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EMA-driven model updating based on material homogenization

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1. Introduction

The printed circuit boards (PCB) are complex geometrical and functional systems connecting electronic components for communication between them. PCBs also play an important role in protecting these components from their damage. It takes the form of a laminated sandwich structure of conductive copper layers and base material which is acting as an insulator. The base material FR-4 is made from a flame retardant epoxy resin and glass fabric, cf. Fig. 1.

The printed circuit boards used in automotive industry are exposed to vibration-, static- and thermal-loadings. Field failures in electronic equipment hardware over a period of 20 years show that these failures are related to connectors, to interconnects, and to component parts. Around 20% of field failures related to operating environments are related to vibration- and shock- loading, [8]. During testing on shakers, the components must survive the load conditions according to the LV 124 / LV148 Automotive Test Standard, [3].

To avoid failure in operation environment, virtual testing of PCBs based on the dynamic models of the printed circuit boards is performed. For that reason, it is important to use in the simulation validated dynamic models of the PCBs whose system responses correlate with the hardware experiment.

To achieve this, modal updating based on global optimization of surrogate model is performed. As a reference are used eigenshapes and eigenfrequencies from the experimental modal analysis (EMA).

2. Experimental modal analysis

The experimental modal analysis was performed with free-free boundary conditions by placing the PCB on the foam, see Fig. 1. The specimen was excited using an automatic impulse hammer (type: PCB 086E80), vibrations were measured by 1D doppler laser vibrometer (type: Polytec PSV 400-H4) in 175 sampling measurement points, see Fig. 1.

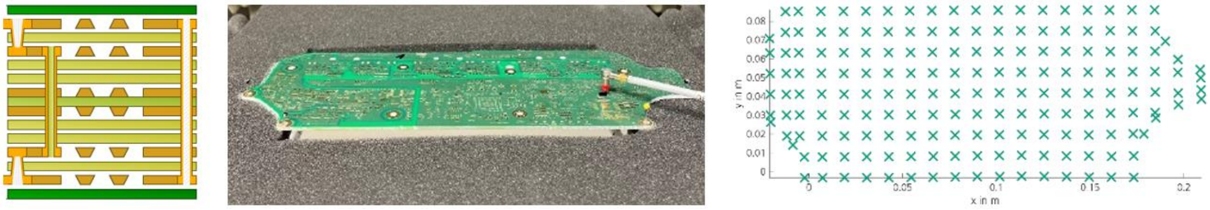


Fig. 1. PCB cross section (solder mask, copper foil, FR4 prepreg, FR4 core), measurement set-up and measurement points [4]

Table 1. Results from EMA – summary of eigenfrequencies, [4]

Mode [-]	Frequency [Hz]	Mode [-]	Frequency [Hz]	Mode [-]	Frequency [Hz]
1	140	7	827	13	1577
2	207	8	927	14	1796
3	350	9	1089	15	2007
4	446	10	1153	16	2209
5	652	11	1311	17	2313
6	777	12	1527	18	2366

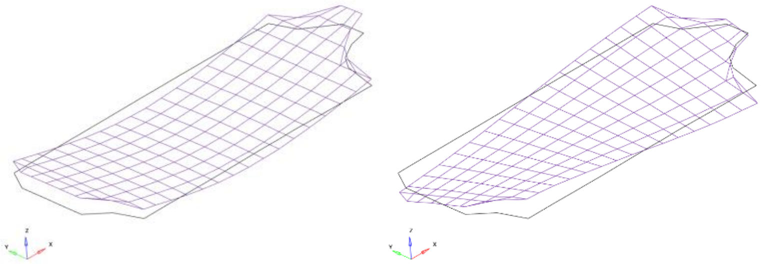


Fig. 2 Example of measured eigenshapes (mode#01, mode#02)

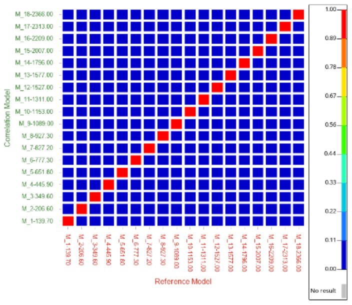


Fig. 3. AutoMAC matrix with proper choice of evaluation points

In total, 18 eigenshapes have been extracted in the frequency range 20-2500Hz, see Table 1. Example of the eigenshapes can be found on Fig. 2 together with AutoMAC matrix showing proper choice of the evaluation points (off-diagonal terms evince very low values).

AutoMAC is a special case of the modal assurance criterion (MAC) that is used to correlate simulation data with experimental data. The MAC is calculated as the normalized L2-scalar product of the two sets of vectors $\{\varphi_r\}$ and $\{\varphi_s\}$. The resulting scalars are arranged into the MAC matrix as follows

$$MAC(\{\varphi_r\},\{\varphi_s\}) = \frac{\left|\{\varphi_r\}^T\{\varphi_s\}\right|^2}{(\{\varphi_r\}^T\{\varphi_r\})(\{\varphi_s\}^T\{\varphi_s\})}\,. \tag{1}$$

If the MAC value is 1 (red color), then eigenshapes $\{\varphi_r\}$ and $\{\varphi_s\}$ are identical, if MAC is equal to 0, eigenshapes are not correlating. MAC values above 0.8 are considered as indicator of high correlation, [6].

3. Model updating

3.1. *Method description*

The model updating approach is based on the idea of tuning unknown parameters of the FE-model such as material parameters, damping, stiffness variation. The choice of these uncertain parameters is based on the performing parametric space sampling in some optimal manner. Afterwards relevant parameters having highest influence on the change of eigenshapes and eigenfrequencies are identified. Change of the eigenshapes is evaluated using MAC whereas set of the selected reference eigenshapes is taken from the experiment.

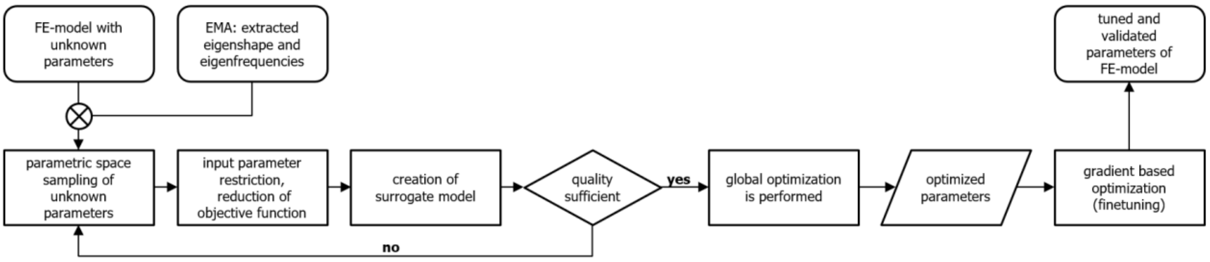


Fig. 4. Model updating workflow

This is followed by the creation of a surrogate model, and if its quality is high in some mathematical or physical sense, global optimization can be performed to maximize correlation of eigenshapes and eigenfrequencies.

Since the optimum is found on surrogate model which could deviate from the results of the real FE-models, authors propose to perform gradient based optimization in the FE-solver with initial conditions given by the global minimum from surrogate model. The output from this last step are tuned and validated parameters of FE-model.

3.2. Method Application and Results

As an input were used all 18 measured eigenshapes and eigenfrequencies extracted from experimental modal analysis, cf. Tab 1. Finite element model of the PCB was created using hexahedral 1st order elements (28523 elements, 58144 nodes) and one element across the thickness with orthotropic material (MAT90RT) defined by parameters E_X, E_Y, E_Z, G_{XY}, G_{YZ}, G_{ZX}, ν_{XY}, ν_{YZ}, ν_{ZX}.

The normal modal analysis was performed for first 30 eigenshapes evaluated in normal direction (Z-axis) in same points as in the measurement, cf. Fig. 1.

For the space filling scheme in DoE study was used Modified Extensible Lattice Sequence (MELS), that equally spreads out points in a space by minimizing clumps and empty spaces, [1]. A total of 250 FE-model variants were simulated for input parameters constrained by material stability conditions, [5]:

$$E_i > \nu_{ij}^2 E_j \, , \tag{2}$$

$$1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{31}\nu_{13} - 2\nu_{21}\nu_{32}\nu_{13} > 0 \, . \tag{3}$$

Since the simulation tasks are independent from each other, parallel execution of the tasks was performed. During these simulations responses such as eigenfrequency and MAC were monitored. Eigenshapes between EMA and FE-model were paired by mode tracking tool.

Using a pareto plot, it was identified that the Youngs modulus in planar directions E_X and E_Y and the planar shear modulus G_{XY} of the FR-4 material have the highest influence on MAC and eigenfrequencies.

Relative dense sampling of parameter space allows to derive surrogate model for relevant input parameters by automatic selection of the approximation methods as least squares, moving least squares, radial basis function (depends on the best approximation). During this phase, the R^2 parameter was monitored. Fitting functions with R^2 less than 0,95 were neglected due to credibility [1]. For this reason, 14 eigenshapes (eigenfrequencies and MAC values) were used as an input for subsequent global optimization method instead of 18 measured from EMA.

For searching global minimum on the surrogate model the genetic algorithm was chosen. Objective function was selected as weighted sum of squares of relative differences:

$$\min \sum_{i=1}^{n} w_i \left(\frac{f_i - \tilde{f}_i}{\tilde{f}_i}\right)^2 , \tag{4}$$

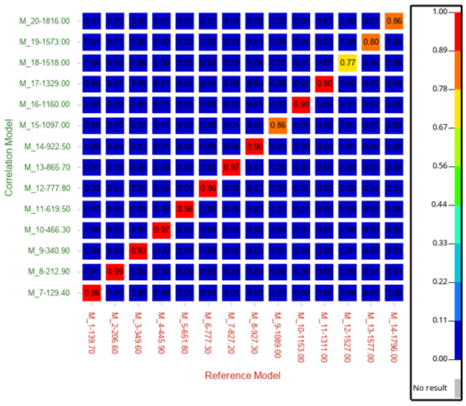
where f_i stands for i-th eigenfrequency of optimized model and $\tilde{f}_i$ are reference of i-th eigenfrequency from EMA, weighting factor w_i takes values from 0 to 1. As a constraint was used MAC with threshold value of 0.8.

In the last step, gradient-based optimization of the FE-model was performed with same objective as in the global optimization.

Comparison of the baseline material properties known from literature [4] with EMA is showing relative good correlation of the eigenshapes but evinces large deviations of the eigenfrequencies. The results of updated FE-model show low differences of the corresponding eigenfrequencies but with several degraded MAC values, see Table 2 and Fig. 5.

Table 2. Results from EMA – summary of eigenfrequencies, [4]

	Frequency [Hz]			Freq. diff. [%]		MAC [-]	
pair #	EMA (target)	Before opti..	After opti.	Before opti.	After opti.	Before opti.	After opti.
1	**140**	100	**129**	28.6	**7.6**	0.96	**0.96**
2	**207**	179	**213**	13.5	**2.9**	0.99	**0.99**
3	**350**	265	**341**	24.3	**2.6**	0.93	**0.93**
4	**446**	384	**466**	13.9	**4.6**	0.97	**0.97**
5	**652**	486	**620**	25.5	**5.0**	0.96	**0.96**
6	**777**	624	**778**	19.7	**0.1**	0.85	**0.96**
7	**827**	643	**865**	22.2	**4.6**	0.87	**0.97**
8	**927**	722	**922**	22.1	**0.5**	0.91	**0.90**
9	**1089**	827	**1097**	24.1	**0.7**	0.91	**0.86**
10	**1152**	918	**1160**	20.3	**0.6**	0.92	**0.90**
11	**1311**	1034	**1329**	21.1	**1.4**	0.92	**0.90**
12	**1527**	1159	**1518**	24.1	**0.6**	0.83	**0.77**
13	**1576**	1250	**1573**	20.7	**0.2**	0.85	**0.80**
14	**1796**	1411	**1816**	21.4	**1.1**	0.89	**0.86**



Correlation Model	M_1-139.70	M_2-206.60	M_3-349.60	M_4-445.90	M_5-651.80	M_6-777.30	M_7-827.20	M_8-927.30	M_9-1089.00	M_10-1153.00	M_11-1311.00	M_12-1527.00	M_13-1577.00	M_14-1796.00
M_20-1816.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.07	0.00	0.07	0.86
M_19-1573.00	0.01	0.01	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.05	0.02	0.08	0.80	0.00
M_18-1518.00	0.04	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.07	0.01	0.05	0.77	0.04	0.00
M_17-1329.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.05	0.00	0.02	0.90	0.02	0.00	0.00
M_16-1160.00	0.00	0.00	0.00	0.01	0.00	0.03	0.02	0.01	0.03	0.90	0.00	0.01	0.02	0.00
M_15-1097.00	0.00	0.00	0.02	0.01	0.02	0.00	0.01	0.06	0.86	0.01	0.00	0.01	0.00	0.00
M_14-922.50	0.00	0.00	0.02	0.01	0.04	0.00	0.00	0.90	0.01	0.00	0.00	0.01	0.00	0.00
M_13-865.70	0.01	0.00	0.00	0.00	0.00	0.00	0.97	0.01	0.00	0.00	0.00	0.00	0.00	0.00
M_12-777.80	0.00	0.01	0.00	0.05	0.00	0.96	0.00	0.02	0.00	0.01	0.00	0.00	0.06	0.01
M_11-619.50	0.03	0.00	0.05	0.00	0.96	0.00	0.00	0.00	0.01	0.01	0.00	0.09	0.00	0.00
M_10-466.30	0.00	0.03	0.00	0.97	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00
M_9-340.90	0.04	0.00	0.93	0.00	0.00	0.00	0.00	0.02	0.07	0.00	0.00	0.01	0.00	0.01
M_8-212.90	0.01	0.99	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
M_7-129.40	0.96	0.00	0.00	0.00	0.05	0.00	0.01	0.00	0.01	0.00	0.00	0.06	0.00	0.00

Fig. 5. MAC matrix correlation between EMA (reference model) and FE-model (correlation model) valideted material properties

4. Summary

Proposed automated workflow allows to perform model updating of relative complex structures as PCBs without consideration of detailed and time demanding models of the PCBs. Homogenized orthotropic material models simplifying complex PCB structure evince relative good correlation of the eigenshapes and eigenfrequencies which can be used in further studies as dynamic or vibration fatigue investigations.

Presented method offers robust alternative to more complex and time demanding model updating of FE-models based on locally homogenized PCBs models, cf. [4], or offers an alternative to very detailed FE-models modeling copper traces in the FR4 material, [2, 7].

Acknowledgements

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