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Numerical simulation of temperature rise distribution on material surface under high-intensity aerial ultrasonic irradiation

高強度空中超音波照射による物体表面の温度上昇分布の
数値シミュレーション

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1. Introduction

Recently, devices capable of emitting high-intensity aerial focused ultrasound (HIAFU) have been developed, and various applications are expected involving the thermal energy generated when an object is irradiated with high-intensity ultrasonic waves emitted from a HIAFU. Likely specific applications are the drying of objects, application of haptics to thermal sensation, welding using heat, and nondestructive inspection using thermosonics. Using the HIAFU developed in previous research, we have succeeded in raising the surface temperature of soft material (silicone rubber) to around 60°C.[1] However, to realize the above applications, it is necessary to verify the safety (regarding alteration or destruction of physical properties) of the target of thermal action. Specifically, it is necessary to verify and predict the temperature rise and heat distribution on the target surface by experiments and numerical simulations. Therefore, in this basic research, we used numerical simulation to conduct a basic study of the surface temperature rise of an object irradiated with high-intensity aerial ultrasonic waves.

2. Numerical method for analyzing temperature rise due to ultrasonic irradiation

To predict the temperature rise due to ultrasonic irradiation on the surface of an object, it is necessary to consider the heat generation and thermal diffusion due to absorption of the ultrasonic waves by the object.[2] The propagation of a sound wave in a homogeneous medium is governed by

$$\frac{\partial p}{\partial t} = -k\nabla \cdot v \qquad (1)$$

where p is the sound pressure, v is the particle velocity, k is the bulk modulus, and t is time. Next, the conduction of heat considering the amount of heat generated in the medium is governed by

$$\rho c \frac{\partial T}{\partial t} = \lambda \nabla^2 T + Q \qquad (2)$$

where T is the temperature, ρ is the density, and λ is the thermal conductivity. The amount of heat Q generated by absorption and attenuation of the ultrasonic waves is calculated by

$$Q = 2\alpha I \qquad (3)$$

where α is the absorption coefficient of the medium and I is the temporally averaged ultrasonic intensity.

In the analysis, the spatial distributions of the sound field and the temperature are obtained by dividing the two-dimensional area into elements and applying the central difference method in the space and time domains.

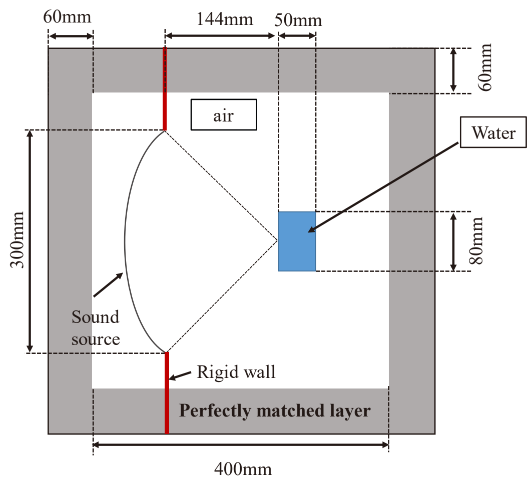

Fig.1 Schematic view of analysis model

3. Analytical model

The analytical model is shown schematically in Fig. 1. The analysis range is constructed from air

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and water; in previous research, an experiment was conducted using a soft material as the heating target, but in the present analysis we use water. In this analysis, as shown figure, the HIAFU is realized by arranging a point wave source. the focus point is at the air–water interface. The parameter values used in the analysis are given in Table 1. The analysis was adjusted so that the instantaneous sound pressure at the focal point of the sound wave was 25 kPa, and the input to the wave source was continuous wave.

Table 1 Parameter of analysis

Parameter	air	water
Speed of sound[m/s]	343.5	1500
Density[kg/m^3]	1.205	997.2
Attenuation coefficient[dB/m/kHz]	16.4	0.022
Specific heat[J/kg/K]	1005	4186
Thermal conductivity[W/m/K]	0.0241	0.582

4. Analytical results

The results for the sound wave distribution in the analysis region are shown in Fig. 2 in the form of color maps of the instantaneous amplitude distribution of the sound pressure when the sound wave reaches the liquid surface.

The results show that most of the sound waves are reflected at the boundary surface. This is because the acoustic impedances of air and water are very different. Fig.3 shows the distribution of sound pressure on the water surface in Fig. 2. The result is normalized by the maximum value among the results, and the experimental results for comparison are also shown. Clearly, a high sound pressure is generated near the center. Moreover, the analysis result agrees well with the experimental result.

Next, Fig. 4 shows the result of the distribution of temperature on the water surface where the temperature change was calculated from the sound wave irradiation to 0.1 s. The result is normalized by the maximum value among the results, and the experimental results for comparison are also shown. From the results, the analysis result has almost the same temperature rise distribution of the experimental result [1]

5. Conclusion

We simulated the temperature rise on the surface of an object irradiated with high-intensity aerial ultrasonic waves from the HIAFU. The analysis result of the temperature rise distribution on the water surface was in good agreement with that of the experimental result.

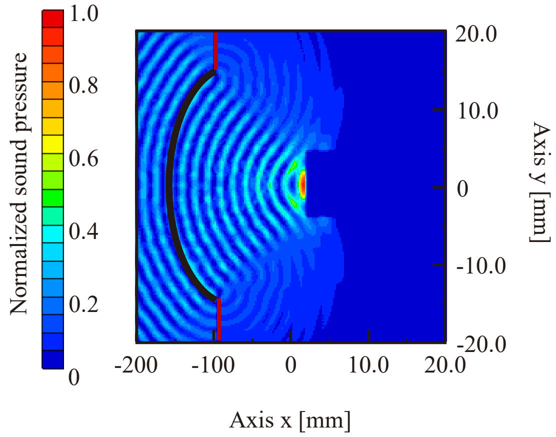

Fig.2 Sound pressure distribution in analysis area.

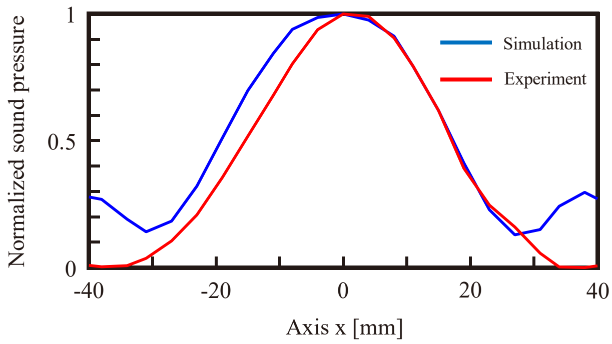

Fig.3 Sound pressure distribution along water surface (absolute value).

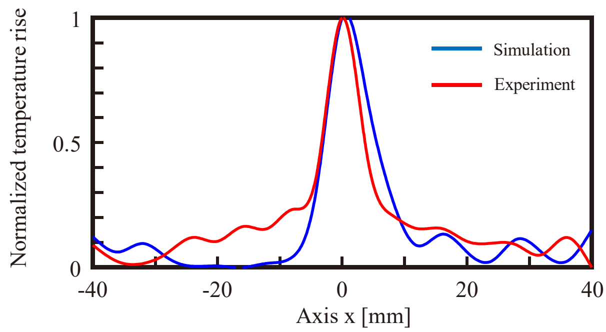

Fig.4 Temperature rise distribution along water surface.

Acknowledgment

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References

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