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Development of the PSO method for the determination of the dynamic response of a pyroelectric sensor

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Abstract. We modeled a pyroelectric sensor by a current source connected in parallel with output impedance. The dynamic behavior of the sensor is described using a transfer function designed using the MATLAB Simulink environment. The transfer function parameters are optimized using the optimization algorithm Particle Swarm Optimization PSO implemented in the MATLAB environment. This optimization is performed from a comparison with the measured signal. The transfer function thus determined is used to determine the dynamic properties of a pyroelectric sensor. To justify the validity of the proposed approach, we used pyroelectric sensor based on PVDF.

Keywords: pyroelectric sensor / transfer function / dynamic properties MATLAB/Simulink / PSO method

1 Introduction

Recently, uncooled infrared (IR) sensors are being increasingly demanded for many applications such as automobile, biomedical, plant monitoring, gas detection, fire monitoring, and security system [1–3]. IR sensors can be classified into two major types including photon sensors and thermal sensors. Compared with photon sensors, thermal type IR sensors, such as bolometer, thermopile, and pyroelectric sensors, can be operated at room temperature with little wavelength dependence of the response over a wide IR range. IR sensors using pyroelectric material have the highest sensitivity in thermal-type IR sensors. To realize uncooled pyroelectric IR sensors, an integration of pyroelectric material and circuitry using silicon devices is required [4].

The dynamic properties of the pyroelectric sensor have been identified theoretically [5–8] (mathematical model, electronic model and transfer function model) and experimentally by using different facilities and experiences [9]. However, it was noticed that after the conceptual design of the sensor, the use (in situ) of the sensor affects those already predefined parameters. The best way then is to redefine the parameters from the recorded actual signal [10].

The objective of this research is headed in that direction. It involves using the actual measurements recorded after the sensor design and develops the PSO algorithm to optimize the parameters of the transfer function of the pyroelectric sensor. This algorithm is based on virtual instrumentation and is developed in MATLAB environment. The number of model parameters is determined as an approximation of the solution of an optimization problem.

2 Transfer function of the pyroelectric sensor

The equivalent circuit includes three blocks of signal conversion for the pyroelectric sensor (Fig. 1) – thermal conversion, thermal to electrical conversion, and current to voltage conversion described by equations (1)–(3) respectively.

$$C_{th}\frac{dT(t)}{dt}+G_{th}T(t)=\eta\phi(t), \tag{1}$$

$$I_p=pA\frac{dT(t)}{dt}, \tag{2}$$

$$C\frac{dV(t)}{dt}+\frac{V(t)}{R}=I_p(t), \tag{3}$$

where T – temperature of the sensor, I_p – pyroelectric current, V – pyroelectric voltage, ϕ – heat flux, C_{th} – thermal capacity of pyroelectric sensor, G_{th} – thermal conductance of pyroelectric sensor, η – absorption coefficient of radiation, p – pyroelectric coefficient, C – equiva-

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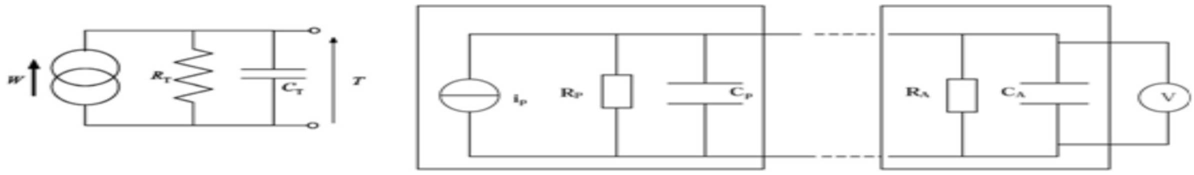

Fig. 1. Equivalent thermo-electrical model with system amplifier.

lent capacitance for parallel connected pyroelectric capacitance C_p and input amplifier capacitance: $C = C_p$, R – equivalent resistance for parallel connected leakage resistance of pyroelectric sensor R_f and input amplifier resistance: $R = R_f$.

Each of the conversion stages shown in Figure 1 are described by differential equations (1)–(3) can be modelled by a Laplace transfer function $G(s)$ defined as the ratio of the Laplace transform of the output signal to the Laplace transform of the input signal under the assumption that all initial conditions are zero. Circuit amplification are used to amplify the signal of the pyroelectric sensor and then added to equivalent thermo-electrical model (Fig. 1).

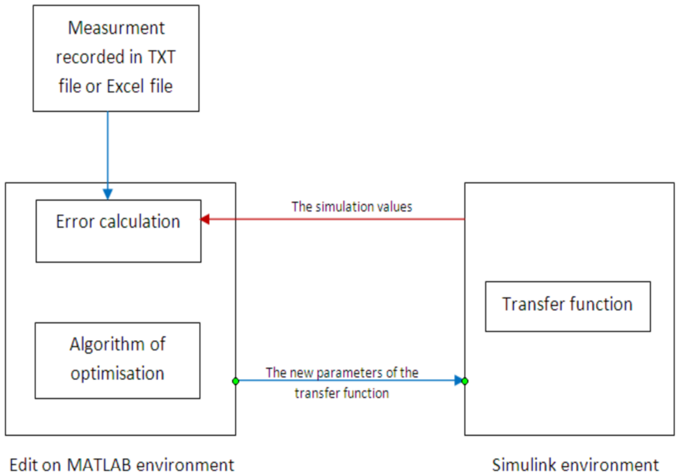

Fig. 2. Mechanism of the system identification parameters.

3 Measurement system and software program

In this section we present our measurement system and the software that we developed with MATLAB platform.

We have tow part in our software program. The first is the implementation of the transfer function on the SIMULINK tool of MATLAB. The second part is the algorithm developed in MATLAB edit file. So the two parts of the software communicate easily because we have the same platform of the programming simulation.

The mechanism of the identification system of the parameters of the pyroelectric sensor, which includes the measurement records and software developed with MATLAB platform is described in Figure 2.

3.1 Measurement system

We use in this case the experimental setup described in Figure 3: an incoming radiation chopped at increasing frequencies (up to 300 Hz) is focused on the sensor while the sensor output and the chopper driver signal are acquired by the oscilloscope connected to the PC with the USB port for real time acquisition (Fig. 4) and all the data of the signal is saved in Excel files.

We add a capacity C_f to the current–voltage amplifier (Fig. 5) to avoid the problem of the parasite signals and we have the low pass amplifier filter.

$$V_s = \frac{R_f}{1 + jR_f C_f \omega} I_p. \tag{4}$$

The detection card is characterized by an integration time constant $\tau_e = R_f C_f$, where R_f is the gate resistance value of the field effect transistor and C_f the capacity.

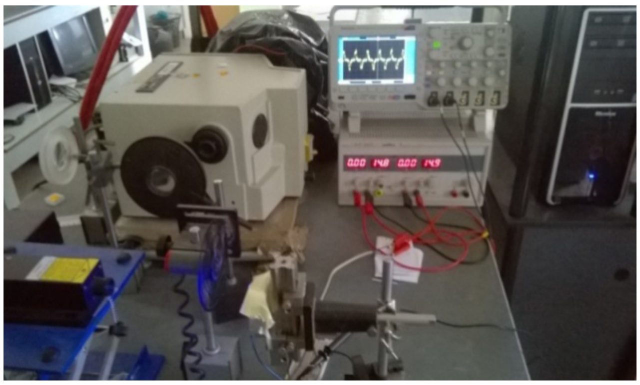

Fig. 3. Experimental setup used for the electric and optical calibration of the pyroelectric sensor.

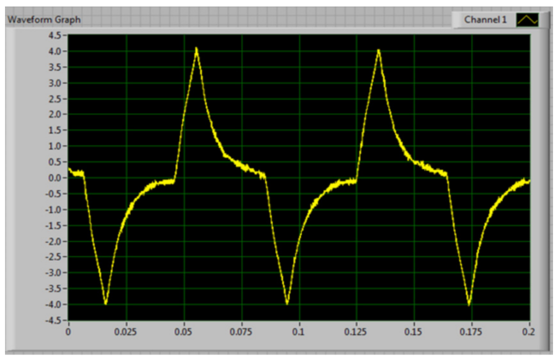

Fig. 4. Real time acquisition signal for the pyroelectric sensor.

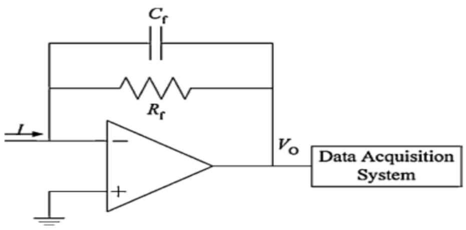

Fig. 5. The amplifier used to amplify the generated currant. C_f is the equivalent capacity of the system amplification.

3.2 Implementation of the transfer function in SIMULINK tool

The Laplace transfer function model $G(s)$ of the pyroelectric sensor described by equation (4) can be easily implemented in Simulink. For simulation study it is convenient to express the transfer function model $G(s)$ in the form of a product of three blocks connected in series and characterised by transmittances of $Gs = (\eta s)/C' dA(C_{th}s + G_{th})$, $G_{Ip} = pAs$ and $G_A = R_f/(1 + \tau_f s)$. It is not a necessary operation but it permits minimization of errors on modification of the detector parameters and easier prediction of consequences of these changes. Figure 6 shows the simulation diagram which is equivalent to the above-mentioned mathematical model of the pyroelectric sensor. The amplitude of the radiation power $\Phi = 0.1$ W.

3.3 PSO method and its validation

The computer program of PSO algorithm for the identification and prediction of the dynamic properties of the pyroelectric sensor was developed in the MATLAB programming edit file. A block diagram of the software algorithm is presented in Figure 7. The transfer function is estimated by employing the SIMULINK tool environment developed in Section 2.

The virtual instrument contains a multi-stage algorithm for the identification of the transfer function. In the first step, the parameters of the model (developed in SIMULINK) are estimated consecutively by employing the random method to have the start of the simulation. The second step was to compare the real signal with the estimated one using the standard error of estimate. The corresponding approximation responses to the measured excitation signal are then calculated. The quality of each approximation response is evaluated using the standard error of estimate [11]:

$$SEE(\Theta_a, \Theta_s) = \sqrt{\frac{1}{N_s - M}\sum_{i=1}^{N_s}[\Theta_a(t_i) - \Theta_s(t_i)]^2}, \quad (5)$$

where $\Theta_s(t_i)$ is the sensor's response at the discrete time t_i and $\Theta_a(t_i)$ is its approximation, N_s is the number of samples in the signal and $M = m + n$ is the number of parameters in the approximation model.

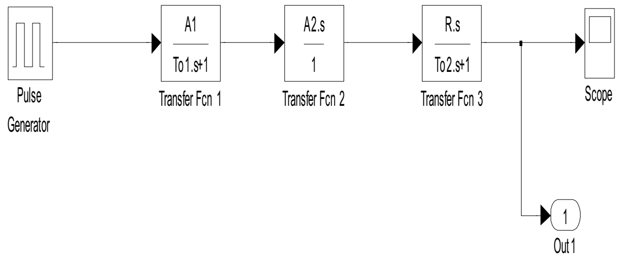

Fig. 6. Simulink block diagram for simulation of voltage response of the pyroelectric sensor.

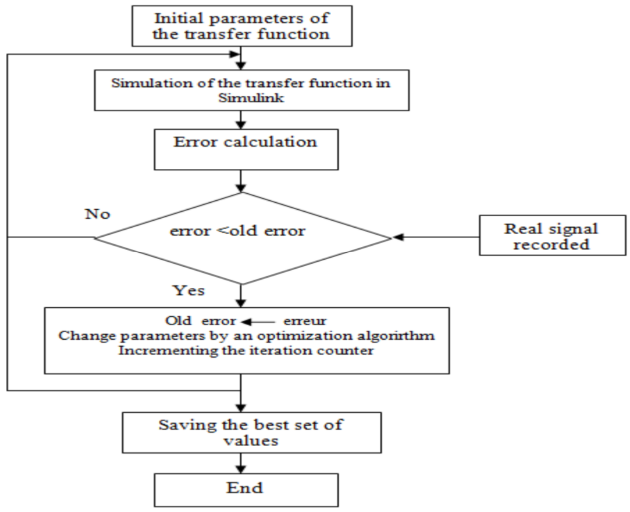

Fig. 7. Block diagram of the software algorithm for the identification and prediction of the dynamic properties of the pyroelectric sensor.

The solution is rearranged into the OE model (output error model) and the parameters of the transfer function were optimized using the Newton–Raphson method. The transfer function with the corresponding approximation response that exhibits the minimum value of SEE after several iterations is selected as the most suitable transfer function for the pyroelectric sensor under test.

The real signal can also be taken from recorded measures in Excel or TXT file. So we can build a model of pyroelectric sensor only from measures recorded without the test facilities.

4 Results and discussions: parameters determination of a PVDF sensor

The measurement system presented in Figure 3 was employed to carry out a case study. The area of the pyroelectric sensor is 25 mm^2. The tested sensor was connected to the measurement electronics. This measurement system was calibrated in the laboratory temperature at 25 °C with the reference temperature having an expanded measurement uncertainty of 2 °C.

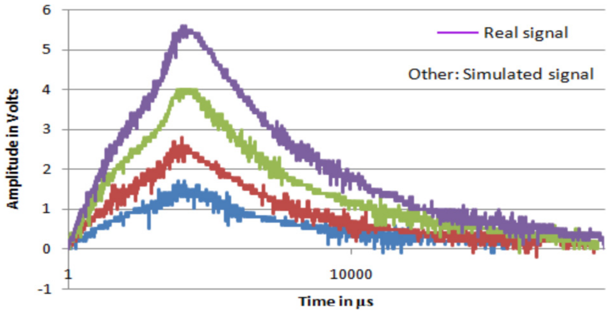

Fig. 8. Evolution of the result of the transfer function using the optimization algorithm.

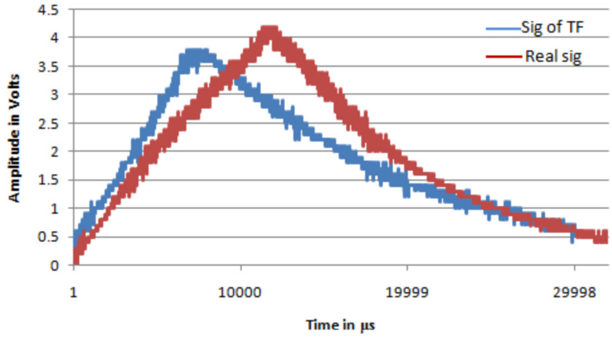

Fig. 9. The signal of the transfer function with the real signal.

The static calibration was conducted in the Laboratory of Materials Measurements and Applications (MMA) at the National Institute of Applied Sciences and Technology (INSAT, Tunisia).

The sensor under test was therefore experimentally validated to be suitable for predicting its dynamic properties (Fig. 8). The prediction error after iterations done with the software is equal to 5.21% and, as a result, it lies within the specified acceptance interval of ±10%.

The accuracy of the estimated transfer function depends on a variety of parameters, such as the signal length, the sampling frequency and the signal noise. A careful visual examination of the resulting approximation response is recommended. In the case of inappropriate results the identification procedure should be repeated, using, e.g., signals with a modified length or down sampled. It is also reasonable to minimize the noise of each signal, e.g., by employing a moving average or an ensemble average of a few measured signals. Another possibility is to change the convergence criteria of the PSO algorithms within the system identification process.

Further testing with different settings and by employing both the simulation and the experimental signals should be performed in order to analyze and improve the capabilities of the developed software.

For the purposes of the system identification, the lengths of the signals in SIMULINK tool were set to 0.01 s (equivalent to radiation after chopper modulation). The minimum values of the SEE are equal to 1.27×10^{-2}. The following transfer functions were identified as the most suitable for the sensor under test:

$$G(s) = 0.064s/[(0.002s + 1) \times (0.0008s + 1)].$$

And the best signal of the optimized transfer function of the pyroelectric sensor by our developed software is presented in Figure 9.

We have as result of the PSO optimization the thermal constant of the pyroelectric sensor wish is $\tau_{th} = 0.002s$. It describes the propagation thermal wave in the sensor after its design and conception. We can therefore compare the theoretical result and the experience result to see the difference and the impact of conception process on the pyroelectric sensor. Also we can have the value of the $\tau_e = R_f C_f = 0.0008s$.

We apply this easy method to identify the C_p of any pyroelectric sensor from measuring its signal output or from recorded measuring of the sensor and apply our developed software to identify the characteristic C_p.

5 Conclusion

In the literature, the determination of the dynamic properties of the pyroelectric sensor is usually performed either from theoretical models or appropriate experimental techniques. We have developed a method for the identification of these parameters by combining these two approaches. The measuring device can record the output signal from the sensor. We designed an appropriate transfer function and developed an optimization algorithm implemented in the MATLAB environment to determine the parameters of the transfer function of the pyroelectric sensor and its dynamic properties. The advantage of this method, in addition to its instrumentation at very low cost (we used the standard electrical components: resistances, capacitors, TLO71 amplifier, oscilloscope and USB interface with a PC), is the determination of the parameters of the pyroelectric sensor just after conception to study the effects of the fabrication process on the sensor specially on its thermal parameters by comparing the theoretical parameters and the experimental parameters we get with our measurement system for a better integration in automated system (intrusion detection, high temperature control, thermal vision system, etc.).

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