Alternate equal time intervals follow when the high-frequency power is turn on and respectively off for several times. For all frequencies of interest the thermopile output is recorded. The same procedure is applied when the REF-power is applied. Finally, the *effective efficiency* of the microcalorimeter load and the overall accuracy of the results can be carried-out, starting from equations (1) and (2), [3], [7], [8].

In the accelerated measurement case, for medium-term measurement intervals, more strategies can be applied. Until now, the accelerated measurement algorithms have used equal-time measurement intervals, the input power being alternated between HF test power and reference power for the same effect on the SUT output. The calibration step can be derived from the measurement step, supposing as true some hypothesis [11], or from a long-term measurement performed on well-known microcalorimeter load. The *effective efficiency* of the SUT will be computed from (3) and (4) or as ratio of the free coefficient from (5); the overall accuracy of the results is a little bit difficult to be estimated in this case. Figure 2 shows the waveforms - acquired and extrapolated - for the microcalorimeter output quantity, the thermopile voltage, when the alternating of the power is performed in equal-time intervals. The fitted curves seems to follow perfectly the acquired data, but a goodness parameter of fitting process, as is RMSE - the root mean squared error - [12], has a typical value of 0.1 % for T_{SW} of about three time-constants [5]. If T_{SW} decreases, this parameter will increase. Table 1 shows this dependence resulted from recently dedicated measurements performed at INRiM – Italy. While the mean of RMSE ratio has the same depreciation as 3:1 switching time ratio, its mode value seems to be about 2 and enough frequently values are situated around of one. This means that it is possible to sequel decreasing T_{SW} below of three time-constant if is increasing the accuracy both in measurement of the thermopile output voltage and in establishing of the sampling time moments. However, a comparison between the results obtained for different T_{SW} shows that a large value of it lead to a good value having a small associated uncertainty [5].

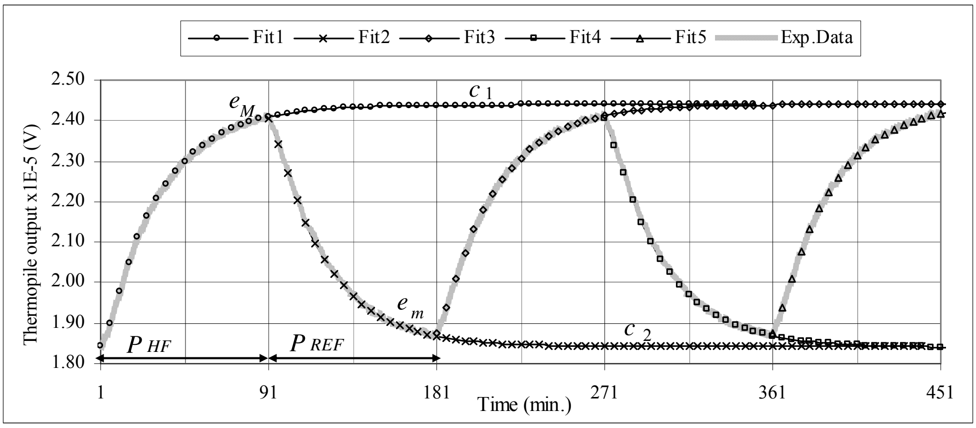

Figure 2. The thermopile output waveforms, acquired and extrapolated by a nonlinear fitting law, in the accelerated-measurements case.

Table 1. The goodness of the fitting process expressed by RMSE values at 10 GHz, T_{SW} of 30 min. and 90 min. for 4 full alternating cycles.

Alternating Cycle	1	2	3	4	5	6	7	8	Average
$RMSE_{30}$	0.1297	0.0034	0.0063	0.0053	0.0066	0.0057	0.0071	0.0031	0.0239
$RMSE_{90}$	0.028	0.003	0.003	0.007	0.003	0.005	0.003	0.004	0.0080
$RMSE_{30}/RMSE_{90}$	4.7	1.1	2.2	0.8	2.1	1.2	2.1	0.8	3.0

The new measurement strategy, proposed in this paper, is based on the variable measurement intervals. There are both some similarities and differences in comparison with the previously strategies:

- the input power alternates as reference power *on*/*off* or test power *on*/*off* for the same effect at the SUT output;
- the microcalorimeter output, i. e. the thermopile voltage, is varying now all the time between the same two limits, these being initially determined by *on*/*off* alternating the reference power for two equal medium-term intervals;
- the up-time becomes now dependent on the test frequency through *effective efficiency* of the SUT; the feeding lines losses and the down-time remain almost constant;
- excepting the beginning, no other transitions phenomena are present, microcalorimeter working in a quite stationary regime and the test frequencies order is not important;
- moreover, the measurements with the reference power must be repeated few times, only when it is considered as necessary to be inserted in the measurement cycle;
- the true-twin configuration can now really working;
- the voltage of the thermopile is now detected as limits, the lower one being without perturbation because it is performed in a quite-ideal required state [11], [13].

Figure 3 shows the simulated waveforms for the microcalorimeter output quantity in the variable-time interval alternating strategy. The upper and the lower thermovoltage output limits are obtained after two equal periods. These are chosen correlated with the time-constant and will remain the same all of the experiment time. The next time intervals are dependent on the power level and on the *effective efficiency* of the SUT. The thermovoltage ratio (3), implied in the *effective efficiency* computation, becomes as following:

$$e_R = \frac{1-e_\tau \exp\left(-T_{\mathrm{HF}}/\tau\right)}{1-\exp\left(-T_{\mathrm{HF}}/\tau\right)} : \frac{1-e_\tau \exp\left(-T_{\mathrm{REF}}/\tau\right)}{1-\exp\left(-T_{\mathrm{REF}}/\tau\right)} = const.\times\frac{1-e_\tau \exp\left(-T_{\mathrm{HF}}/\tau\right)}{1-\exp\left(-T_{\mathrm{HF}}/\tau\right)}. \tag{6}$$

The constant term in (6) is always greater than one and the variable ratio is always subunitary because e_τ ratio is less than one. In the measurement strategy, e_τ ratio should be chosen to obtain a small influence of the time-constant τ because this parameter is also obtained from the experiment. The time and the low level voltage of the thermopile output must be measured accurately and with a good resolution. The simulated results presented in Figure 3 are obtained in a typical case for τ of 30 min., the long-term thermovoltage asymptotic values of 0.7 mV at P_{REF} and 0.72 mV at P_{HF}. An error of 0.05 % appears in the result computed with (6) as a consequence of the 1 min. sampling resolution.

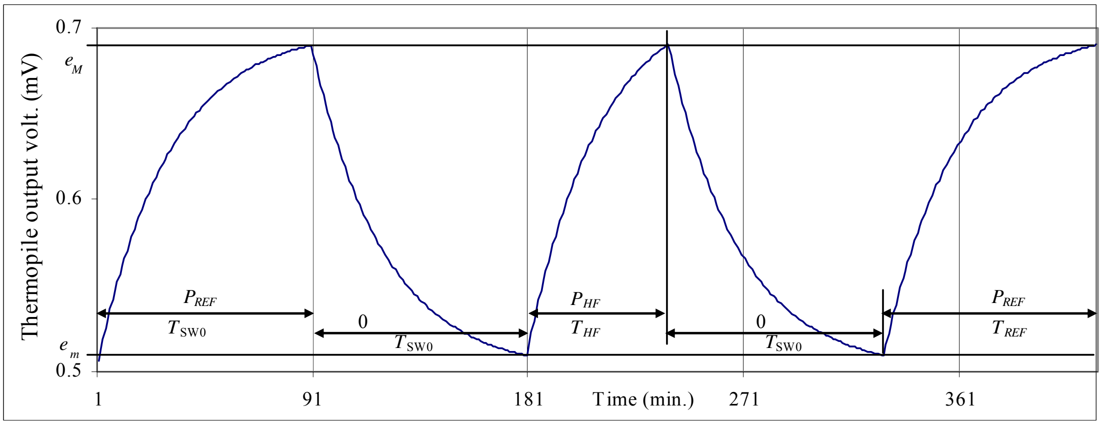

Figure 3. Microcalorimeter output quantity in the variable time interval case: the simulated results.

This algorithm is firstly developed to be verified and applied in a certified measurements at INRiM - Italy as an improvement of the accelerated medium-term method [2], [4]. Also, the features of this new algorithm should be useful in the high frequency losses measurement for magnetic amorphous wires and GMI sensors on the samples designed and supplied by the Romanian Institute of Research and Development for Technical Physics – Iasi.

IV. Conclusion

The measurements based on microcalorimeter can be performed by applying various strategies and algorithms. The long-term measurement algorithm is time-consuming, but it is sill remaining the reference one for the other developed accelerated algorithms. Besides the equal time-interval accelerated algorithms, used even in key microcalorimeter measurements, the new one proposed in this paper seems to have several advantages. The main advantage results from the used equation (6), which is very simple and has a small sensitivity to the thermal load time-constant, a parameter known following the experiment. Another notable advantage is the fact that the microcalorimeter is now working in a quite-stationary regime as result of the constant keeping of its output quantity limits. Finally, this new algorithm can assure the smallest overall measurement time possible and freedom in the test frequencies order and in the test power level selection.

Acknowledgments

This work has been supported by the Romanian Ministry of Education and Research under the CERES Project no. 06-11-58/2006, MATNANTEC 46/2006 and CHIRAL-EMC in the frame of the CEEX Program.

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