Topology Optimization of Ultrasonic Transducers for Microsystem and IC Packaging

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ABSTRACT

In this study, we introduce the method of topology optimization for ultrasonic transducers for flip-chip and wire bonding. The objective function of topology optimization is prepared with shifting the resonance frequency for a longitudinal vibration mode of the transducers. After comparing solid isotropic material with penalization (SIMP) method with rational approximation of material properties (RAMP) on 2D model which is used to formulate topology optimization, we optimize 3D model based on results of 2D models. The topology optimization schemes are implemented by MATLAB, and the finite element models are established and the resonance frequency and modes are calculated in COMSOL. The target longitudinal mode at the resonance frequency is tracked using weighted modal assurance criterion (WMAC). Considering the availability of the new design, we manufacture and test the prototype of ultrasonic transducers based on the 3D optimization result.

Keywords: ultrasonic transducer, flip-chip bonding, wire bonding, topology optimization

1 INTRODUCTION

Ultrasonic transducer is a core part for the semi-conductor chip bonding machine as an important role of transmission ultrasonic energy into chip at the moment of bonding. To perform the ultrasonic bonding operation properly, the resonance frequency and longitudinal vibration mode of ultrasonic tool is required. Until recent days, however, the most of practical aspect of the ultrasonic tool design follows the trial-and-error approach which depends on designer's experience. This limits the design innovation in the field of microsystem and IC chip packaging which have been rapidly developing the packaging equipment due to change the device form factors [1, 2]. To overcome this limitation, we applied topology optimization [3] technique to design the piezoelectric ultrasonic transducers.

Topology optimization performs an optimization with the objective function regardless of initial topology of the model. The objective function using this study is shifting the resonance frequency for a longitudinal vibration mode. The SIMP and RAMP methods are used to formulate topology optimization. Optimal criteria (OC) method is employed to update the design variables for each finite element [4] and WMAC is used to track a longitudinal mode of vibration [5, 6]. For expandability of application, these schemes apply to COMSOL with MATLAB. After the optimization process in 2D, we can compare the converged shapes between SIMP and RAMP, and choose one interpolation function to apply in 3D finite element model. Considering the machinability and the availability of the design, we test prototype of ultrasonic transducers for flip-chip bonding based on the result of 3D optimization. To evaluate the transducers design, the vibration displacements of the transducers are measured by laser vibrometer. Also we test the transducers in the accelerated operation environment about 1,500-equivalent hours to assure the reliability of the transducers.

2 TOPOLOGY OPTIMIZATION

For topology optimization, the relative volume density of each element must be decided between 0 to 1, which is used when updating mass and stiffness of model. If the volume density of element is 0, it means a material is not existed in the element part. In contrast, if the volume density of element is 1, the material is existed. During the iterative calculation of topology optimization, Young's modulus and mass density are determined by interpolation function as Eq.(1).

$$E = \mu \times E_0 \ , \quad \rho = \mu \times \rho_0 \ . \tag{1}$$

In SIMP method, The μ in the interpolation function is the power law interpolation, whereas RAMP method apply the fraction form in Eq. (2). The variable p and q in the Eq. (2) is determined by Poisson's ratio [4].

$$\begin{aligned} \mu_{\text{SIMP}} &= (x_e)^p, \\ \mu_{\text{RAMP}} &= \frac{x_e}{1+q(1+x_e)}. \end{aligned} \tag{2}$$

The objective function of this study is minimizing a difference between the resonance frequency for a longitudinal vibration mode of the initial model and the target frequency at the same mode. The objective function is as

$$\begin{aligned} \min \;:\; & F = \frac{(\omega_i^2 - \omega_t^2)^2}{\omega_t^2}, \\ \text{Subject to} \;:\; & \frac{V(x)}{V_0} \geq f, \\ :\; & [\mathbf{K} - \omega_i^2 \mathbf{M}]\mathbf{v}_i = 0, \\ :\; & 0 < \mathrm{x}_{\min} \leq \mathrm{x}_e \leq 1. \end{aligned} \tag{3}$$

where ω_i is the resonance frequency at the iterative calculation process, and ω_t is target frequency. In Eq.(3), f is volumetric constraint which is used 0.7 in this study. $\mathrm{x}_{\min}$ prevents any singular matrix, and here we set the value as 0.001.

For the sensitivity analysis, we derive a derivative of objective function in Eq. (3) with respect to the design variable [5]. The sensitivity of the objective function based on the energy is

$$\frac{\partial F}{\partial x_e} = 2\left(\frac{E'}{E}(\mathrm{E}_{\text{strain}}) - \omega_i^2 \frac{\rho'}{\rho}(\mathrm{E}_{\text{kinetic}})\right)\left(\frac{\omega_i^2}{\omega_t^2} - 1\right), \tag{4}$$

where $\mathrm{E}_{\text{strain}}$ and $\mathrm{E}_{\text{kinetic}}$ are the strain energy and kinetic energy, respectively. The energy based sensitivity function has an advantage such that one can easily put the sensitivity function into finite element software such as COMSOL.

The WMAC is used for tracking the longitudinal mode for each optimization step [5]. Like Eq. (5), WMAC is modified from MAC(modal assurance criterion), which includes a weighting matrix D_ρ which is based on the density of each element.

$$\mathrm{WMAC}(\Phi_{\text{ref}}, \Phi_{\text{pre}}) = \frac{\left|\Phi_{\text{ref}}^T D_\rho \Phi_{\text{pre}}\right|^2}{\left(\Phi_{\text{ref}}^T D_\rho \Phi_{\text{ref}}\right)\left(\Phi_{\text{pre}}^T D_\rho \Phi_{\text{pre}}\right)}. \tag{5}$$

To update a design variable based on sensitivity, we also choose the modified OC algorithm for dynamic problem because sensitivity of dynamic problem may occur negative value [4].

3 OPTIMIZATION RESULT

We compare the optimization shapes of two different interpolation functions (SIMP and RAMP), for flip-chip bonding and wire bonding transducers. The objective of the topology optimization is the resonance frequency shift into the targer frequency.

To optimize the model, we need to choose a design domain and fixed domain. Figure 1 shows ultrasonic transducer for flip chip bonding. We assume that the region near bonding point as the fixed domain (dark in Figure 1) which will not change the element density during the optimization steps. The width of the fixed domain is set to 16mm, and the target frequency is set to 60kHz. Figure 2 shows the optimization results by using SIMP and RAMP method.

Figure 3 shows the design domain of wire bonding transducer. The fixed domain in this model has a width in 8mm, and the target frequency is 70kHz. The optimization results by using SIMP and RAMP method are shown in Figure 4.

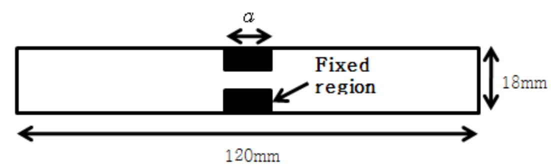


Figure 1: Design domain of flip-chip bonding transducer.


(a) RAMP


(b) SIMP

Figure 2: Optimization result for flip-chip bonding transducers.

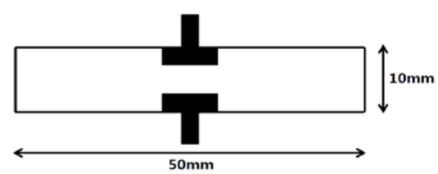


Figure 3: Design domain of wire bonding transducer.


(a) SIMP

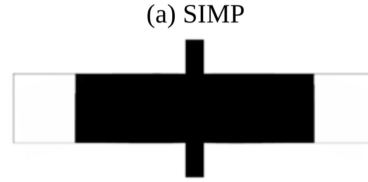
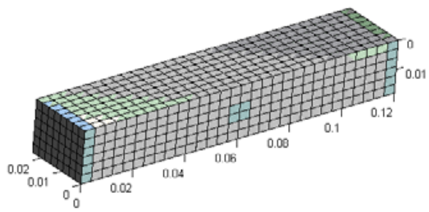
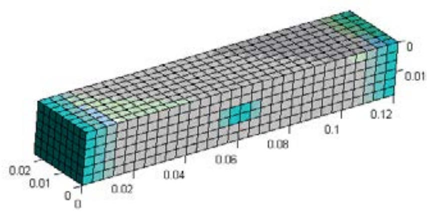

(b) RAMP

Figure 4: Optimization result for wire bonding transducers.

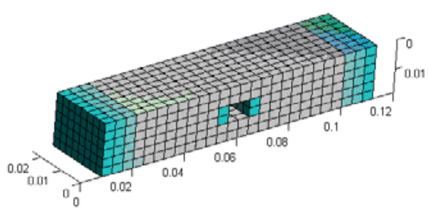
The optimization in 3D transducer model is performed on flip-chip transducer counted on the results of 2D models using SIMP interpolation function. Figure 5(a) is 3D model and all constraint of optimization is same on 2D model for flip-chip bonding transducer using SIMP method because the model has the most reasonable shape and the fast convergence among 2D models. 3D optimized model, as shown in Figure 5(e), has an uneven hole which cannot be seen in 2D optimized model. Figure 5(b-d) show the optimization steps in the topology optimization process.



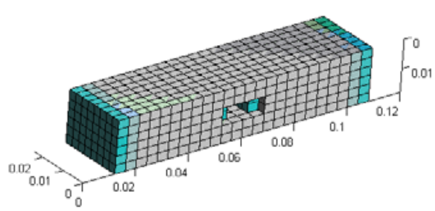
(a) Initial model (design domain)



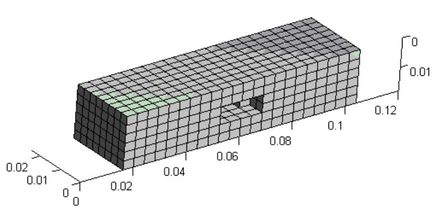
(b) Optimization step (iteration = 4)



(c) Optimization step (iteration = 7)



(d) Optimization step (iteration = 9)



(e) Final design

Figure 5: 3D topology optimization.

4 TEST RESULT

Considering the availability of the design optimization, we manufacture and test a prototype of ultrasonic transducer based on 3D optimization result. Figure 6 is the manufactured model which is made of SUS440C by wire cutting process. For operation of the prototype transducer, we give the prototype of model ultrasonic which is 60kHz with 1kV by using an ultrasonic generator. The displacement amplitude of transducer is measured by laser vibrometer (GRAPHTEC AT series 3700). The difference between the resonance frequency and the target frequency is less than 3% (Table 1 and Figure 7). Also we test the prototype transducers in the accelerated operation environment more than 1,500-equivalent hours (real 300 hrs) to assure the reliability of the transducers. For the accelerated operation test, we gave the constant 0.2MPa vertical pressure and the intermittent ultrasonic vibration in horizontal direction as the loading profile in Figure 8.

Table 1: Resonance frequncy and error in prototype transducer.

	FE Analysis	Experiment
Frequency (kHz)	58.868	58.349
Error (%)	1.88	2.75

Figure 6: Prototype transducer.

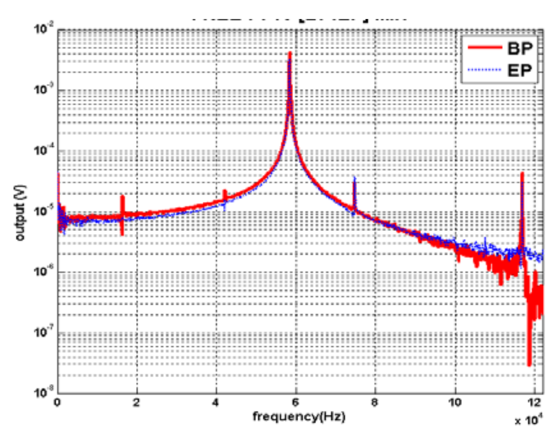


Figure 7: Frequency spectrum of ultrasonic transducer.

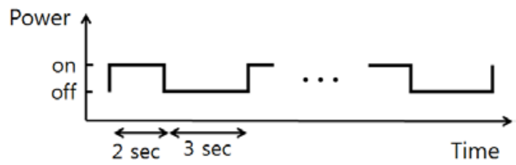
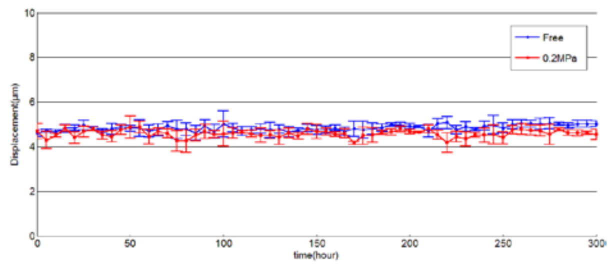
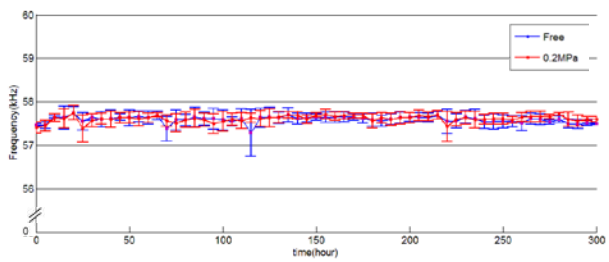


Figure 8: Ultrasonic loading profile



(a) Ultrasonic amplitude



(b) Operating frequency

Figure 9: Reliability test for 300 hours.

Figure 9 shows the ultrasonic amplitude and the operating frequency of transducers which is measured every 10 hour for 300 hours from the initial step of the reliability test setup. The variance of the ultrasonic amplitude and frequency is quite reliable, and all of the prototype transducers designed by topology optimization show very stable performance even after the accelerated environment test.

5 CONCLUTION

In this study, we introduced the method of topology optimization for the ultrasonic transducers which are used in flip-chip and wire bonding. The SIMP and RAMP interpolation schemes were used to formulate topology optimization and OC algorithm for the update method. The objective resonance frequency and longitudinal modes were tracked using Weighted Modal Assurance Criterion (WMAC). All the process was implemented under coding in MATLAB along with modeling and computation in COMSOL.

We compared the results between 2D and 3D optimization, and manufactured a prototype transducer which were based on the 3D optimization results. To ensure the validity of topology optimization, the ultrasonic amplitude and frequency spectrum of the prototype was measured. The frequency difference between the design model and the prototype is within 1%, which directly validates the accuracy of developed procedure of 3D topological optimization for the design of ultrasonic transducers. Also we can assure that the design by topology optimization is reliable after successfully doing the 1,500-equivalent hours (real 300 hrs) accelerated environment test.

Acknowledgments

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