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Visualization of sound field and sound source vibration using laser measurement method

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ABSTRACT

Visualizations help us to understand the sound field behavior. A well-known method of sound field visualization is Kunt's experiment which visualizes standing waves using light particles. Comprehending of both accurate and transient information on sound fields requires measurement of information at multiple points, and also their visualization. Microphones are commonly used to implement such measurements, which means that numerous microphones are needed. On the other hand, Laser Doppler Vibrometer (LDV) can be used to measure an average sound pressure over a laser path. We have conducted fundamental research on sound field measurement and visualization using LDV and Computed Tomography (CT) without ordinary microphones. The measured value contains integrated information on the laser path. If we have data on an area measured from all directions using LDV, we can estimate the sound field in the area without having to measure at many points using microphones. The new technology of observing sound field and vibration is proposed and being put to practical use in this way. The sound field is generated by sound source and it is important to know the relationship between sound field and sound source. It is very useful to observe both sound field and sound source vibration simultaneously. In this paper, we describe the integrated visualization of sound field and sound source vibration using 3D laser measurement method. We used Processing programming language in order to realize the interactive visualization of sound field and sound source vibration. In addition, we conducted an experimental measurement of impulse responses with laser CT and Time Stretched Pulse (TSP) signal.

INTRODUCTION

Sound visualizations help us to understand the behavior of sound field. However, accurate sound visualization requires a lot of work and time. In order to visualize sound fields, we have to measure a sound pressure or intensity correctly at so many points. Therefore, we usually measure the sound using a number of microphones or measure it many times by moving microphones.

On the other hand, a sound measurement method using a Laser Doppler Vibrometer (LDV) have attracted attention in recent years. LDV measures the line integration of sound field over the laser path. If we have LDV measured data on an area from different directions, we can estimate the sound field without measuring at many points using microphones. This kind of signal processing is known as computed tomography (CT) based on reconstruction from projections. X-ray CTs are used in medicine to observe inside the body without contact or damage. Similarly we can observe a sound field by using laser CT. We have done the fundamental research on sound field measurement and visualization using LDV and CT without ordinary microphones (Oikawa et al. 2005; Ikeda et al. 2006; Ikeda et al. 2008a; Ikeda et al. 2008b).

The sound field is generated with the sound source and it is important to know the relationship between sound source and sound field. Consequently, if the sound field and sound source vibration observation can be done at the same time, it is very useful.

In this paper, we describe the united visualization of sound field and sound source vibration using 3D laser measurement method. We realized the interactive visualization of sound field and vibration by programming language "Processing". We also describe a fundamental experiment of impulse response measurement using laser CT. We can get impulse response on any point in measurement area by observation from the outside.

SOUND PRESSURE MEASUREMENT USING LASER DOPPLER VIBROMETER

It is possible to get the sound pressure changes by measuring the refractive index changes of air (Nakamura 2001). From the state equation for adiabatic change of gas, we get the relationship between volume changes and refractive index changes:

$$\frac{\Delta V}{V} = -\frac{\Delta n}{n-1}, \tag{1}$$

where V is the volume and n is the refractive index. Furthermore, we have

$$\frac{P}{P_0} = -\gamma\frac{\Delta V}{V}, \tag{2}$$

$$P_0\gamma = c^2\rho, \tag{3}$$

where P_0 is the atmosphere pressure, P is the sound pressure, γ is the specific heat ratio, ρ is the density, and c is the sound velocity. From eq. (1), (2), and (3), we have

$$P = \frac{c^2\rho}{n-1}\Delta n, \tag{4}$$

where P and Δn is the function of position $\mathbf{s}$. Then

$$P(\mathbf{s}) = \frac{c^2\rho}{n-1}\Delta n(\mathbf{s}). \tag{5}$$

If we pass the laser from LDV into the sound field against a reflection wall and measure the reflected laser light, we can calculate the refractive index changes which produces the sound pressure changes instead of distance changes. The light path length, l_c, is the line integrated value of refractive index over the laser path. So

$$l_c = \int n(\mathbf{s})d\mathbf{s}. \tag{6}$$

This equation shows that l_c is a projection of $n(\mathbf{s})$. The measured velocity by LDV

$$v_{LDV} = \frac{dl_c}{dt} = \int \frac{dn(\mathbf{s})}{dt}d\mathbf{s}. \tag{7}$$

That is, v_{LDV} is a projection of $dn(\mathbf{s})/dt$. If we have projections of sound field, v_{LDV}, from any direction and make CT calculation, we are able to estimate $dn(\mathbf{s})/dt$. On the other hand, the refractive index changes

$$\Delta n(\mathbf{s}) = \int \frac{dn(\mathbf{s})}{dt}dt, \tag{8}$$

and from eq. (5) and (8)

$$P(\mathbf{s}) = \frac{c^2\rho}{n-1}\int \frac{dn(\mathbf{s})}{dt}dt. \tag{9}$$

Finally we can estimate $P(\mathbf{s})$ from v_{LDV} by eq. (9).

RECONSTRUCTION OF 3D SOUND FIELDS

Reconstruction from projections was first suggested by Radon (Radon 1917), and this sort of signal processing is known as CT based on reconstruction from projections (Avinash, Kka, and Slaney 1988; Shepp and Logan 1974). We performed 2D sound field reconstruction experiments based on the laser CT technique (Oikawa et al. 2005; Ikeda et al. 2006).

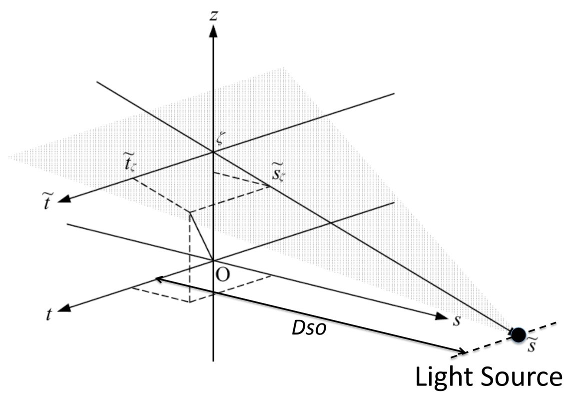

Figure 1: 3D CT calculating condition. We use (t,s,z) coordinate system. A light source is put on s-axis, and a reflected wall is the plane parallel to t-z plane. The rotating axis is z-axis. The distance between rotating axis and light source is D_{SO}.

We describe 3D sound field reconstruction by expansion of 2D reconstruction. In 2D sound field reconstruction, laser scanning positions are on a 1D line over the reflection wall. In the case of 3D sound field reconstruction, we scan the laser on the 2D surface over the reflection wall. In this paper, we use the filtered back-projection algorithm to calculate the reconstruction (Avinash, Kka, and Slaney 1988). Figure 1 shows the 3D CT calculating condition. The 3D sound field reconstruction $g(t,s,\zeta)$ on (t,s,z) coordinate system, which means $dn(\mathbf{s})/dt$, is follows:

$$g(t,s,\zeta) = \frac{1}{2}\int_0^{2\pi} \frac{D_{so}^2}{(D_{so}-s)^2}\int_{-\infty}^{\infty} R_\beta(p,\zeta)$$
$$h\left(\frac{D_{so}t}{D_{so}-s}-p\right)\frac{D_{so}}{\sqrt{D_{so}^2+\zeta^2+p^2}}dpd\beta. \tag{10}$$

Here $R_\beta(p,\zeta)$ is the measured projections, v_{LDV}, D_{SO} is the distance between rotating axis and light source, $h\left(\frac{D_{so}t}{D_{so}-s}-p\right)$ is the impulse response of filter for CT calculation, β is the angle of rotation, and p is the transverse on projection.

VISUALIZATION OF SOUND FIELD AND SOUND SOURCE VIBRATION

We measure the vibration of speaker and the 3D sound field generated by this using scanning LDV (Polytec PSV-300). To observe the sound field using laser CT technique we have to measure projections of sound field from the outside. If it is possible to move or rotate the sound field for example the direct sound generated by speaker, we can rotate the speaker instead of the LDV head to measure some projections, i.e., we rotate the sound field for observation itself instead of the LDV head. The LDV is a measurement equipment for measuring vibration of some object. It is possible to take measurements of sound source vibration and sound field at the same time. We input a trigger signal, which is synchronized with the source signal to speaker, to LDV, and let the trigger input the starting time of measurement, and then make a recording the vibration of speaker.

The 3D representation is useful to visualize large amounts of spatial information such as sound field information. Especially it is important to realize the various representation in order to understand complex sound fields. Processing programming language, which is developed by Ben Fry, is powerful tools for visualizing of data (Fry 2008). It it possible to realize the interactive representation using it, and we can realize the intuitive interface for sound field measurements. In this paper we use Processing language for representation.

Experiments

We used an ordinary speaker (YAMAHA NS-10M) and a power amplifier (YAMAHA P4050), and drove it with 4kHz sinusoidal pulse. We rotated the speaker instead of the LDV head. A turn table with NSK mega-torque motor system (EA32 drive unit and YS type motor) was used for the rotation of the speaker, and the speaker was put face up on the turn table in the echoic chamber. The distance between the LDV and the reflection wall is 3 m. The speaker is located in the midst.

The laser light source was set on a plane 30 cm above the speaker. We scanned the laser reflecting wall with the He-Ne laser light of LDV. The maximum deflection angle was 32 degrees from side to side, and 16 degrees from up to down. The turning angle of speaker was 360 degrees in every 15 degrees, i.e., we took 24 laser projections and used them to make the reconstruction. The number of laser scanning points was 101 horizontally and 51 to the vertical direction for each projection. The interval between measurement points was less than 10 mm.

The reconstructable area is a commonly observed area by all projections. It is the area in the column of 40 cm in radius and 20 cm in height, in which it centered on the rotation axis of the speaker. For the vibration, the front surface of speaker was measured. The distance between the speaker surface and LDV was 5.35 m. So we can assume that the laser light vertically hits the front surface. The front side of speaker (38.3 cm in length and 21.5 cm in width) was digitalized by 3735 points (83 points in length and 45 points in width) in total. The vibration was measured in each point using the same signal as for sound field measurement.

Figure 2 and 3 shows the vibration of speaker, the 3D sound field generated by it, the source signal and the measured signal at the center point of sound field observation area. Figure 2 shows them before wave travels in the sound field observation area. Figure 3 shows them after that. Each picture shows at about 0.16 ms, 0.31 ms, 0.50 ms, 1.75 ms, 2.13 ms and 2.50 ms since the speaker has been driven. For sound fields the CT reconstruction is performed from projection, and the representation on the y-z-plane and the plane 30 cm above the speaker are shown in picture. The rotating axis is z-axis. Figure 2 (a), (b) and (c) shows just vibration of the speaker because the sound does not arrive at the sound field observation area. The source signal is one period of 4kHz sinusoidal. However we can see that the tweeter and the woofer move half period passed one. Figure 3 shows that the wave from the tweeter is traveling, and that the sound is also coming from the woofer. Though the input signal is one period of 4kHz sinusoidal wave, we can confirm that the vibration and wave sound is longer than one period of sinusoidal signal.

IMPULSE RESPONSE MEASUREMENT

We measure the impulse response by this using LDV and CT technique and make a comparison between ordinary microphone method and our proposed method. We get impulse response on any point inside the measurement area by CT technique as follows. First we get the projections of Time Stretched Pulse (TSP) response. Secondly we calculate the projections of impulse response by making a convolution of TSP response and inverse TSP signal. Finally we take CT calculation of the impulse response projections and we can get the impulse response on any position.

Experiments

We drove a speaker unit (Panasonic EAS16P595B6) by TSP signal and measured TSP response for a direct sound radiated from the speaker using LDV and sound level meter (RION NL-32). The length of TSP signal was about 0.5 s. Figure 4 shows the measurement condition for a scanning LDV. The distance between LDV and concrete wall was 3 m, and the speaker unit was put on the intermediate between them. The laser reflection area on concrete wall was a rectangle shape, 0.91 m long and 0.73 m wide. The number of scanning points was1739 points, 37 points long and 47 points wide. The sampling frequency was 51.2kHz, and the averaging time was 8 for LDV measurement.

We used the speaker unit that has a symmetry of rotation with respect to central axis. We assume that the sound field radiated form it has also rotational symmetry. Therefore we can assume that the sound field projections from any direction are same, and we can reconstruct the 3D sound field using only a projection from one direction. That is, we have impulse response of any point in 3D field by using just one projection on CT calculation. We calculated CT with a rotational resolution of 10 degrees. In order to compare the impulse responses measured by both CT calculation and sound level meter, we had a measurement of impulse response using sound level meter on 0.2 m distance from speaker unit central.

Figure 5 shows the sound field projections observed by scanning LDV. The (a) and (b) are wave front generated by the speaker at 100 ms and 150 ms from the beginning of TSP signal, respectively. We can see the frequency changes of TSP signal. Figure 6 shows the impulse responses measured by sound level meter and CT calculation, respectively. The impulse responses by sound level meter and CT calculation are measured on 0.2 m distance from the speaker unit central. They are very similar. We can see some sound wave after the direct sound. We guess that the speaker vibrates because it is not fixed enough. Figure 7 shows the traveling wave at 1.0 ms, 1.5 ms and 2.0 ms.

CONCLUTIONS

In this paper, we have described the united visualization of sound field and sound source vibration using LDV. We could measure the sound source vibrations and sound pressures using LDV and visualize the vibration and sound pressure distribution. We calculated the reconstruction of 3D sound field from the laser projections using CT technique, and visualized the sound pressure distribution in any cross-section interactively. To visualize the vibration and sound field, we used Processing programming language and realized the interactive interface. We will consider the intuitive data display method and visualizing method, and measurement for various sound source and sound field. We also have described the impulse response measurement by LDV. We were able to get the impulse response on any position by CT technique and were able to know the change of impulse response in 3D field.

In this paper, we targeted the direct sound. We will research on the impulse response measurement including the reflected sound in the future and construct a measurement system for that. We expect that the additional improvement can be achieved in real-world measurement. We are currently working on this. This research was supported by Waseda University Global COE Program 'International Research and Education Center for Ambient SoC' sponsored by MEXT, Japan.

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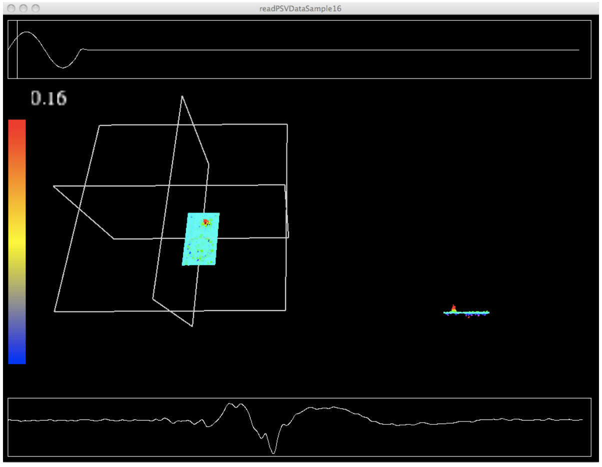
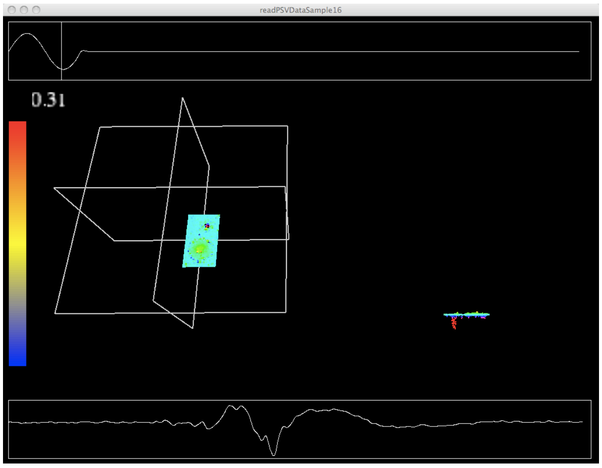
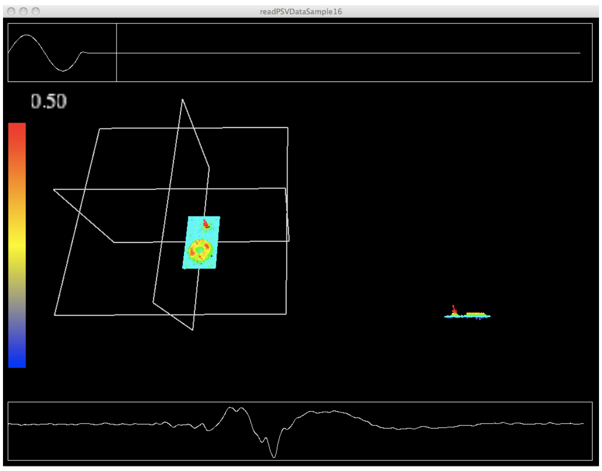


(a) 0.16ms

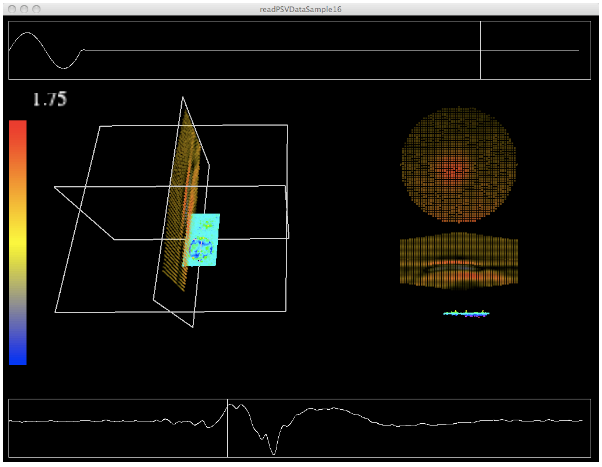


(b) 0.31ms

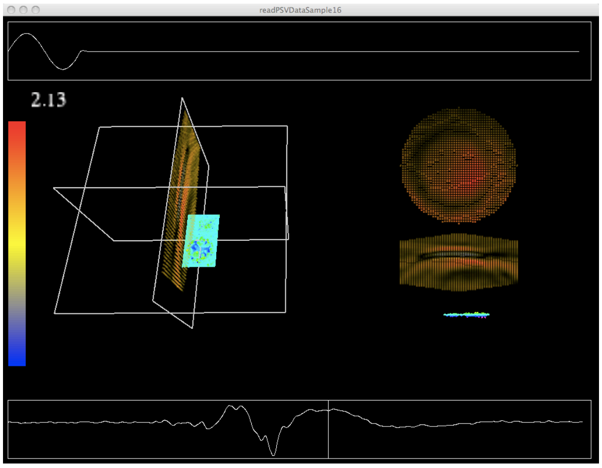


(c) 0.50ms

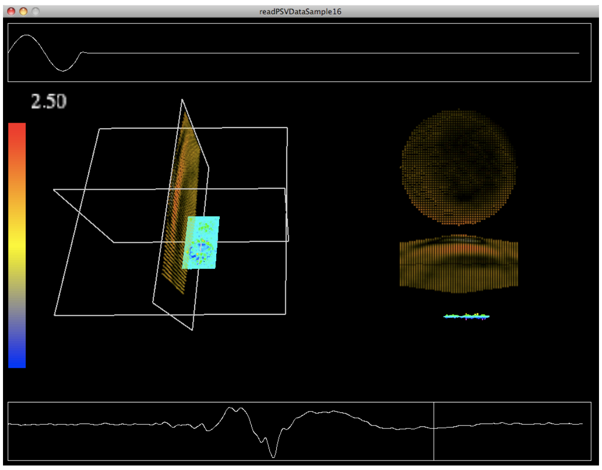
Figure 2: Visualization of sound source vibration and sound field before sound wave travels. The vibration of speaker, the 3D sound field generated by it, the source signal and the measured signal at the center point of sound field observation area are shown. The source signal is waveform at the top of each picture, and the measured signal is waveform at the bottom of picture. The source signal is one period of 4kHz sinusoidal. We observe just the vibration of speaker.



(a) 1.75ms



(b) 2.13ms



(c) 2.50ms

Figure 3: Visualization of sound source vibration and sound field after sound wave travels. These show that the wave from a tweeter is traveling, and that the sound is also coming from a woofer. The cross-section of representation on x-y-plane, y-z-plane and z-x plane are shown in this picture.

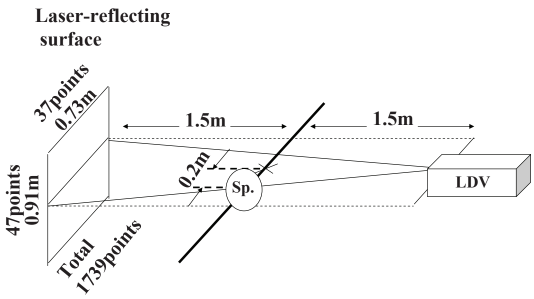
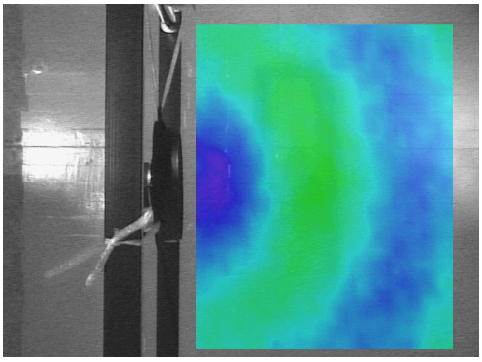
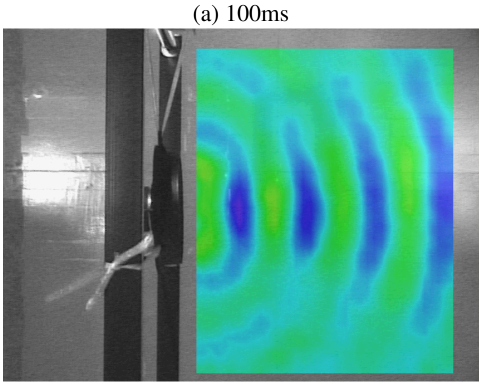


Figure 4: Impulse response measurement condition. The distance between LDV and concrete wall is 3 m, and the speaker unit is put on the intermediate between them. The laser reflection area on concrete wall is a rectangle shape, 0.91 m long and 0.73 m wide. The number of scanning points is1739 points, 37 points long and 47 points wide.



(a) 100ms



(b) 150ms

Figure 5: Sound field projection observed by scanning LDV. Green color shows higher measured velocity part and blue color shows lower part by LDV. The (a) and (b) are wave front generated by speaker at 100 ms and 150 ms from the beginning of TSP signal, respectively.

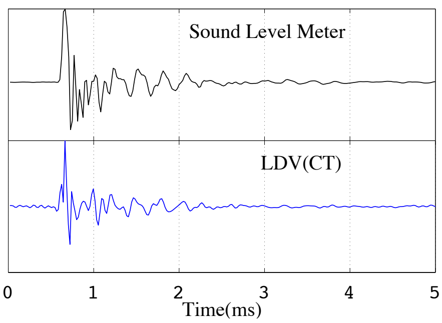
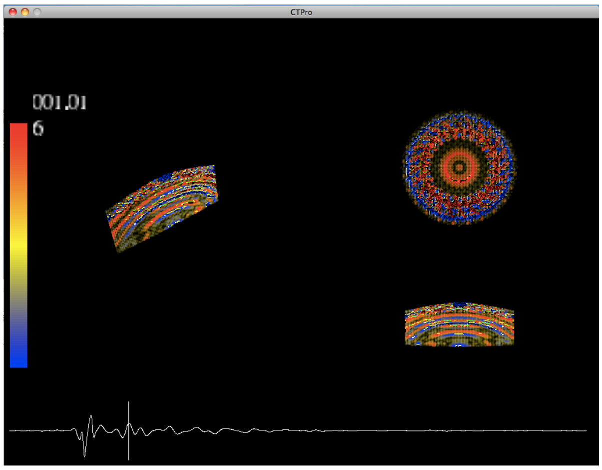
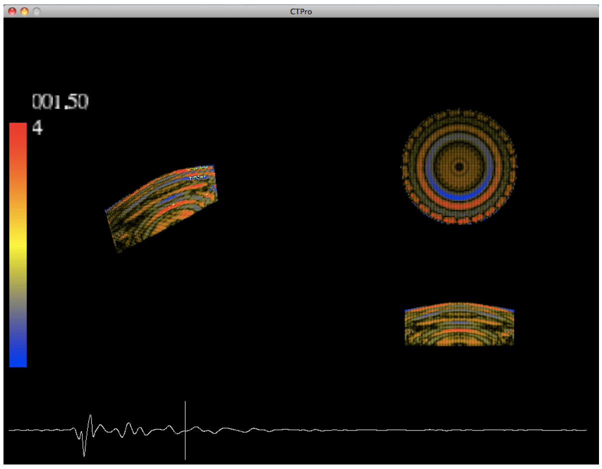


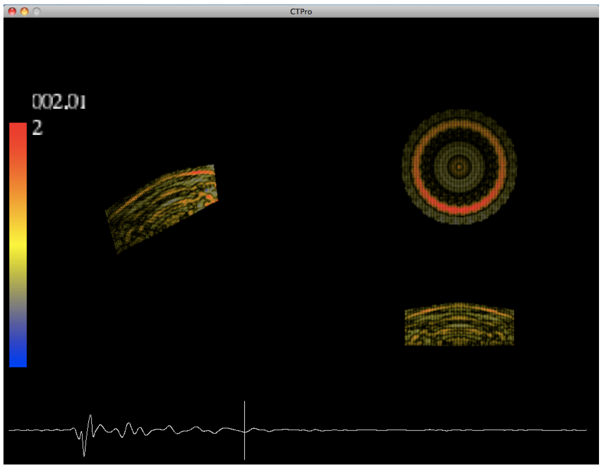
Figure 6: Comparison between impulse responses. The top is the impulse response measured by sound level meter and the bottom is by CT calculation, respectively.



(a) 1.0ms



(b) 1.5ms



(c) 2.0ms

Figure 7: Traveling wave at 1.0 ms, 1.5 ms and 2.0 ms. The cross-section of representation on x-y-plane, y-z-plane and z-x plane are shown in this picture.