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NON-CONTACT VIBRO-ACOUSTIC TESTS BASED ON NANO-SECOND LASER ABLATION

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Abstract. *This paper discusses a method for vibro-acoustic tests based on nano-second laser ablation with plasma formation. The shockwave that is yielded by consuming a part of the plasma energy becomes the pulse sound source. The authors have proposed an acoustic test approach based on laser-induced breakdown. However, the process of generating the laser-induced breakdown fluctuates depending on the conditions of the spot radius, the focal length of the convex lens, and laser pulse energy. Moreover, since the pulse sound source is created by the laser-induced breakdown when the local intensity of the laser beam reaches* 10^{15} *W/m*^{2}*, it is difficult to create the pulse sound source with small amplitude. It is possible that the laser ablation creates the pulse sound source with smaller amplitude, because the laser ablation threshold against metal that is* 10^{12} *to* 10^{14} *W/m*^{2} *is less than the laser-induced breakdown threshold. The validity of the proposed method is verified by demonstrating the relationship between changes in the frequency range of the pulse sound source by laser ablation and materials of the irradiated surface. Furthermore, it is shown that the pulse sound source by laser ablation has a hemispherical nondirectional property in the area facing the surface of LA generation.*

1 INTRODUCTION

Impulse sound sources have been used to experimentally measure acoustic properties, such as the reverberation time of a sound field and frequency transfer properties. Several methods have been proposed to generate impulse sound sources, including the use of speakers [1], spark discharge [2], and a wire explosion [3]. However, these methods require setting up some type of device (e.g., speakers and wires) in a sound field, which depending on the size or shape may disturb the sound field. In addition, when a sound field is inside a closed container or filled with materials harmful to humans, such as carbon dioxide, setting up a sound source is extremely difficult.

In our previous study, we proposed a method for acoustic tests using a point sound source generated by laser induced-breakdown (LIB) (hereafter referred to as a "LIB sound source") [4]. LIB is a phenomenon where electrons emitted from atoms and molecules that absorb multiple injected photons produce a plasma via a focused laser beam into a gas [5, 6]. A portion of the energy in the plasma is subsequently consumed to generate a shockwave, which can be used as the sound source. We produced a point sound source by focusing a high-power Nd:YAG pulse laser beam using a convex lens to increase the energy density of the beam up to the threshold to induce LIB (10^{15} W/m^2), and validated the LIB acoustic excitation in a very tiny space by comparing the resonant frequencies obtained from a theoretical calculation with those obtained from the experiment [4]. Because the pressure of the LIB sound source is high (a couple of hundred Pa to several kPa), it is difficult to produce a sound source with a low sound pressure.

Herein we study a method for vibro-acoustic tests in which a portion of the energy of a laser ablation (LA)-induced plasma is consumed to generate a shockwave, which is used as a sound source (hereafter referred to as the "LA sound source"). LA is induced at a threshold of 10^{12}–10^{14} W/m^2, which is lower than that for LIB [7]. Thus, LA should generate a lower sound pressure compared to LIB. Because LA is produced at a laser beam–irradiation point, the variation in the LA production position is negligible. LA has been applied to various fields, including studies on LA-induced impulses [8] and propulsion of flying objects [9] as well as in practical applications for machine processing [10] and medical services [10]. In addition, LA has been used to measure the frequency response functions in target structures [11, 12]. However, to our knowledge, studies have not applied LA to vibro-acoustics.

Herein we develop a vibro-acoustic system based on an LA sound source using a high-power Nd:YAG pulse laser. We initially examined two relationships: one between the laser pulse energy and the sound pressure level of the LA sound source and one between the laser pulse energy and frequency characteristics. Then we demonstrated that LA sound sources are highly reproducible. Finally, we studied the material and dimensions of the target to be irradiated with a laser beam, and the frequency and directional characteristics of the LA sound source.

2 ACOUSTIC PROPERTY OF THE LA SOUND SOURCE

A vibro-acoustic system using the LA sound source is developed. We examined the sound pressure of the LA sound source, reproducibility, and frequency characteristics.

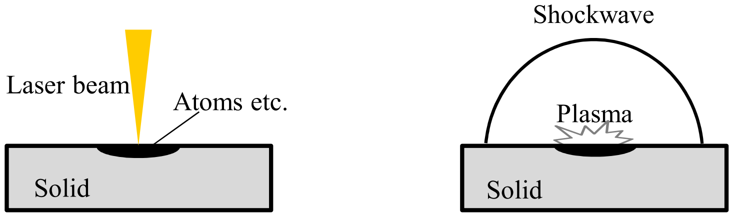
2.1 LA sound source

Figure 1(a) depicts the mechanism to generate a pulse sound source by LA. Upon irradiating a solid surface with a high-power pulse laser, the solid absorbs the laser beam. Atoms, molecules, and ions are subsequently emitted from the solid, and the emissions absorb the laser beam to form a high-temperature, high-density plasma. A portion of the plasma energy is then consumed to generate a shockwave, which is a pulse sound source (Fig. 1(b)).

LA is produced when the energy density of the laser beam I [W/m^2] reaches 10^{12}–10^{14} W/m^2 [7]. I is expressed as

$$I = \frac{E}{ST}, \tag{1}$$

where E [J] is the laser pulse energy, T [s] is the duration of laser pulse, and S [m^2] is the area where the laser is focused. According to Eq. (1), when the energy density of the laser beam is below the LA threshold, further focusing the laser beam onto a smaller area increases the energy density.



(a) Laser irradiation (b) Plasma formation and generated shockwave

Figure 1: Principle of shockwave generation based on LA.

2.2 LA sound source

Figure 2 depicts a vibro-acoustic system using an LA sound source on an optical table, which consists of an Nd:YAG pulse laser (Continuum Surelite III-10, wavelength: 1064 nm, laser beam diameter: 9.5 mm, pulse width: 5 ns, maximum output: 1 J, radial divergence angle: 0.45 mrad), a convex lens, and a target to produce LA (hereinafter referred to as "target"). LA is generated by irradiating the target with a laser beam focused via a convex lens. Candidate targets include tiny materials set in the sound field or structures that construct the sound field. If LA is produced in the structure that constructs the sound field, a large number of particles (plume) are emitted from the laser-irradiated area, inducing an undesirable impulse due to the excitation force of the structure [11,12]. Furthermore, LA produced on the structure will cause spatial pressure pulsation, inducing a vibro-acoustic force that propagates as a shockwave.

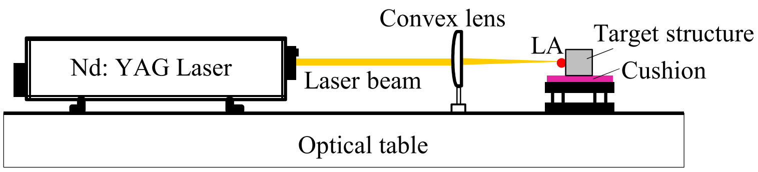


Figure 2: Acoustic excitation system using a sound source generated by LA.

2.3 Sound pressure measurement method

Figure 3 illustrates the system used to measure the sound pressure of the LA sound source. The Nd:YAG pulse laser, convex lens, and target were set on the optical table. To produce LA, the distance between the convex lens and target was 3–5% shorter than the focal length of the convex lens. The target was an aluminum cube (mass: 21.3 g, natural frequency: 70 kHz) placed on a cushion without constraints. Each face of the cube measured 20 mm. A microphone (UC-54, RION Co., Ltd., measurement frequency range, 20 Hz-100 kHz) and pressure sensor (113B28, PCB Inc., sensitivity: 15.23 mV/kPa, natural frequency: ≥ 500 kHz), which were 300 mm and 5 mm from the sound source, respectively, measured the sound pressure of the LA sound source. The response times and spectra of the sound pressure were recorded using a spectrum analyzer (A/D: NI PXI-5922, software: CAT-System, CATEC Inc.). The sampling frequency, number of sampling points, measurement frequency, and number of measurements were 1.5 MHz, 32768, 100 kHz, and 5, respectively.

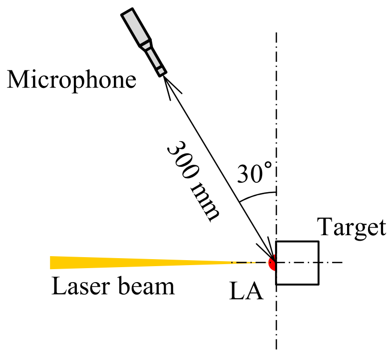


Figure 3: Layout of microphone.

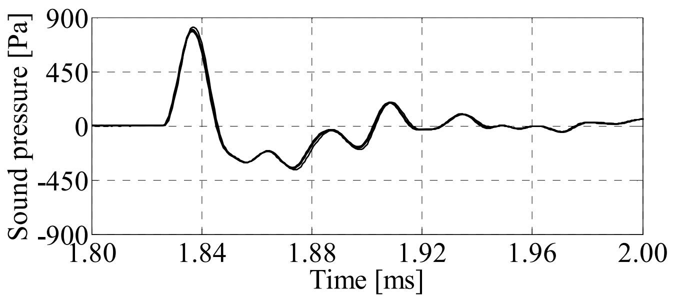


Figure 4: Time responses of sound pressure generated by LA (laser pulse energy: 470 mJ, focal length: 300 mm, average peak sound pressure: 799.0 Pa).

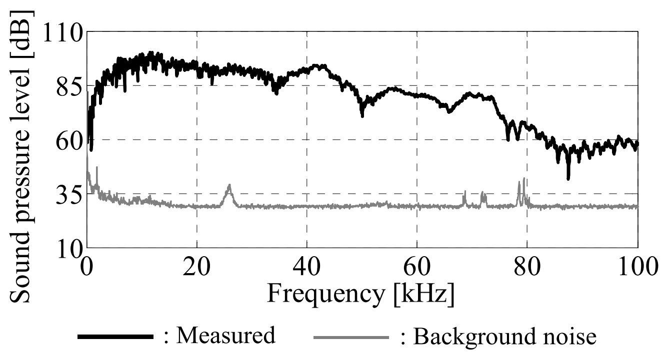


Figure 5: Spectra of sound pressure level of pulse sound source generated by LA.

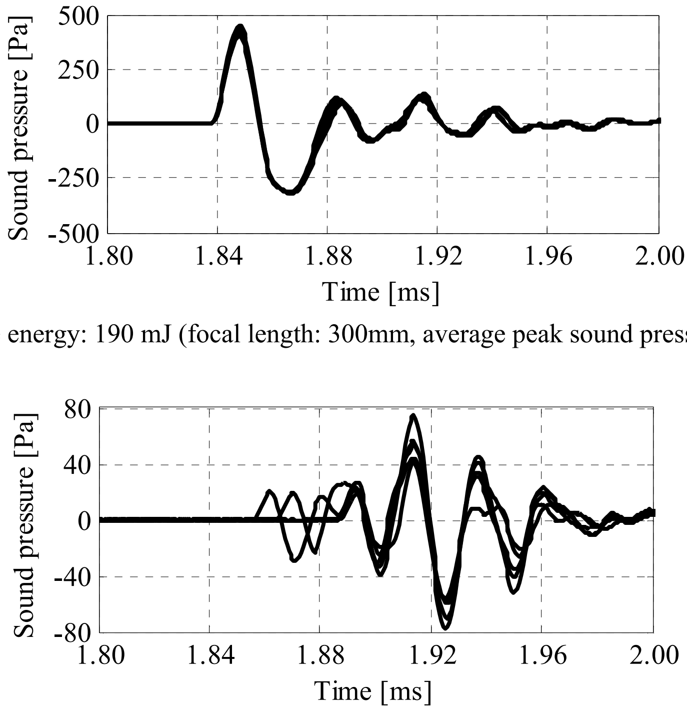
2.4 Sound pressure of the LA sound source and its frequency characteristics

In this section, we demonstrate that the LA sound source is a useful vibro-acoustic source for examining the sound pressure, frequency characteristics, and reproducibility of the LA sound source. Figure 4 shows the time responses of the measured sound pressure generated by the LA sound source magnified around the time when the sound pressure is generated. To confirm reproducibility, five independent measurements are superimposed, and the average peak sound pressure is 799.0 Pa. The laser pulse energy, focal length of the convex lens, and total data acquisition time were 470 mJ, 300 mm, and 20 ms, respectively. The sound pressure is initially detected after ~1.8 ms delay because the 300-mm distance between the sound source and microphone caused a 0.8-ms delay and the trigger measurement had a 1-ms delay. The distributions indicate an impulse sound source with a pulse width of ~20 μs and a very high reproducibility.

Figure 5 depicts the average power spectrum of the sound pressure level for the above conditions (470-mJ pulse energy and 300-mm focal length) and the background noise spectrum. The LA sound source has an impulse waveform that contains nearly uniform acoustic excitation components up to a high frequency region of ~70 kHz, but the size of the power spectrum slightly varies likely due to the microphone's characteristics.

3 INFLUENCE OF THE LASER PULSE ENERGY

We examine the influence of the laser pulse energy on the level, pulse width, frequency characteristics, and reproducibility of the sound pressure of the LA sound source.



(a) Laser pulse energy: 190 mJ (focal length: 300mm, average peak sound pressure: 427.1 Pa)

(b) Laser pulse energy: 70mJ (focal length: 300mm, average peak sound pressure: 53.9 Pa)

Figure 6: Sound pressure as a function of time for two laser pulse energies.

3.1 Frequency characteristics of the LA sound source

Figures 6(a) and (b) describe the time responses of the measured sound pressures generated by the LA sound source magnified around the time when the sound pressure is generated with laser pulse energies of 190 and 70 mJ, respectively. (The other measurement conditions are the same as described in Section 2.4). To confirm reproducibility, five independent measurements are superimposed. Figure 7 depicts the average power spectra of sound pressure levels for both laser pulse energies (190 and 70 mJ) as well as the background noise.

In the present experimental conditions, an LA sound source is generated, but not an LIB sound source. The similarities of the distributions in Figs. 6(a) and 4 indicate an impulse sound source with a pulse width of ~20 μs and a very high reproducibility. The almost uniform acoustic excitation components are contained up to a high frequency region of ~70 kHz, although the size of the power spectra slightly varies (Fig. 7). The generated sound pressure of the LA sound source decreases as the laser pulse energy decreases, but LA sound source consists of multiple pulses, causing the time when the sound pressure is generated to fluctuate (Fig. 6(b)).

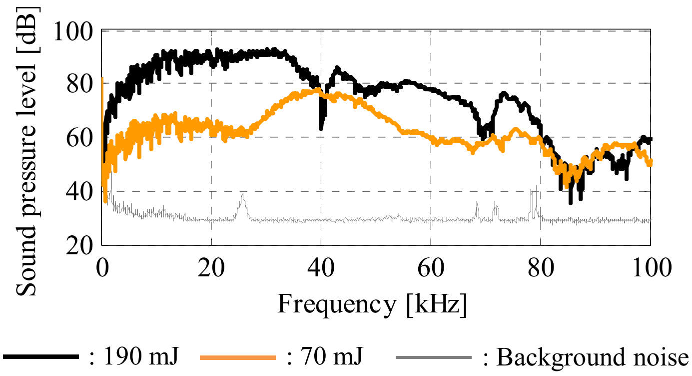
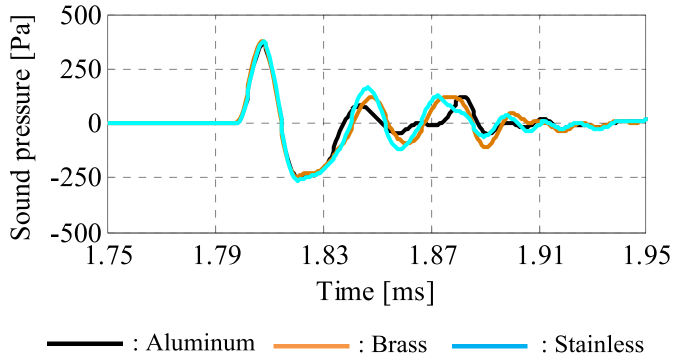
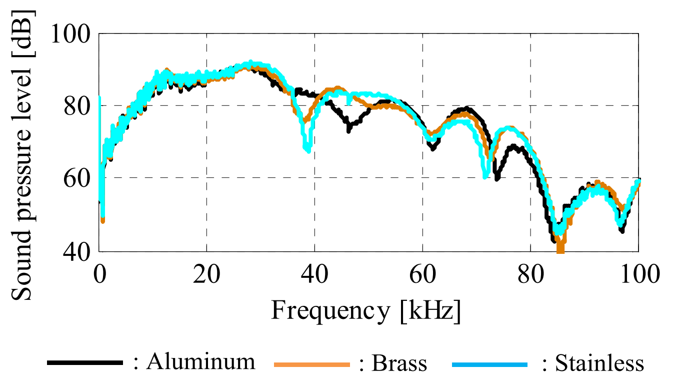


Figure 7: Power spectra of sound pressure generated by LA for two laser pulse energies.



(a) Sound pressure as a function of time for three materials



(b) Sound pressure as a function of frequency for three materials.

Figure 8: Acoustic property as a function of target for three materials.

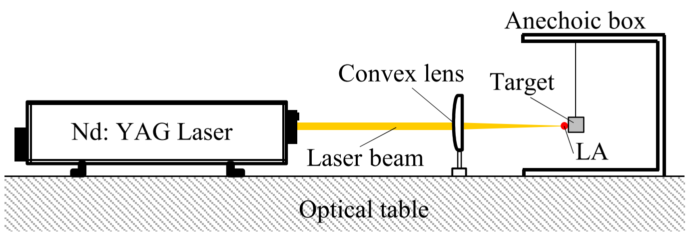
4 TARGET MATERIALS AND THEIR NATURAL FREQUENCY

The time responses of the sound pressure generated by the LA sound source and the power spectra were measured to investigate the effects of the target materials and their natural frequencies on the acoustic properties of the LA sound source. In addition to the aluminum cube used in the previous section, a brass cube (mass: 68.0 g, natural frequency: 47 kHz) and a stainless steel cube (mass: 62.8 g, natural frequency: 69 kHz) were prepared as target materials. The laser pulse energy was 190 mJ, and the focal length of the convex lens was 300 mm.

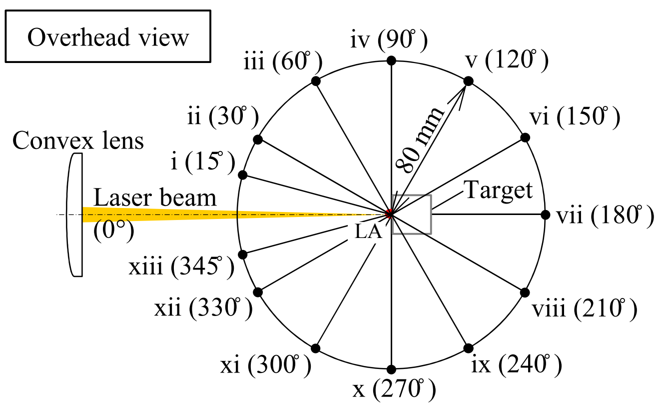
Figure 8 depicts the time responses of the measured sound pressures generated by the LA sound source magnified around the time when the sound pressure is generated and the corresponding power spectra. The time responses and power spectra of the LA sound source from these three target materials coincide well. In addition, the natural frequencies of the targets negligibly affect the acoustic properties of the LA sound source. Therefore, neither the sound pressure level nor the frequency characteristics of LA sound source depends on the target material or its natural frequency.

5 TARGET DIMENSIONS AND DIRECTIONAL CHARACTERISTICS OF AN LA SOUND SOURCE

Figure 9 illustrates the vibro-acoustic system used to measure the directional characteristics of the LA sound source. Because the sound generated by the LA sound source propagates to the back of the target due to diffraction, the reflection from optical devices should be supressed when studying the directional characteristics of the LA sound source. In addition to



(a) Experimental system for measuring directionality of sound source generated by LA (side view).



(b) Layout of microphone in the anechoic box for directional test (overhead view)

Figure 9: Directional test of LA sound source.

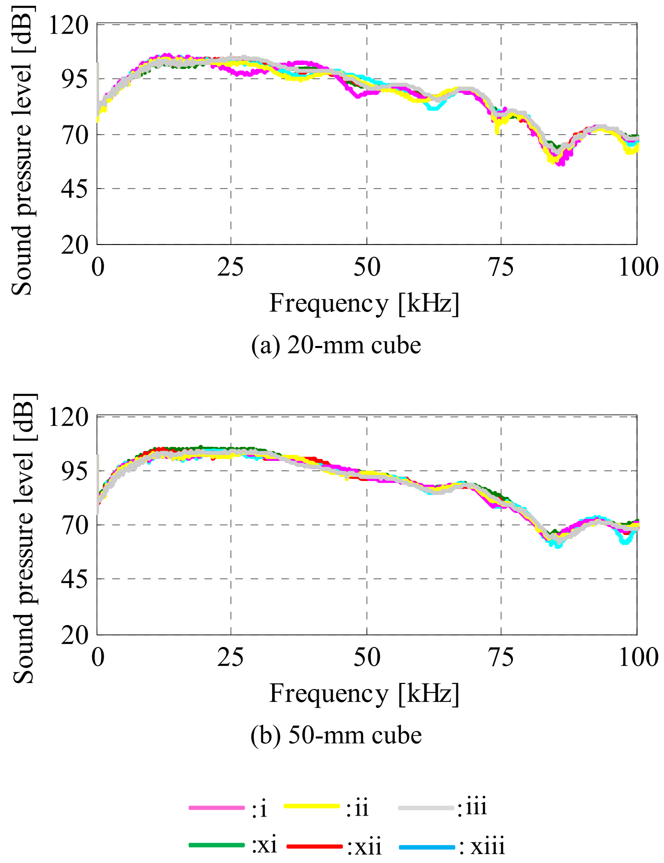


Figure 10: Measured power spectra at each point.

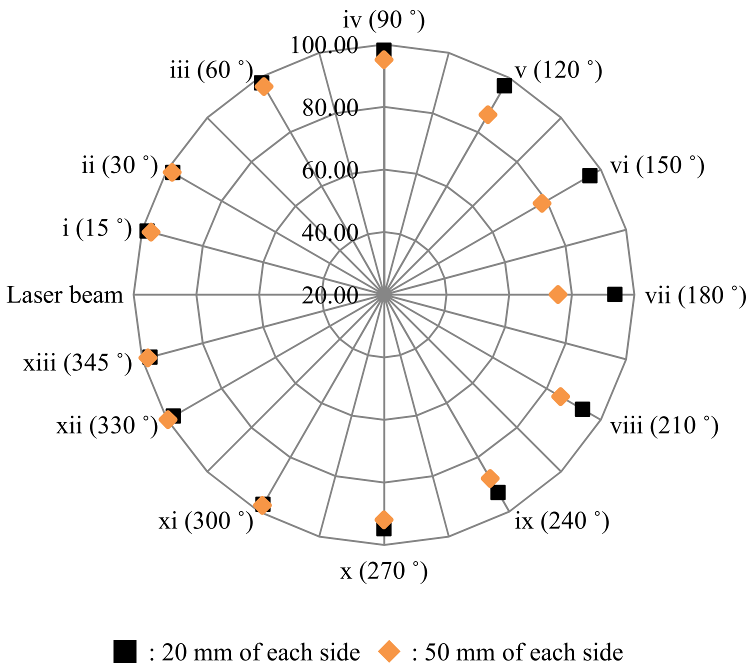


Figure 11: Star plot of the sound pressure levels and measurement positions for two targets (40 kHz).

the vibro-acoustic system described in Section 2.2, a simple anechoic box was installed on the optical table. The anechoic box, which was prepared using a grass wool insulator (50-mm thick) attached onto wood (40-mm thickness), exhibited effective acoustic properties over the measured frequency range. The target was suspended with a string without other constraints. To study the effects of the target dimensions on the directional characteristics of the LA sound source, two different targets, an aluminum cube with 20-mm faces (mass: 21.3 g, natural frequency: 70 kHz) and an aluminum cube with 50-mm faces (mass: 335 g, natural frequency: 28 kHz), were tested. To measure the directional characteristics of the LA sound source, 13 microphones (points i–xiii) were located 80 mm from the LA sound source (Fig. 9(b)). The laser pulse energy was 190 mJ, and the focal length of the convex lens was 300 mm.

Figure 10 depicts the average power spectra of the sound pressures measured on the front of the LA sound source (points i, ii, iii, xi, xii, xiii). Figure 11 superimposes the directional characteristics of the LA sound source at 40 kHz. The sound pressure levels and frequency characteristics are almost independent of position in the area facing to the LA-generated surface (points i, ii, iii, xi, xii, xiii). In particular, fluctuations in the sound pressure level are ~2 dB over this area. However, the sound pressure levels and frequency levels in other areas vary due to the diffraction of the acoustic wave. Despite this variation, almost the same frequency characteristics are confirmed for our target areas (e.g., points v and ix), whereas the LA sound source has a hemispherical nondirectional property in the area facing the surface of the LA generation, but, depending on the target dimension, has a directional property in the other areas.

6 CONCLUSIONS

Herein a new vibro-acoustic system is used for vibro-acoustic tests. LA, which is induced by a high-power Nd:YAG pulse laser, generates a shockwave that is utilized as the sound source. Measuring the acoustic property of the LA sound source using a microphone reveals that the LA sound source contains acoustic excitation components up to a high-frequency range of ~70 kHz. Additionally, the pulse sound source has a high reproducibility. Although the LA sound source is generated at a laser pulse energy lower than the threshold energy at which LIB is generated, the frequency region where sound excitation occurs should be carefully considered because the sound source may consist of multiple pulses.

Target materials used to generate LA and their natural frequencies have negligible effects on the acoustic property of the LA sound source. Moreover, the LA sound source has hemispherical nondirectional characteristics in the area facing the surface of LA generation, but the characteristic change in other areas, depending on the target dimensions.

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