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Laser-induced acoustic point source for accurate impulse response measurements within the audible bandwidth

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Abstract: Laser induced air breakdown is proposed as a sound source for accurate impulse response measurements. Within the audible bandwidth, the source is repeatable, broadband, and omnidirectional. The applicability of the source was evaluated by measuring the impulse response of a room. The proposed source provides a more accurate temporal and spatial representation of room reflections than conventional loudspeakers due to its omnidirectionality, negligible size and short pulse duration.

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1. Introduction

An ideal impulse response of an acoustic system is obtained when the source and receiver do not influence the system response. This can be achieved only if the source and receiver are point-like and feature flat response. These characteristics are easily obtained for receivers but are difficult to obtain for acoustic sources. A flat source response is commonly acquired by applying deconvolution if the source features sufficient sound energy in the frequency band of interest. However, if the source is directional, the response of the source changes for different directions thus reducing the applicability of deconvolution on the measured impulse response of the system. Point sources are usually approximated by neglecting the size of the source and assuming sufficient omnidirectionality. In practice, most sources are not sufficiently point-like, thus producing an inaccurate estimate of the impulse response of the system. For instance, spherical loudspeakers are typically assumed to be point-like, although they are directional at high frequencies and have considerable size.[1,2] Electrical sparks are small, but they are not repeatable and feature directional radiation patterns.[3]

A potential candidate for an omnidirectional and repeatable acoustic point source with sufficient sound pressure is the laser-induced air breakdown, LIB.[4–6] A high energy pulsed laser is focused to produce air breakdown that generates a small explosion with rapidly expanding plasma. The expanding plasma produces a short and high peak level pressure pulse, the frequency content of which spans beyond 100 kHz.[5,6] In the vicinity of the breakdown point, the pressure pulse propagates as a non-linear supersonic shock wave.[5] However, the shock wave is rapidly attenuated, and the propagation velocity is reduced to normal sound velocity.[7] Nonlinear propagation effects can be minimized by reducing the amplitude of the produced pressure pulse,[5] which is function of the deposited energy.[6] This energy can be adjusted by altering the laser pulse energy, pulse duration, and the focused beam size, provided that the intensity threshold for producing air breakdown is exceeded.[6] The LIB can be regarded to be a massless source because it produces no acoustic reflections itself. This means that LIB has minimal source influence. However, the optics required to focus the laser beam may produce acoustic reflections, something that can be minimized by using longer focal distances. This increases the laser beam spot size and decreases the beam intensity, which can degrade pulse-to-pulse repeatability.[6] The response of a small tube inside a small anechoic box have been measured using LIB,[6] and the impulse response of an acoustic scale model using the LIB was recently found to be similar to its computer simulated response within the 1–40 kHz bandwidth.[8] Although the point-like characteristics of LIB has been studied previously,[5,6,8] little information has been provided about the characteristics of LIB within the audible bandwidth.

The aim of this work is to study the characteristics of the LIB as an acoustic point source across the audible bandwidth. First, the repeatability, frequency response, directivity, and sound pulse propagation as a function of distance from the LIB were measured. Second, the LIB performance was evaluated by comparing the room impulse responses obtained with the LIB to those obtained with a spherical loudspeaker and a directional loudspeaker.

2. Apparatus and methods

All measurements were carried out inside a room ($6.35\,\mathrm{m} \times 5.58\,\mathrm{m} \times 2.72\,\mathrm{m}$). One of the bottom corners of the room was selected as origin of the coordinate system. The source position was (1.62, 1.61, 1.41 m), see Fig. 1(a). The receiver was a 1/4 in. free-field microphone (Type 46BF, G.R.A.S., Denmark) connected to a signal conditioner (Type 12AG, G.R.A.S., Denmark). A linear filter that matched the manufacturer specifications up to 20 kHz was used to compensate for the non-flat pressure response of the microphone. The receiver signal was digitized at 400 kHz using a data acquisition device (NI PXI-5922, National Instruments, Austin, TX) connected to a computer running LABVIEW (National Instruments, Austin, TX). The sensitivity of the measurement chain was calibrated to 1 V/Pa using a 1 kHz sine signal with 94 dB sound pressure level (SPL) obtained from a calibrator (B&K type 4231, Brüel and Kjær, Denmark).

The LIB was produced by focusing a high energy Nd:YAG pulsed laser beam (CFR400, 1064 nm/8 ns pulse duration, 7 mm laser beam diameter, 4.5 mrad divergence, Quantel-Laser, France) with a plano-convex 75 mm focusing lens (LA1608-B, Thorlabs, Newton, NJ), see Fig. 1(a). The laser device consisted of a laser head, which produces

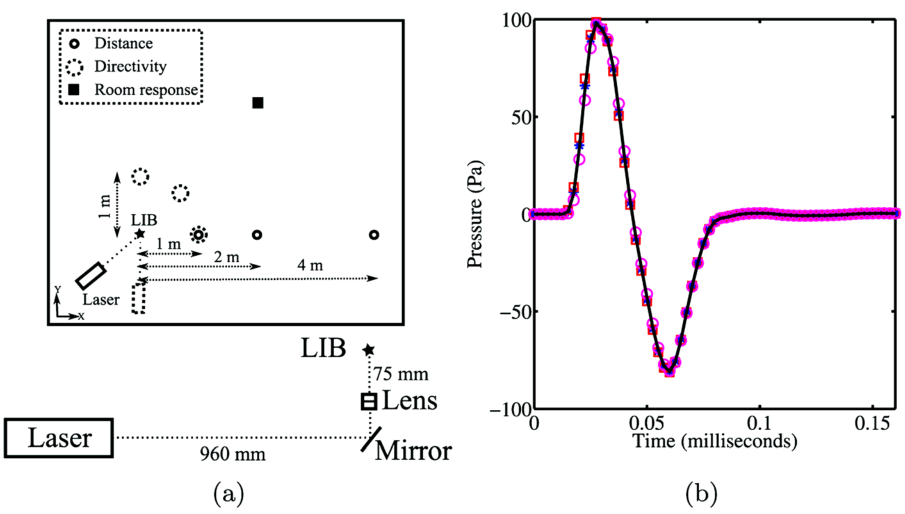

Fig. 1. (Color online) (a) Measurements setup. (b) Averaged pressure pulse wave-forms of three sets of 30 measurements (circles, squares, and stars, respectively) and the average of 100 measurements (solid line).

the laser beam, and was placed inside the room [see Fig. 1(a)], and a power unit, that was placed outside the room. The laser beam was directed upward using a 45° tilted mirror (NB1-K13, Thorlabs, Newton, NJ) at 960 mm distance from the laser and the lens was positioned above the mirror [see Fig. 1(a)]. Laser energies between 200 and 415 mJ and 50, 75, and 100 mm focal distance lenses were evaluated prior to the experiment. The 75 mm focal distance lens and 415 mJ laser energy were selected to reduce the reflection produced by the lens while maintaining high pressure pulse repeatability and level. A 2 Hz pulse repetition rate was chosen to allow 0.5 s room response time.

2.1 Acoustic properties of the LIB

The repeatability of the LIB was determined in the time domain by comparing the mean of three sets of 30 pressure pulses to the mean of 100 pulses measured at 1 m. In addition, the mean and standard deviation (SD) of the magnitude response of the 100 pulses were calculated using the Fourier transform of the first arriving windowed pulse (120 μs) and normalized to the window length. The pulse duration was determined by calculating, from the beginning of the pulse, the time necessary to obtain 99% of the total energy inside the 120 μs window. The magnitude and phase response of the averaged pulse were calculated to evaluate the linearity of the pulse within the audible bandwidth. The magnitude responses at 0.5, 1, 2, and 4 m were studied to assess the propagation characteristics of the pressure pulse [solid circles in Fig. 1(a)].

The LIB directivity was determined by measuring the maximum deviation between the magnitude response of the pressure pulses at 1 m of distance for 0°, 45°, and 90° azimuthal angles from the axis formed by the laser beam [dashed circles in Fig. 1(a)]. The laser head was oriented along the y axis direction as illustrated in Fig. 1(a) (dashed box).

2.2 Room impulse response

The impulse response of the room was acquired using the LIB and two additional sources. A custom-made spherical loudspeaker (12 elements, Vifa MG10SD09-04, China), connected to an amplifier (240 Power Amplifier, QUAD Electroacoustics, UK), and a directional active loudspeaker (8020B, Genelec, Finland) were utilized. The laser head was kept at the same position to maintain similar conditions between measurements. The loudspeaker measurements were digitized using a data acquisition device (NI PXI-4661, National Instruments, Austin, TX) with 44.1 kHz sampling rate. The loudspeakers were centered at the LIB position. The receiver position was (3.7, 4.1, and 1.4 m), i.e., 3.26 m from the source [see Fig. 1(a)].

The room featured a ceiling made of sound absorbing perforated plasterboard backed with mineral wool and a sound reflective hard parquet floor. There were several diffusers (tilted gypsum plates and Quadratic-Residue diffusers) and absorbers (mineral wool) distributed column-wise across half of the surface of three of the walls. Furthermore, loudspeakers were installed close to the walls and in the ceiling. Based on the source-receiver position inside the room, the origin of the first three reflections was estimated by calculating the distance between the source and receiver positions with respect to the reflective surfaces. The first reflection was expected to be from the ceiling, followed by a floor reflection. The third reflection was expected to be from a lateral wall [upper wall in Fig. 1(a)]. The reflection from the ceiling was expected to have less amplitude compared to the floor reflection due to the acoustically absorbing ceiling.

The first 350 ms of the room response using the LIB were recorded 50 times and averaged. The room response was resampled at 44.1 kHz to match the sampling rate of the loudspeaker measurements. The room responses using the loudspeakers were measured using a 10 s exponential sweep[9] with a gain that ensures approximately 60 dB of signal-to-noise ratio.

To compensate for the source response, the impulse responses were deconvolved with the free-field response of the sources between 100 Hz and 20 kHz. The free-field response of the sources was obtained by windowing the direct sound in the measured room responses to maintain the same directionality toward the receiver. The duration of the loudspeakers response was estimated as the time, from the beginning of the response, necessary to obtain 99% of the total impulse response energy measured in an anechoic chamber within a 5 ms window.

3. Results

3.1 Acoustic properties of the LIB

The average pressure pulse waveform of three sets, comprising 30 consecutive LIB pulses each (circles, squares, and stars, respectively), and the average pressure pulse waveform of 100 consecutive LIBs (solid line) are presented in Fig. 1(b). The waveforms of the averaged pulses do not differ noticeably. The mean pulse duration is 62 μs ($\pm$1.65μs SD) and its peak pressure is 98.4 Pa ($\pm$4.22 Pa SD), which corresponds to 133.8 dB of peak pressure level.

The magnitude response of the pressure pulse at 1 m averaged over 100 measurements is plotted in Fig. 2(a) (upper box) for the audible bandwidth. The magnitude response shows a maximum of 123 dB SPL at 13 kHz and decays $-$6 dB per octave toward lower frequencies. The SD for this magnitude response is less than 0.8 dB for all frequencies. The phase response of the pressure pulse, Fig. 2(a) (lower box), is linear for frequencies above 100 Hz. Magnitude responses measured at 0.5, 1, 2, and 4 m are illustrated in Fig. 2(b) for frequencies less than 20 kHz. The magnitude response attenuates 6 dB when doubling the distance. At frequencies more than 9 kHz, the sound attenuation in air is observable. The magnitude responses do not reveal nonlinear propagation effects.

The magnitude response of the pressure pulse measured along 0°, 45°, and 90° directions deviates by less than 0.5 dB at frequencies above 10 kHz, and no noticeable differences are found at frequencies less than 10 kHz [see Fig. 2(c)].

3.2 Room impulse responses

The first 14 ms of normalized room responses measured with the spherical loudspeaker (upper box), the directional loudspeaker (middle box), and the LIB (lower box) are presented in Fig. 3. The measured room response (dashed-dotted line) and the result of the deconvolution with the free field response of the sources (solid line) are plotted overlapped.

The duration of the impulse responses of the three sources are 0.113 ms for the LIB, 4 ms for the spherical loudspeaker, and 1.27 ms for the directional loudspeaker. The first reflection (see Fig. 3) is from the ceiling, and it arrives 2.6 ms after the direct sound. The second reflection is from the floor, and it arrives 3 ms after the direct sound. The third reflection is from a lateral wall [see Fig. 1(a) upper wall]. Two different reflections are observable between the floor and wall reflections in the response measured with LIB. These reflections were found to be from a loudspeaker installed in the ceiling (ceiling LS in Fig. 3) on top of the source position and from the laser head. The reflection from the lens is hardly seen after the direct sound pulse.

4. Discussion

The measured pressure pulse produced by LIB [see Fig. 1(b)] is intense (98 Pa peak pressure) and short (62 μs). The repeatability of LIB depends mainly on the laser configuration, but other parameters, e.g., dust, may affect the generation of LIB and consequently produce deviations in the waveform from pulse to pulse. However, the mean waveform of several repetitions is similar between sets of measurements, and the SD of the magnitude response is less than 0.8 dB for all frequencies. The magnitude response at 1 m distance shows that most of the energy within the audible bandwidth is concentrated between 9 and 20 kHz [see Fig. 2(a) upper box]. Below this range, the magnitude response decays $-$6 dB per octave toward lower frequencies. Although the LIB produces most of its acoustic energy above 9 kHz, the high repeatability of the pressure

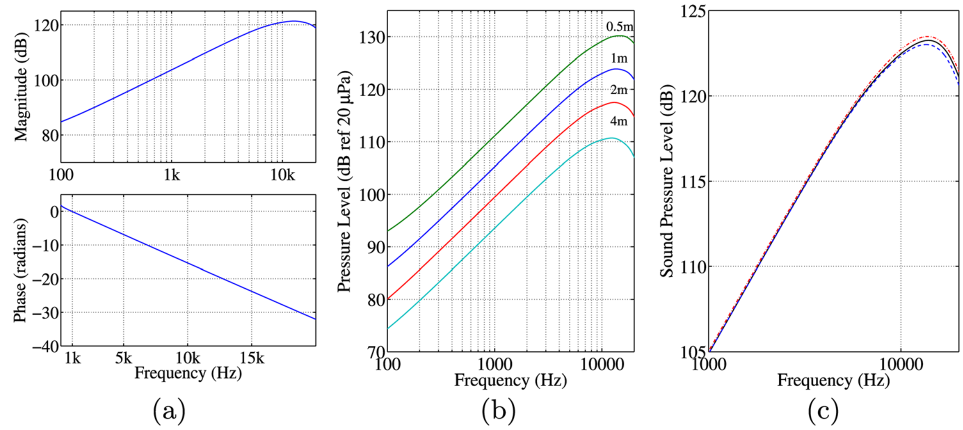

Fig. 2. (Color online) (a) Magnitude (upper box) and phase (lower box) responses of the pressure pulse produced with laser-induced air breakdown. (b) Magnitude responses measured at 0.5 m (upper curve), 1 m, 2 m, and 4 m (lower curves) distance from the source. (c) Magnitude responses at 1 m for 0° (solid line), 45° (dashed line), and 90° (dashed-dotted line) directions.

pulse permits averaging to improve the signal-to-noise ratio at lower frequencies, if necessary. This increases the usable bandwidth of the measurement. The magnitude responses as a function of distance, Fig. 2(b), show that the pulse attenuates mainly through geometric spreading and air absorption. Hence non-linear effects are not noticeable beyond 0.5 m travel distance. In addition, the LIB radiates omnidirectionally with 0.5 dB maximum deviation above 10 kHz. This was expected because the plasma size is smaller than the wavelength at 20 kHz.[4] These results show that with the employed laser parameters, the LIB emits fairly identical high pressure pulses that are broadband and omnidirectional.

The point source assumption of the LIB is supported by the room responses illustrated in Fig. 3. The short duration of the LIB pressure pulse produces distinct and separable reflections even when they occur close in time. This is especially observed for the ceiling and floor reflections, which are clearly separated in the room response obtained with LIB (lower box, dashed-dotted line) but which are mixed in the response obtained with the spherical loudspeaker (upper box, dashed-dotted line). The LIB pulse duration (0.113 ms) differs from previous measurements (0.062 ms) mainly due to the anti-alias filtering used in the resampling and to the measurement distance

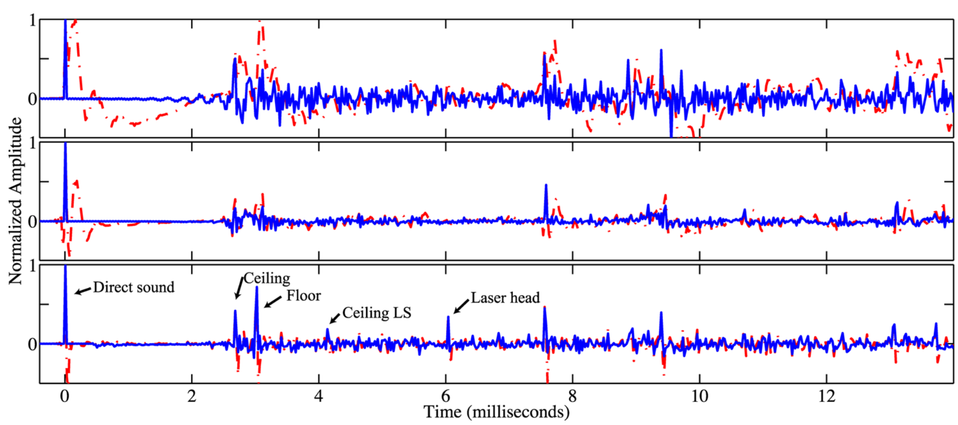

Fig. 3. (Color online) Measured (dashed-dotted line) and deconvolved (solid line) room impulses responses for spherical loudspeaker (upper box), directional loud-speaker (middle box) and LIB (lower box).

difference. The deconvolution process compensates accurately for the source response because LIB is broadband and omnidirectional and provides sufficient sound energy. The deconvolved response obtained with LIB (lower box, solid line) shows distinct impulses for all reflections. In contrast, with the spherical loudspeaker (upper box, solid line), the floor reflection in the deconvolved response is hard to detect due to interference with reflections produced by the different driver elements in the array.[1] Furthermore the amplitude of the ceiling reflection is reduced due to ceiling absorption when compared to the floor reflection amplitude in the LIB room response. The reflection produced by the loudspeaker above the LIB position is also noticeable (ceiling LS in Fig. 3). This reflection is not evident in the response obtained with the directional loudspeaker (middle box, solid line) due to the loudspeaker directivity. The masslessness of the LIB is proven by the presence of a reflection from the laser head. This reflection is absent in the other room responses due to the acoustic shadow produced by the loudspeakers.

The LIB presents characteristics close to an ideal point source thus providing an accurate measurement of the impulse response of the acoustic system. Although the impulse response measurement was done for a room, the LIB can also be used in other applications where the use of a real point source is important, e.g., in near-field head-related-transfer functions of a dummy-head.[2]

5. Conclusions

The acoustic characteristics of the laser-induced air breakdown, LIB, were measured across the audible bandwidth. A room impulse response measured with the LIB was compared to the responses obtained with a spherical and a directional loudspeakers. The LIB resembles an ideal acoustic point source emitting repeatable pulses in an omnidirectional radiation pattern. The pulses feature sufficient sound pressure level and broadband frequency response. With the experimental configuration, the LIB provided a more accurate representation of the room reflections than a spherical and a directional loudspeaker.

Acknowledgments

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