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Topology optimization of large ultrasonic tools for uniform vibration using level-set method

Yuji Wada†, Kentaro Nakamura (FIRST, Tokyo Tech)

1. Introduction

To make uniform vibration distribution of ultrasonic welding tools is vital for industrial applications. The shape design is complicated and requires a lot of know-how due to its wave nature [1]. Topology optimization is a structural optimization method that determines the arrangement of components and materials, including voids, to maximize or minimize the objective function within a design space [2,3]. The authors [4] have attempted to make the uniform vibration distribution of the tool using a density model, which is a popular method of topology optimization. Uniform vibrations are obtained under the grayscale condition, but when the vibrating body are re-meshed from the threshold of the density, the desired vibration characteristics are no longer satisfied.

Level-set type topology optimization [5] can avoid the above problems because it determines the optimal structure by the evolution of clear interfaces. In this study, we aim to establish a methodology for designing vibratory tools through topology optimization using level-set method.

2. Optimization model

Fig. 1 shows the (a) Flowchart of the optimization, (b) finite element mesh for the level-set function, and (c) finite element mesh for the structural analysis. In this study, we use different meshes for the vibrational structure analysis and the level-set function updated using the reaction-diffusion equation (RDE). The structural mesh is generated from the boundaries extracted from the level set function thresholds. The topological derivative, a distribution function for the evolution of the level-set functions, is obtained from the structural analysis and returned to the level-set mesh.

Fig. 2 shows the optimization model of the ultrasonic tool with the driving frequency of 50 kHz. We assume the quarter symmetry, scaled model of the tool geometry used by Adachi and Ueha [1], excluding the slits and trap horns. The dimensions are scaled using the longitudinal wavelength λ from 20 kHz to 50 kHz. The objective function for the optimization is the one proposed for the density model [4]. The objective function maximizes the lowest output θ_k=Re[$(\mathbf{f}_0\mathbf{u})^*(\mathbf{f}_k\mathbf{u})$] of the observation force $\mathbf{f}_k$ (k=1-6) on the output surface in **Fig. 2(b)**,

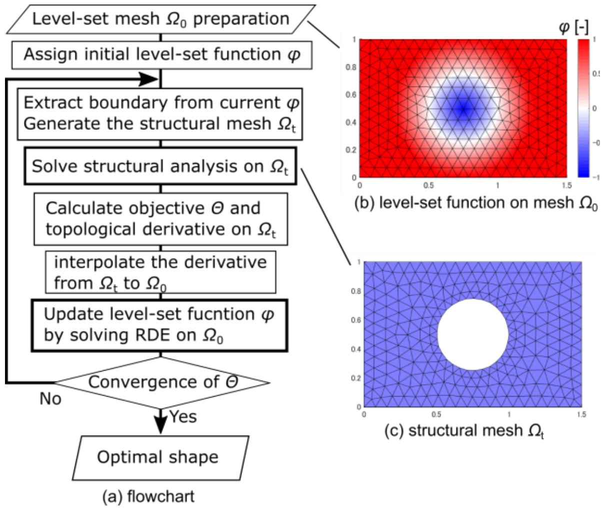

Fig. 1 (a) Flowchart of the optimization; (b) finite element mesh for the level-set function, and (c) finite element mesh for the structural analysis.

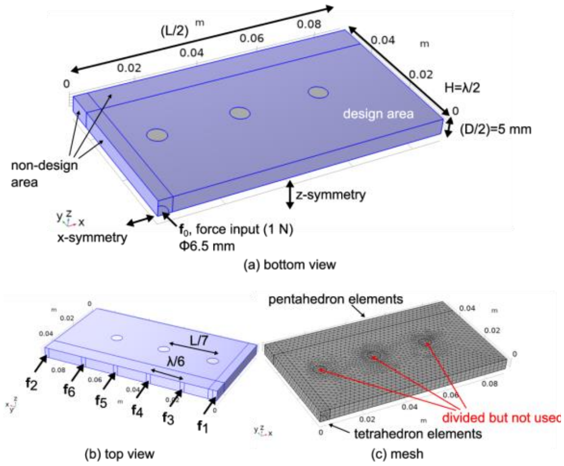

Fig. 2 Optimization model of the ultrasonic tool with the driving frequency of 50 kHz in x- and z-symmetry. λ is longitudinal wavelength at 50 kHz and L=1.75λ.

using the MINMAX method, which expects the output to be uniform. $\mathbf{u}$ is the displacement field under the vibration input force of $\mathbf{f}_0$. 30 patterns of the optimization for the different initial level-set function is tried where a grid of holes of radius λ/36 or λ/48 are placed in the design area. The tools are fabricated for the two cases with the highest uniformness among the optimization results.

E-mail: †ywada@sonic.pi.titech.ac.jp

3. Optimal shape and vibration measurement

Figs. 3 and 4 show the optimal shapes with the eigenmode nearest to the driving frequency of 50 kHz with 6 and 20 initial holes, respectively. The contour shows the vertical displacement distribution. Uniform vibration mode is obtained where the performance ratio of the minimum vibration amplitude of the top surface to the maximum is 50.8% and 59.7%, respectively.

Fig. 5 shows the photograph of the fabricated tool. The hole drilling was done by a wire electrical discharge machine. A commercially available bolt-clamped transducer (BLT) with a horn (FBL50152H-FC, Fuji Ceramics) is bonded to the machined tool using instant glue.

Figs. 6 and 7 show the vibration velocity distributions measured with a laser Doppler velocimeter (CLV1000, Polytec). The measurement was performed three times each, the performance ratios were 46.1 % and 51.1% for 6 and 20 initial holes cases, respectively. The calculated and measured results generally agreed well.

4. Conclusion

We designed, fabricated, and measured the vibration of a uniformly vibrating ultrasonic tool using level-set topology optimization. The optimization results showed a generally uniform vibration distribution, and the fabricated tool exhibited the expected vibration distribution.

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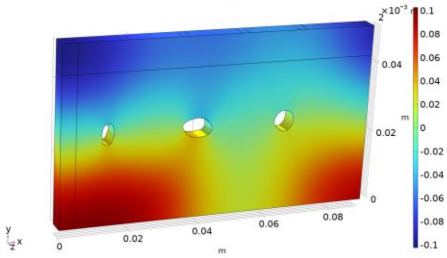

Fig. 3 Optimal shape of the 6 initial holes (3 holes in the model) has the eigenmode at 50.012 kHz.

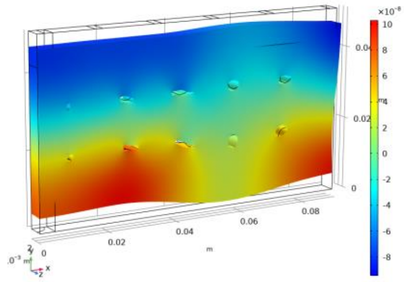

Fig. 4 Optimal shape with the 20 initial holes (10 holes in the model) has the eigenmode at 50.012 kHz.

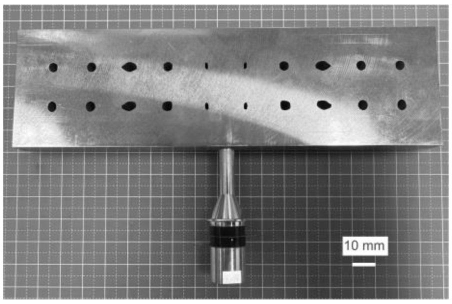

Fig. 5 Photograph of the fabricated tools with BLT of the 20 initial holes for a single side.

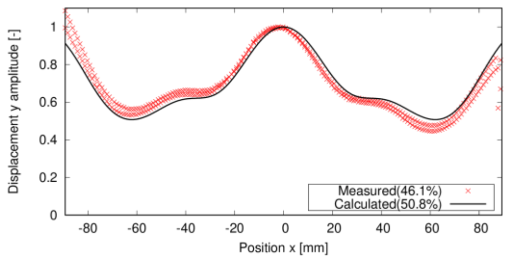

Fig. 6 Vertical vibration velocity measured using LDV for the tools of the 6 initial holes.

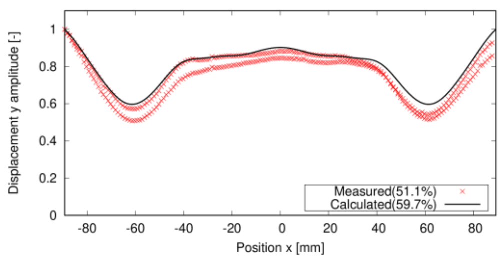

Fig. 7 Vertical vibration velocity measured using LDV for the tools of the 20 initial holes.