A method for thermal model generation of MEMS packages

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ABSTRACT

MEMS applications are frequently thermally operated, so knowing the thermal characteristics of their packages is very important. This paper presents a method for the generation of reduced order dynamic thermal models, either from simulated or from measured transient results. The applicability of the method is presented on a benchmark package used for (pressure) sensor applications.

Keywords: reduced order models, thermal models, package models

1 INTRODUCTION

Packaging of micro–electro-mechanical systems (MEMS) is a very difficult and broadly researched subject today. Beyond the usual demands for microelectronics packages MEMS packages have to fulfil special requirements. The special requirements are originating either from the fact that MEMS usually contain tiny mobile parts that make packaging especially difficult, or from the fact that in case of intelligent sensor packages special openings have to assure the direct contact of the silicon with the ambient outside the package.

System level design of MEMS requires appropriate framework and reduced order or compact models of the devices for the various domains considered [1],[2].

In our paper we focus on generating compact thermal models for multi-domain system level simulation. We present two different ways for compact thermal model generation that are available in commercial tools. We provide a comparison of the applicability of the methods on a benchmark package.

At the end of the paper we outline the idea of generating a package thermal library that can provide instantaneously the thermal model of a package for system level design.

2 COMPACT MODEL GENERATION FROM TRANSIENT RESULTS

The basic idea of this method is to generate a simple RC ladder network that provides the same thermal transient response for a given excitation as the measured one on a real system, or the one obtained by thermal simulation.

Since thermal responses of microelectronics systems have time constants in a large time-range (several orders of magnitude) it is convenient to use the logarithm of the time

$$z = \ln t\,, \tag{1}$$

as the independent variable of the equations. We can define the $R(z)$ *time-constant density* function, which gives the intensity of the different time-constants in the response. The $R(z)$ function is a continuous spectrum in case of infinite distributed networks, like thermal RC networks (Figure 1b).

The thermal transient response is closely related to the time-constant density. The unit-step response can be expressed as

$$a(z) = \int_{-\infty}^{\infty} R(\zeta)\big(1 - \exp\big(-\exp(z-\zeta)\big)\big)d\zeta\,, \tag{2}$$

which is a convolution-type formula. Differentiating both sides yields

$$\frac{d}{dz}a(z) = R(z) \otimes w(z) \tag{3}$$

where ⊗ is the convolution operator and

$$w(z) = \exp\big(z - \exp(z)\big) \tag{4}$$

is a weighting function [3][4].

To restore $R(z)$ from the measured or simulated $a(t)$ unit-step response — according to eqs.(1–4) — the following steps should be carried out:

- $a(t)$ has to be transformed to logarithmic time scale,

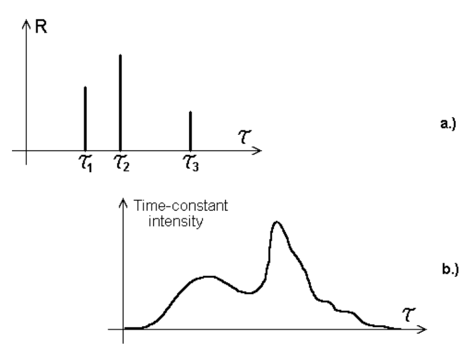

Figure 1 a.) Discrete τ lines of a lumped network,
b.) Continuous τ spectrum of a distributed structure

- $a(z)$ has to be differentiated numerically,
- $\frac{d}{dz}a(z)$ has to be deconvolved by $w(z)$.

There is no straightforward way to execute the inverse operation of convolution, the so-called deconvolution and it is very sensitive to inaccuracies and noise of the input function. Workarounds of this problem and problem-oriented implementations are detailed in [5].

The most suitable deconvolution solution in our case is the Fourier-domain inverse filtering. The input data may be either the time-domain or the frequency-domain response.

To compensate the noise enhancement effect of deconvolution, a pseudo-random noise is added to the $w(z)$ function. The relative amplitude of this noise should be equal to the signal-to-noise ratio of the input function.

Just before the inverse Fourier transformation step a Gauss filtering of adaptively controlled bandwidth is applied in order to preserve the highest possible resolution while keeping the noise level low.

In the last step the *R(z)* function has to be discretized and approximated by R and C values. Details of this problem are discussed in [5] in comparison with the well-known asymptotic waveform evaluation (AWE) [6] method.

The above scheme was implemented in the THERMODEL tool [7]. All Fourier transformation steps are using Fast Fourier Transform (FFT) algorithm resulting in very low run time.

The output of this tool is the SPICE net-list of a single thermal RC network for driving point impedance (see Figure 2) and a twin ladder network for transfer impedance. In the latter case the time-constants of positive amplitude form one RC network and those of negative amplitude form the other.

3 COMPACT MODELS FROM DIRECT GENERATION OF THE TIME-CONSTANT SPECTRUM

The time-constant spectrum function can also be calculated directly with a simulation tool, that is capable to calculate the thermal responses in the domain of the **s** complex frequencies. It is easy to prove (see [3]) that the $R(z)$ spectrum can be obtained from the complex impedance $\mathbf{Z}(\mathbf{s})$ according to the equation

$$R(z) = \mp\frac{1}{\pi}\operatorname{Im}\mathbf{Z}\big(\mathbf{s} = -\exp(-z)\big). \tag{5}$$

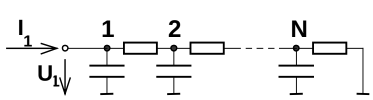

Figure 2 RC ladder model for thermal impedance between the driving point and the ambient

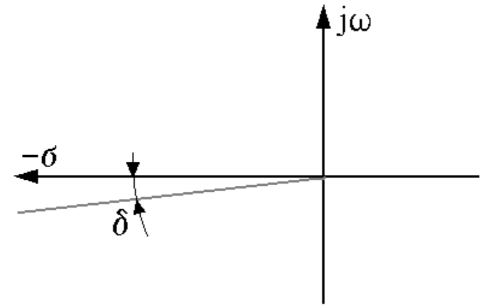

Figure 3 The line **s**(*z*) on the complex plane

Eq.(5) suggests that the calculation of the time-constant spectrum is very simple: only the imaginary part of the **Z** impedance has to be calculated along the negative real axis of the complex plane. But the poles of the lumped RC network or of singular lines of a distributed system lie along the same axis. These singularities make eq.(5) non-applicable for calculating the time-constant spectrum.

It is still possible to work around this problem by calculating the time-constant spectrum along a line (like eq.(6)) very close to the real axis (see Figure 3), thus avoiding the singularities.

$$\mathbf{s} = -(\cos\delta + j\sin\delta)\exp(-z) \tag{6}$$

Even if δ is small an error is introduced into the calculated time-constant spectrum function, $R_C(z)$, which can be proven to be equal to the convolution of the exact $R(z)$ and the introduced error $e_r(z)$:

$$R_C(z) = R(z) \otimes e_r(z), \tag{7}$$

where

$$e_r(z) = \frac{\sin\delta\exp(-z)}{1 - 2\cos\delta\big(\exp(-z) + \exp(-2z)\big)} \tag{8}$$

This $e_r(z)$ function is a narrow pulse — as shown in Figure 4 — depending on the disorientation angle δ. The smaller δ is the narrower the pulse will be, which means that choosing an appropriately small δ, any accuracy

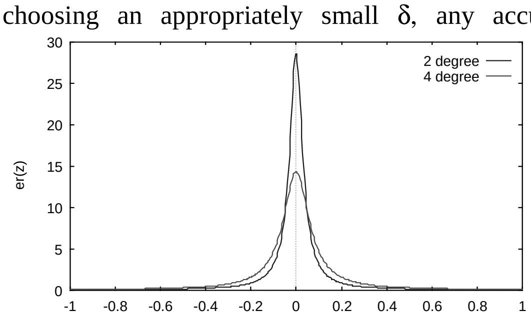

Figure 4 The $e_r(z)$ function

requirements can be fulfilled. The resolution is determined by the half-value width of this pulse:

$$\Delta_e = 2\ln\left(2-\cos\delta+\sqrt{(2-\cos\delta)^2-1}\right)\approx 2\delta \qquad (9)$$

According to eq.(9) the resolution is 0.1 octave (a ratio of 1.072) for $\delta=2°$. Another important role of the half value width is the determination of the appropriate Δz step during the calculation of the spectrum: $\Delta z < \Delta_e/2$.

4 EXPERIMENTS FOR COMPACT MODEL GENERATION ON THE SP10 PACKAGE

We have simulated the thermal behavior of the benchmark pressure sensor package with the ANSYS [8] FEM program and the SUNRED [9],[10],[11] FDM based field solver.

4.1 ANSYS Transient Results Processed by THERMODEL

Using the time-domain calculation facilities of the ANSYS program we have simulated the transient behavior of the structure. The chip was driven by a step-function dissipation of 1 W. The time response at the center of the chip is plotted in Figure 5.

Using the evaluation methods presented in Section 2 the spectrum of the time constants in the response can be extracted. The time-constant spectrum obtained by THERMODEL [9] is shown in Figure 6. The R/C values of the compact thermal model of the structure are presented in Table 1.

Table 1 R and C values

N	R [K/W]	C [Ws/K]
1	2.89	4.74e-02
2	7.54	3.12e-02
3	1.62e+01	2.03e-01

4.2 Model Generation by the Transient and Time-constant Analysis features of SUNRED

SUNRED simulations were run on one hand to compare the results to those of the ANSYS run, and, on the other hand, to compare the run time requirement of the transient simulation by ANSYS, SUNRED and of the direct time-constant analysis feature of SUNRED. This comparison is presented in Table 2.

The thermal transient curve delivered by SUNRED is plotted in Figure 7. The time-constant spectrum calculated by deconvolution is shown in Figure 8.

The time-constant spectrum delivered directly by the time-constant analysis feature of the SUNRED program is plotted in Fig.9.

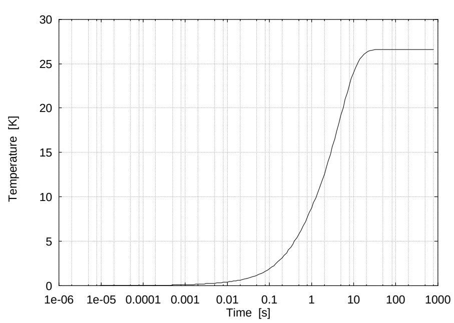

Figure 5 Simulated step response (by ANSYS)

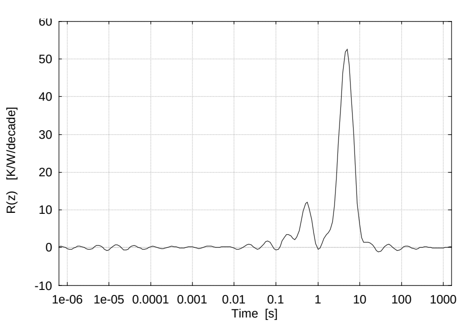

Figure 6 The time-constant spectrum (ANSYS)

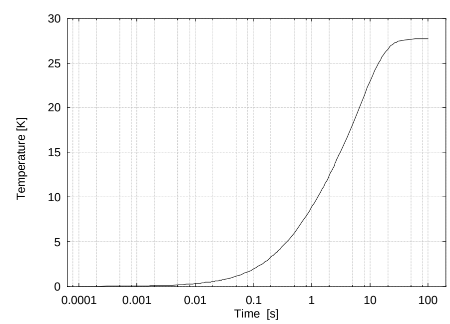

Figure 7 Simulated step response (by SUNRED)

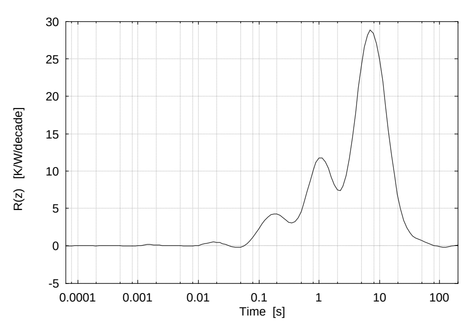

Figure 8 The time-constant spectrum (SUNRED)

Table 2 Comparison of the tools

Tool	Nr. of nodes	Time-scale	Points/decade	Run time* [min/decade]
ANSYS transient	17823	logarithmic	10	33.3
SUNRED transient	8192	quasi-log	20	20.3
SUNRED time-constant	8192	logarithmic	10	313

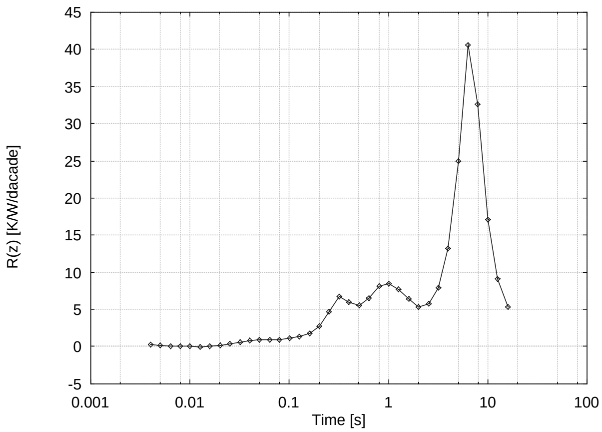

Figure 9: Spectrum obtained by direct time-constant analysis

5 CONCLUSIONS

As it is visible from the presented results our methods work well and provide very similar results either based on ANSYS transient simulation or direct time-constant calculation by SUNRED. The results were also controlled by measurement. The run-time requirements are however lower in case of calculating from transient results (see Table 2). The ANSYS/SUNRED runtimes are however not comparable directly, because in our experiments ANSYS runs on a DEC AXP 500 MHz while SUNRED on a PC with a Pentium 200 MHz processor.

6 FUTURE PLANS

The presented model generating method is accurate, but requires considerable time and experienced user to model first the physical structure for the field solver, then make the simulations and finally to generate the compact model. System designers however would require immediate answer to their questions of how a modification in the package design influences the behavior of their MEMS. For this purpose we suggest to build up a library of packages similarly to the library of MEMS elements presented in [1] and pursued by MEMSCAP, out of which a dedicated tool may obtain results for the questioned package. The drawback of the idea seems to be the large amount of simulation that has to be accomplished in advance to obtain such a library, so these simulation experiments have to be planned and optimized very carefully. Currently we are working on the feasibility study of the idea.

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* Note, that the ANSYS runs were on a DEC AXP 500 MHz computer, while SUNRED was running on a PC with a 200 MHz Pentium processor