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Thermal Modelling of a Thermopneumatic Actuator

FERNANDO VIDAL-VERDÚ, RAFAEL NAVAS-GONZÁLEZ AND MARÍA JOSÉ BARQUERO
Dto. de Electrónica.
Universidad de Málaga.
SPAIN
Complejo Tecnológico, Campus de Teatinos, Málaga, SPAIN

Abstract: To get a good dynamic response from a thermomechanical actuator while not destroying the heating element is a common challenge. Actuators are usually driven by a PWM signal whose duty cycle determines the power transferred to the actuator. This involves the operation of the semiconductor devices as power switches. The thermal response of these devices is characterized by parameters like the thermal resistance or the thermal impedance. Device manufacturers include these data in the datasheets and some give an RC ladder model to allow the simulation of the thermal behavior with an electrical simulator like SPICE. This procedure can be extended to the thermomechanical actuators to characterize them in a similar way. Specifically, this paper reports the procedure to obtain an RC model of a thermopneumatic actuator proposed by the authors to be part of a tactile display. The characterization has been carried out with common instrumentation and software tools.

Key-Words: Thermopneumatic actuator, characterization, modelling, RC ladder model

1 Introduction

Active thermal control has been used to perform direct mechanical actuation through electrothermal expansion or phase transition resulting from Joule heating. Examples of such actuators are bimetallic or polymer based benders, Shape Memory Alloy devices or thermopneumatic micropumps that are used in applications like medicine or rehabilitation engineering [1].

The resulting thermomechanical actuators provide good performance in terms of displacement, force, and work per cycle. However, they usually have a poor dynamic response. In order to improve this aspect, a strategy reduces the thermal resistance by cooling to decrease the deactivation time [2]. Moreover, the power dissipated is increased to rise the temperature quickly. However, the injected power cannot be increased arbitrarily, since it could destroy the heating element. It is possible to use the heater also as a temperature sensor in the control loop to optimize the response and avoid that a too high temperature damages the device [3][4]. This approach allows an accurate control but the cost is high in terms of complexity and circuitry, thus it should be used when a smart isolate device is being designed or just to research into the device activation. Otherwise, for instance if the system to be designed is composed by several actuators (a tactile display for visually impaired people is a good example [3][5]), an open loop activation is recommended to simplify the circuitry and reduce the price. However, in order to optimize safely the dynamic response, the devices must be modeled to perform extensive simulations.

Thermal modeling is usually done for power semiconductor devices like power transistors or thyristors. Resistors as well as diodes are used as sensing elements to monitorize the temperature [6] and get the thermal features. Data as thermal resistance or thermal impedance curves are then provided to know the temperature of the device when it is activated [7]. These curves are usually enough for many applications, but they do not cover all possible situations. However, an RC model can be got from these data. Such model is very easy to manage with an electrical simulator and good estimations of the thermal behaviour can be made without risk [8].

Although such procedure was first applied to power devices, it can also be used on thermal actuators [1][4]. This paper presents the modeling of a thermopneumatic actuator for tactile displays that follows this approach to get the model from data obtained from experiments and common software tools.

2 Thermopneumatic actuator

Thermopneumatic micropumps and microvalves are based on sealed cavities that have a flexible side. The cavities are filled with a low boiling point liquid (for instance methyl chloride) and a resistive heater is built inside. When the heater increases the temperature in the cavity, the pressure grows because of the gas resulting from the liquid-gas phase transition, and the flexible side of the cavity is displaced.

This idea was proposed by the authors to build tactile displays. Fig. 1 shows the actuator as built to get the results of this paper. It consists of a small cylinder made of brass with an end sealed with tin and the other with a flexible diaphragm. A signal diode has been chosen as heater due to its small size, although it can be replaced by a resistor or other semiconductor devices. Further improvements will place the heater inside the cavity. With regard to the substance in the cavity, the authors proposed acetone or methanol. A good sealing must be made in case of using such substances. Other authors have proposed wax or parafine [5] that have less leakage problems, although the dynamic response is worse. We provide a model for the actuator filled with methanol in this paper. The diaphragm has been implemented with a 150μm thick latex membrane, although it is stretched and so the final thickness is lower.

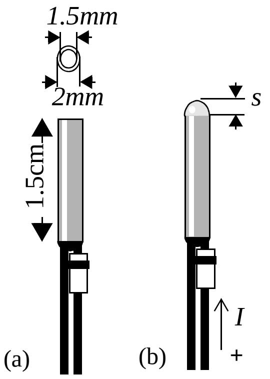


Fig. 1 Thermopneumatic actuator.

3 Procedure

Thermal resistance is usually provided to characterize a device under static conditions. This parameter is given by the equation

$$R_{thjx} = (T_J - T_X)/P_D \quad (1)$$

where T_J is the junction temperature of the DUT (device under test), and T_X the reference temperature at X, which can be the encapsulation (T_C) or the ambient (T_A). Briefly, the procedure to obtain R_{thjx} is:

1.- Calibration of the parameter sensitive to the temperature (TSP). This parameter can be the voltage drop at a pn junction, or through a sense resistor.

2.- Apply power and sample pulses (the duty cycle is 99.9%, thus the excitation is considered dc).

3.- Measure T_J (through the TSP), T_X and P_D in the windows opened by the sample pulses once the steady state is reached.

4.- Calculate the thermal resistance as (1).

Thermal resistance is not enough to estimate the junction temperature if the device is not activated in dc. Devices are commonly activated with power trains whose duty cycle determines the average power. Thermal impedance $Z_{thjx}(t)$, or an RC ladder model is provided instead to characterize the device. The latter is obtained by fitting the experimental data from the transitory response of the device. This response can be the so called heating curve or the cooling curve, i.e. when the device is heating up or when it is cooling down. Experimental data in the last case are got in two steps:

1.- Apply power (PD) to the device until it reaches the thermal equilibrium.

2.- Remove the power supply and sample the TSP and the reference temperature T_X.

This can be better than sampling the heating curve because of two main reasons. First, in the heating curve case the power transfer is interrupted by the sample pulse and this affects the measurement, what does not happen in the cooling curve case. Second, the electrical transitory is quite long when the power is removed, thus it is necessary to open a wide sample window to wait for it is over and take the correct measurement in the heating curve case.

Once a set of experimental data are got from the cooling curve, it is possible to derive an RC model from them. It is usually a semi-automatic procedure [4] because the choice of the order of the RC ladder is usually made by trial and error. Once the order is chosen, different approximation procedures can be used to find the parameter values of the model that provides the same dynamic response. Here we have used MATLAB tools to obtain the model. Specifically, the tool Simulink Parameter Estimation.

4 Circuitry and Experimental Setup

We have used the PIC18F4431 microcontroller together with some circuitry to take the measurements referred in the previous section and control the power applied to the device through a pulse train of proper duty cycle. Data taken by the microcontroller is transferred serially to a PC to perform computations and show graphics.

As said above, the first step is the calibration of the TSP. Since we have used a simple signal diode as heater, the voltage drop through it can be used as TSP. This voltage is quite linear with the temperature if the diode is biased with a constant current I_{cal}. Hence, a constant current source has been implemented to bias the diode (see building block B at Fig. 3). Moreover, it has been attached to a power variable resistor that works as heater to generate different temperatures for the calibration process (a grease has been used to reduce the thermal resistance). Finally, the temperatures and the voltage drops has been registered by a multimeter with proper probes (thermocouple and voltage probes). Fig. 2 shows the result of the calibration process.

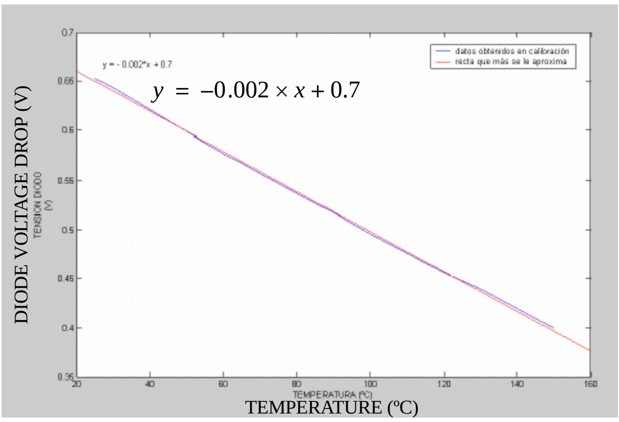


Fig. 2 Calibration of the TSP.

Further steps require the control of the power supplied to the device and the measurement of its dissipated power and the TSP. Fig. 3 shows the circuitry implemented to carry out this task. The cicuitry provides a power regulated by the duty cycle of the microcontroller PWM output signal S_C. Specifically, this signal drives the switch S to feed the diode with the current I_S provided by the transistor BDX34C at building block A. The voltage drop at the resistor Rsense gives information about the current through the diode I_D ($I_{cal} \ll I_S$), and it is measured with the differential amplifier D (building blocks F are voltage followers with high input impedance) while the drop in the diode V_D is also read to compute the amplitude of the power pulse $P_D = I_D \times V_D$. The voltage drop at the diode is also our TSP, but here we perform a differential measurement, we use a similar diode that is also biased in the same way but it is kept at ambient temperature, then we measure the difference of the voltage drops at both diodes with an instrumentation amplifier (INA112). The ambient temperature is also read with a thermocouple. The microcontroller can compute the temperature at the diode junction from these data and those from the calibration at Fig. 2. The use of a reference diode at ambient temperature allows the compensation of interferences due to the variation of this temperature. Fig. 5 shows a photograph of the described circuitry and experimental set-up.

The procedures to measure the thermal resistance and impedance have been implemented in the microcontroller and the personal computer. Specifically, the microcontroller performs the steps related to power regulation, sampling and A/D conversion, and serial communication with de PC. Tasks that involve more computational overhead and graphical representation are carried out in the PC.

5 Validation

The above described system and procedure has been validated with the commercial power diode MUR880E. Thermal resistance depends on the dissipated power [9], specifically we have observed that the larger the power the lower the value of the thermal resistance. Hence, we have biased the diode to obtain the same thermal resistance that is reported in the datasheet R_{thjc} = 1.51 ºC/W. Moreover, data of thermal impedance are normalized in the datasheet with respect to this value of thermal resistance. It has been measured the juntion to case thermal impedance since this is the data provided in the datasheet. The device has been attached to a bulky heatsink to reduce the variations of the case temperature. The reference temperature is taken from this heatsink with a thermocouple. The thermal impedance is computed as

$$r(t)_{thjx} = (T_J(t) - T_X(t)) / P_D R_{thjx} \quad (2)$$

from the data obtained with the experimental setup described above (the reference X is the encapsulation). However, we first have to obtain the equivalent heating curve from the experimental data of the cooling curve as $T_{heating}(t) = T_{max} - T_{cooling}(t)$ (they are theoretically identical [8]).

Time (ms)	measured r(t)	datasheet r(t)	error (%)
0.01	0.020	0.018	11.1
0.10	0.068	0.060	13.3
1.00	0.190	0.180	5.5
10.00	0.390	0.390	0.0
100.00	0.600	0.600	0.0
1000.00	0.900	0.900	0.0

Table 1 Data for the MUR880E

Table 1 shows the comparison between the values of the thermal impedance obtained and provided in the datasheet, where it can be observed a great coincidence. Largest errors are detected at short times. This is due to the extrapolation made to provide data at the beginning of the curve (for times below 100µs). This extrapolation (it is made with

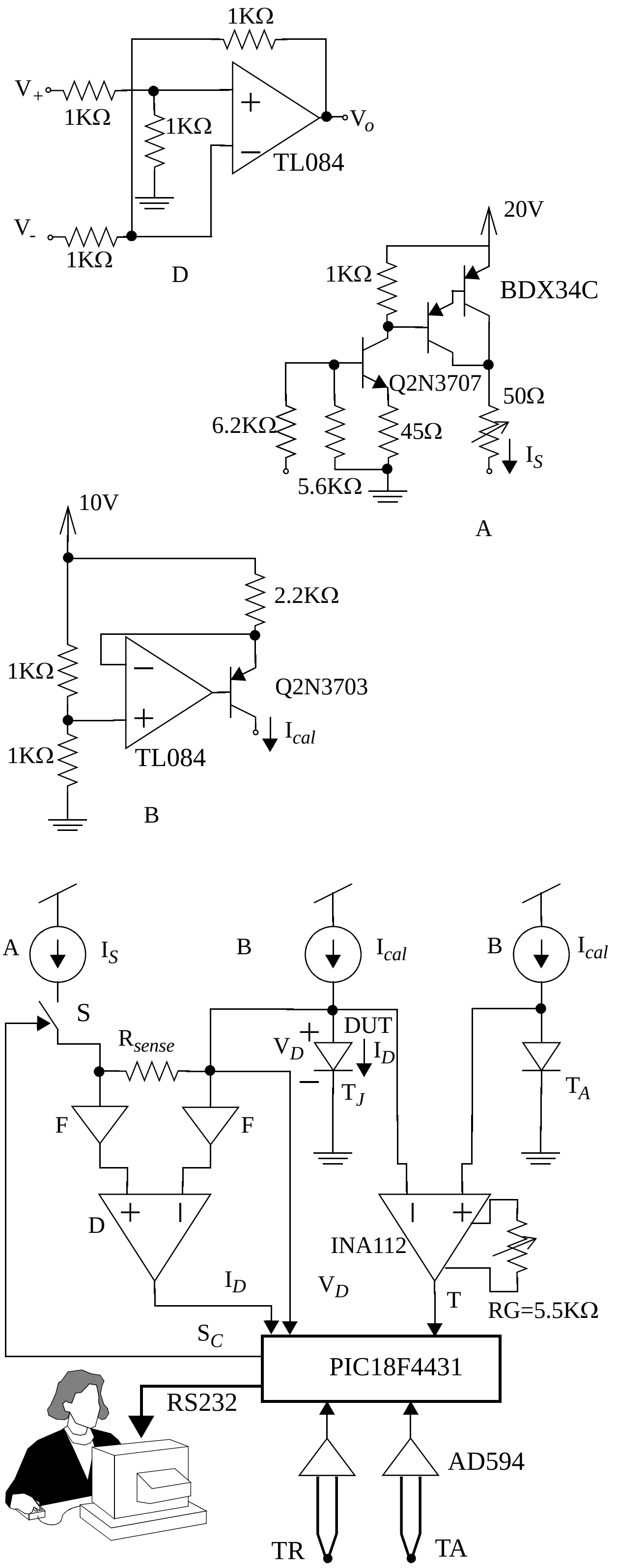


Fig. 3 Circuitry and experimental set-up.

Labview utilities) has to be made because the electrical transitory (see Fig. 4) masks the thermal one at this first stage of the process [10]. The error is

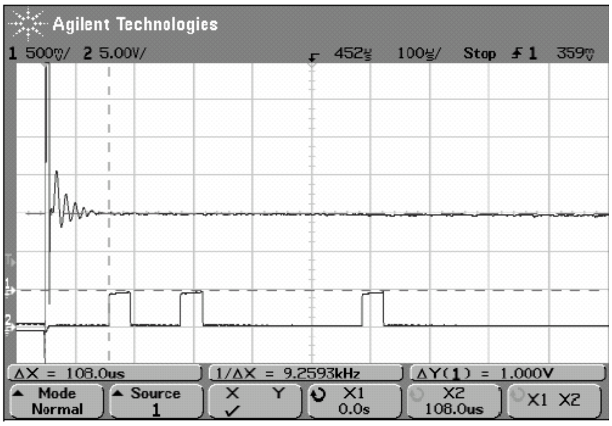


Fig. 4 Electrical transitory at the begining of the meaurement process.

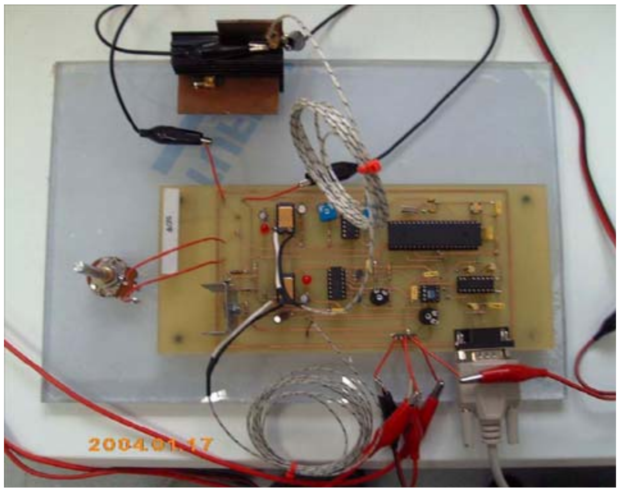


Fig. 5 Fotograph of the experimental set-up.

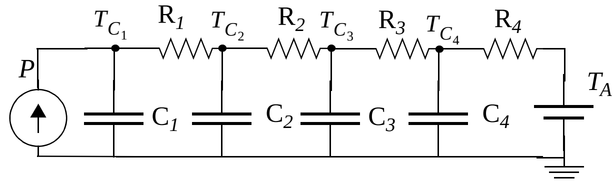
small as time increases. However, note that the datasheet provides curves at logarithmic scale and it is not possible to obtain accurate values from these curves. Nevertheless, the comparison shows a good agreement between data from our procedure and those from the manufacturer.

6 RC ladder model

To get the RC ladder model from the experimental data we have used the software tool Simulink. First, we chose a model of order *n*, then we write the state equations of the model and draw the corresponding block diagram with Simulink. The resistances and capacitances of the model are the parameters to estimate. It is done by the tool Simulink Parameter Estimation. Although it sounds quite short and direct, it is a bit cumbersome process because the order of the model is chosen heuristically. The initial values of the parameters have also to be set carefully for the program to converge into a suitable solution. Another condition is that the summation of the resistances in the model must be the value of the thermal resistance. Fig. 6 shows the 4th order model we have used for the results in this paper. The state equations and their corresponding diagram in Simulink are shown at bottom of Fig. 6.

7 Results and discussion

The procedure to obtain the thermal resistance and the RC model has been applied to the thermal actuator described in the section 2 Fig. 7(a) shows the curve obtained with the Simulink Parameter Estimation and the experimental data. The latter were a set of 46 data, ten per decade in a logarithmic scale. The first measured datum was for 100us because of the electrical transitory (see Fig. 4). Fig. 7(b) shows the errors between the experimental and the fitting curve. Finally, Fig. 7(c) shows the corresponding RC ladder model, and 146ºC/W is the measured junction to ambient thermal resistance. To validate the model we have taken another set of measurements that are the temperature increments over the ambient temperature generated by an excitation with different frequencies and duty cycles. The same measurements are made with the model of Fig. 7(c) and the electrical simulator PSPICE. The results are shown in Table 2, were an ambient temperature of 25ºC has been added to the measured increments (this has been done to get more uniform data, because the ambient temperature was not always the same, although it was around 25ºC). Actually, the accuracy of the data in Table 2 is not as high as shown if we take into consideration noise, interferences and even ripple caused by the square wave excitation. More further work has to be done in calibration and error corrections. However, these data that are shown as given by the used tools show a good agreement between the model and the experimental data. This is specially true for low frequencies, below 10kHz, while there is a larger difference for increasing frequencies. There are two main reasons for this. First, the first data we measure is for 100us, and the data below this time are extrapolated by the model. Although this is a common reported problem for this characterization, some further tuning of the model and also some strategies can be implemented [11] to get better results at these high frequencies. Second, note also that the experimental measurements of the junction temperature for different frequencies and duty cycles are also made in a sample window. Power supply is then interrupted in this sample window that is 100us width to avoid the electrical transitory. This interference is specially noticeable for signals with periods below 100us, i.e. frequencies above 10kHz.



$$\dot{\boldsymbol{T}}_C = \boldsymbol{M}\boldsymbol{T}_C + \begin{bmatrix} \frac{1}{C_1} \\ 0 \\ 0 \\ \frac{1}{R_4C_4} \end{bmatrix}^T \begin{bmatrix} P \\ 0 \\ 0 \\ T_A \end{bmatrix} \qquad \boldsymbol{T}_C = \begin{bmatrix} T_{C_1} \\ T_{C_2} \\ T_{C_3} \\ T_{C_4} \end{bmatrix}$$

$$\boldsymbol{M} = \begin{bmatrix} -\frac{1}{R_1} & \frac{1}{R_1C_1} & 0 & 0 \\ \frac{1}{R_1C_2} & -\left(\frac{1}{R_1}+\frac{1}{R_2}\right)\frac{1}{C_2} & \frac{1}{R_2C_2} & 0 \\ 0 & \frac{1}{R_2C_3} & -\left(\frac{1}{R_2}+\frac{1}{R_3}\right)\frac{1}{C_3} & \frac{1}{R_3C_3} \\ 0 & 0 & \frac{1}{R_3C_4} & -\left(\frac{1}{R_3}+\frac{1}{R_4}\right)\frac{1}{C_4} \end{bmatrix}$$

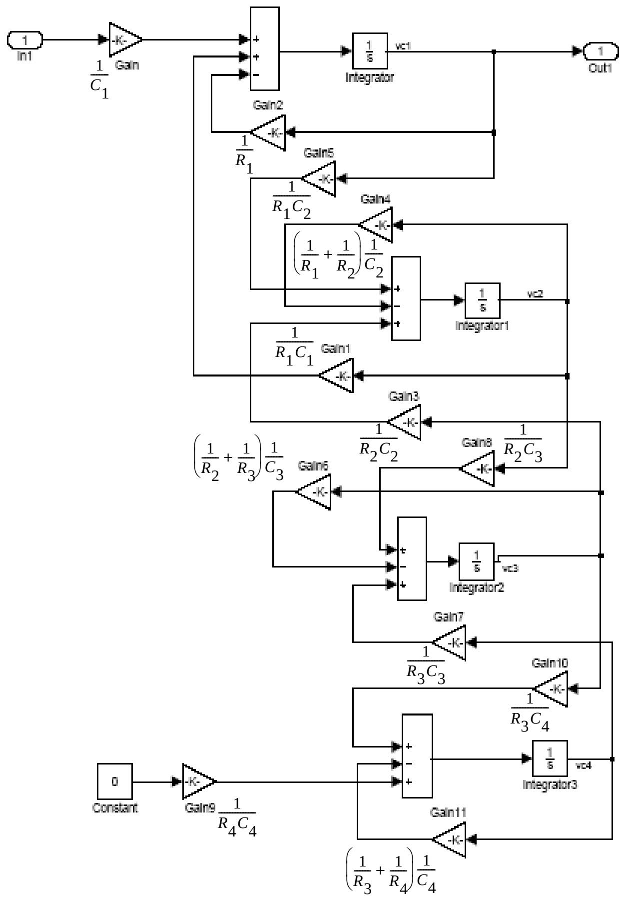


Fig. 6 State equations and Simulink diagram of the 4th order RC ladder model.

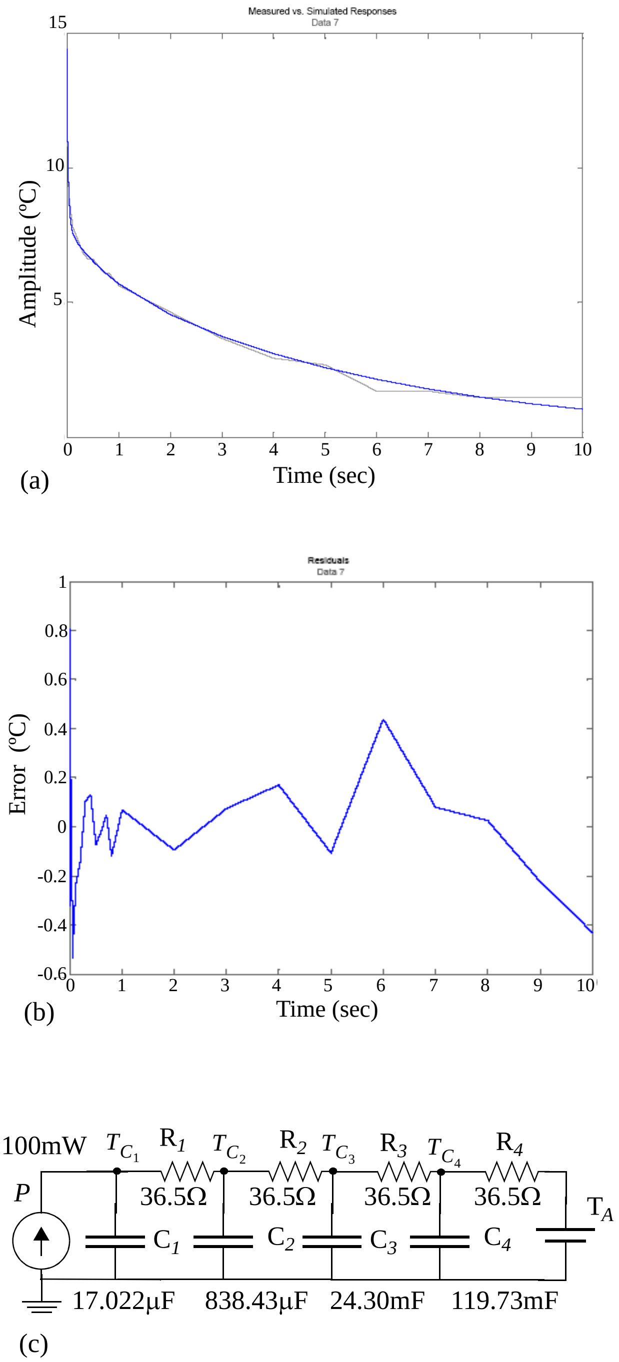


Fig. 7 Fitting curve provided by the Simulink Parameter Estimation and experimental data (a), approximation errors (b), and resulting 4th order RC ladder model (c).

Finally, the power pulse amplitude can also be a source or error because all the simulated results are affected by this value.

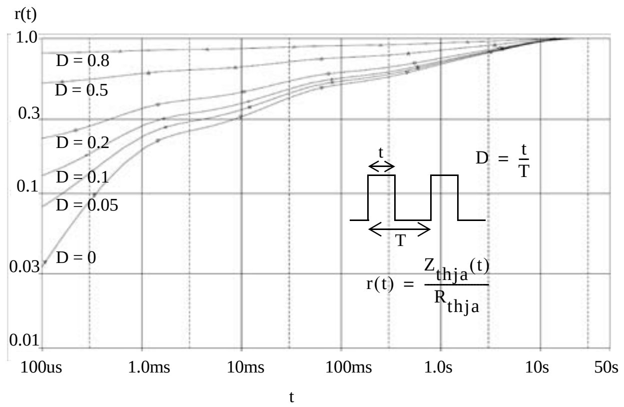


Fig. 8 Impedance curves of the actuator.

Fig. 8 shows the thermal impedance curves of the actuator. They have been obtained from the model with r(t) given by the equation (2) and the ambient temperature as the reference. The remaining curves for duty cycles higher that zero are calculated by the equation

$$r_D(t) = D + (1 - D)r(t) \qquad (3)$$

that is reported in [12]. Other ways to calculate these curves are also reported in [12] that provide less conservative results.

In addition to the above said improvements, a better model could be got just increasing the order of the RC ladder. An increasing number of measured data in the cooling curve could also be worthy. The increment of the power pulse and then of the initial temperature of the cooling curve would give also a better resolution because the relative errors will be smaller. Nevertheless, the thermal resistance depends also on the temperature [9], specifically its value decreases with the temperature, hence the model could underestimate the real temperature in this case. It is better to have a model that gives a worst case although most of the times it overestimates the junction temperature.

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Freq (kHz)	D=20%			D=50%			D=80%		
	T_{Jexp}	T_{Jmod}	Δ	T_{Jexp}	T_{Jmod}	Δ	T_{Jexp}	T_{Jmod}	Δ
0.5	27.20	27.56	-0.36	31.10	31.80	-0.70	36.10	37.10	-1.00
1	28.91	28.17	0.74	32.16	32.40	-0.24	35.98	37.48	-1.50
3	27.20	28.50	-1.3	31.59	33.30	-1.71	36.23	37.90	-1.67
5	28.42	28.90	-0.48	33.04	33.50	-0.46	37.64	38.20	-0.56
10	27.43	29.60	-2.17	32.09	34.30	-2.21	36.72	38.90	-2.18
25	28.91	32.00	-3.09	33.30	36.65	-3.35	37.70	37.10	0.6

Table 2 Experimental vs. Simulated data

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