Noise reduction by spatio-temporal filtering on parallel phase-shifting interferometry

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***Abstract*—Visualizing sound field is important to fully understand the acoustic behavior and phenomena. Recently, sound field visualization by using parallel phase-shifting interferometer (PPSI) has been proposed. PPSI can observe sound field quantitively and instantaneously without placing any object inside the field. However, the system has introduced some unwanted noise to the output fringe image. There is continuous development in signal processing method to reduce the noise in PPSI system. In this paper, different type of spatio-temporal filter has been tested to improve noise reduction in PPSI system upon establishing.**

Keywords—Spatio-temporal filtering, optical visualization, high-speed imaging, phase-shifting interferometry

I. Introduction

Visualizing sound field is important for understanding acoustic phenomena. It is useful for detecting source positions of sound, constructing audio equipment, and understanding processing of sound generating and propagation. By far, various measurement and visualization methods have been proposed. Recently, parallel phase-shifting interferometer (PPSI) have been proposed [1-4]. Since the change in air density due to sound could change the refractive index and effect the light, it is possible to obtain acoustic information by using optical system. PPSI enable uses to measure sound without interference the sound field due to its contactless nature. Furthermore, PPSI measures multiple points simultaneously and instantly with a high-speed camera. It can measure the phase difference of light changed by the sound, and the information could be obtained as a video which make it possible to observe time-varying phenomena.

However, the PPSI has also introduce the unwanted noise to the capture PPSI image. There are various methods that can be used to reduce the noise from the fringe image has been introduced to the PPSI since they were first develop. For example, the fringe image reconstruction method calls Hyper ellipse fitting in subspace method (HEFS) [5,6] which reduces great amount of pepper noises from the capture PPSI data. Furthermore, the spatio-temporal filter was shown to be useful for extracting sound field from noisy image [7-9].

In this paper, in order to further improve the quality of output image and noise reduction processing of PPSI further upon establishing. The four different types of spatio-temporal filter were tested and compared to see which perform best on the PPSI output data.

II. Visualization of Sound Field

A. Optical measurement of sound

Optical measurement is used for investigating the behavior of phase of light ϕ, which is modulated by the refractive index of the air n:

$$\phi(\mathbf{r}, t) = k \int_L n(\boldsymbol{l}, t) d\boldsymbol{l} \tag{1}$$

where $\boldsymbol{r}$ is the k is the wave number of lights, t is time, $\boldsymbol{r}$ is the position of vector, L is the optical path. the refractive index of air n$(\boldsymbol{r}, t)$ is represented as

$$n(\boldsymbol{r}, t) = n_0 + \frac{n_0 - 1}{\gamma p_0} p(\boldsymbol{r}, t), \tag{2}$$

where $p(\boldsymbol{r}, t)$ is sound, p_0 and n_0 are the pressure, and refractive index at the atmosphere ,respectively, and γ is the specific heat ratio. Then, the phase of light effected by sound pressure ϕ_s can be considered from Eq. (1) and (2) as follows:

$$\phi_s(\boldsymbol{r}, t) = k_l \frac{n_0 - 1}{\gamma p_0} \int_L p(\boldsymbol{l}, t) d\boldsymbol{l} \tag{3}$$

Therefore, the sound pressure can be acquired by investigating the phase of light.

B. Parallel phase-shifting interferometry (PPSI)

Interferometry is a method that measures the phase difference by using light interference, and one of them is PPSI. PPSI is a parallelized version of phase-shifting interferometry (PSI) [10] that multiple interference fringe could be obtained simultaneously [11,12]. The schematic diagram of PPSI system is shown in Fig. 1. The laser emits monochromatic light, which are split into reference light and object light. When, the reference light reaches the first

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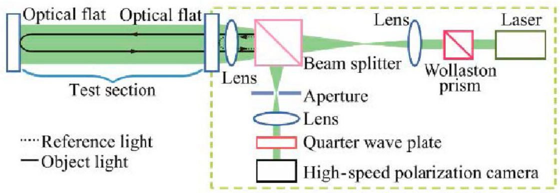

Fig. 1. The schematic diagram of PPSI system

optical flat, it is reflected and goes to the beam splitter. The object light passes through the first optical flat to the test area, then reflected by the second optical flat, and goes to the beam splitter. The two polarizations are combined and reflected by the beam splitter. After that, the high-speed polarization camera captures the interference fringes.

III. Spatio-temporal Filer for PPSI

A. Spatio-temporal filtering

The spatio-temporal filter [7,8] was proposed based on the physical model of sound. By considering the homogenous wave equation in the frequency domain,

$$(\Delta + {k_s}^2)p(\boldsymbol{r}, \omega) = 0, \tag{4}$$

where Δ is the Laplace operator, ω is the angular frequency, $k_s = \omega/c$ is the wave number and c is the speed of sound. The solution satisfying Eq. (4) could be represented by the summation of the plane wave. Considering the wavenumber spectrum of the plane wave, the spectrum only exists on a circle of radius $k_s = \omega/c$ assuming that the visualized data are two-dimensional sound fields. Since the spatio-temporal spectrum of the audible sound field is focused on specific region, using a bandpass filter to extract sound in that region are proven to be effective.

B. Type of spatio-temporal filter

There are two main ways to design the bandpass filter, first it was designed by cascading stage method, which cascade a low-pass filter and a high-pass filter. Another is design by a single stage method, which convolution the filter kernel of low-pass filter and high-pass filter as shown in Fig. 2. In this paper we used single stage method to design the bandpass filter.

The lowpass filter kernel could be transformed to high pass filter kernel as:

$$H_{HP} = 1 - H_{LP} \tag{5}$$

where H_{HP} is a high pass filter kernel and H_{LP} is lowpass filter kernel.

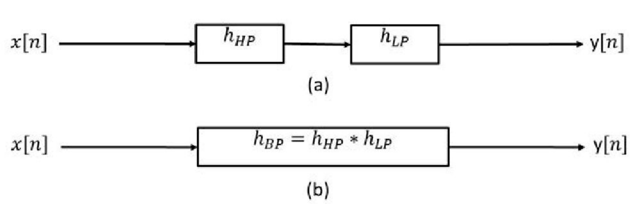

Fig. 2. Bandpass filter design method (a) cascading method, (b) single stage method.

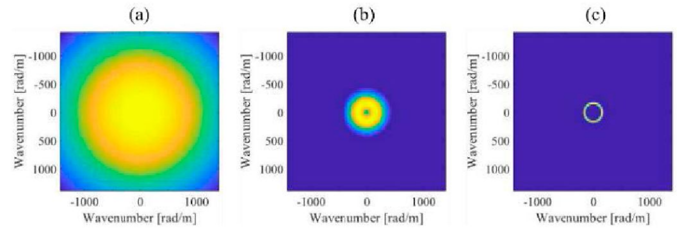

Fig. 3. The cosine spatial bandpass filter center frequency at 10000Hz with different width. (a) β = 0.001, (b) β = 0.01, (c) β = 0.1

There are four different types of filter that were used in this paper which are:

1) Cosine filter: Cosine bandpass filter is the first spatial-temporal bandpass filter that was introduced to the PPSI system its design based on the cosine function. The filter kernel H_{Cosine} could be computed as

$$H_{Cosine} = \frac{(cos(\beta \times (R - k)) + 1)}{2} \tag{6}$$

where β is the width of the filter, R is the mesh grid, k is the radius of the circle determine by ω/c. If the β value is too big or too small it can affect the bandwidth of the cosine filter as shown in Fig. 3.

2) Ideal filter: The Ideal filter are designed to completely remove frequency outside the pass band from the signal. The ideal lowpass filter has filter kernel H_{ILP} as

$$H_{ILP} = \begin{cases} 1, & R \leq k \\ 0, & R > k \end{cases} \tag{7}$$

3) Gaussian filter: The Gaussian filter has the impulse response same as the gaussian function. The main characteristic are having no overshoot to a step function input while minimize the rise and fall time. The kernel of gausian lowpass filter H_GLP could be represented as

$$H_{GLP} = e^{-\frac{R^2}{2k^2}} \tag{8}$$

4) Butterworth filter: The Butterworth filter are design to have the most flattest frequency response in their passband, it also refers to as a maximally flat amplitude filter. The kernel of butterworth lowpass filter H_BLP could be computed as

$$H_{BLP} = \frac{1}{1 + (\frac{R}{k})^{2n}} \tag{9}$$

where n is the filter order.

IV. Experiment and Results

A. Evaluation

Normally, after the PPSI data are captured from the high-speed polarization camera, the phase retrieval method must be applied to extract and visualize the phase data. Originally, the traditional M-step phase shifting algorithm were used for phase retrieval [13]. After that, the hyper ellipse fitting in subspace method for phase retrieval (HEFS) were introduced to the system, it results in lesser noises that occur in PPSI output data. Furthermore, the spatio-temporal filtering is introduced to the system.

Overall, After the spatial filter have been applied on the output data. The output PPSI image could be observed more

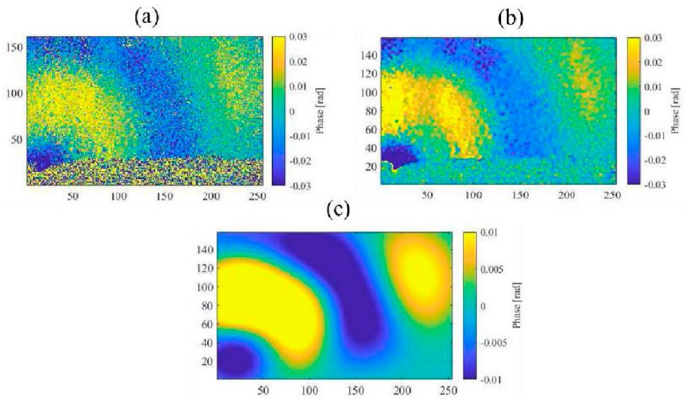

Fig. 4. PPSI data output after process by (a) M-step phase shifting algorithm (b) HEFS phase retrieval method (c) Spatio-temporal filter method.

easily as we could see from Fig. 4. To further observe the performance of each type of spatial-temporal filter, the signal-to-noise ratio testing must be tested. By simulating the sound field that are captured from PPSI data and adding control amount of random noise to the simulated data, we could test and observe the performance of different types of spatio-temporal filters compared to each other.

B. Sound Field Simulation

The behavior of the propagated sound field is generated by using the three-dimensional green's function [14]. The sound wave ϕ propagating away from sound source is generated as:

$$\phi(\boldsymbol{r}|\boldsymbol{r}_0) = \frac{e^{ik}\|\boldsymbol{r}-\boldsymbol{r}_0\|}{4\pi\|\boldsymbol{r}-\boldsymbol{r}_0\|}, \tag{10}$$

where $\boldsymbol{r}_0$ is point source which is evaluated at the observation point $\boldsymbol{r}$:

$$\|\boldsymbol{r}-\boldsymbol{r}_0\| = \sqrt{(x_i-x_0)^2+(y_i-y)^2+(z_i-z_0)^2}, \tag{11}$$

where (x_0, y_0, z_0) is the coordinate at the point source and (x_i, y_i, z_i) is the coordinate inside the field. In the PPSI system, the sound field is visualized by observing the deflection of the light which interacts the sound field along z-direction. The Three-dimension sound field could be simulated as

$$\phi(\boldsymbol{r}|\boldsymbol{r}_0) = \int_{Z_{min}}^{Z_{max}} \frac{e^{ik}\|\boldsymbol{r}-\boldsymbol{r}_0\|}{4\pi\|\boldsymbol{r}-\boldsymbol{r}_0\|} dz. \tag{12}$$

where Z_{max} and Z_{min} is the border of the observation area along z direction. The time direction of the propagated sound field could be created by multiplying the time factor $e^{-j\omega t}$.

C. Adding Control Amount of Random Noise

In order to see the performance of the Spatial filter the several levels of random noise were added to the simulate video. -20dB, -10dB, 0 dB, 10dB, -20dB SNR were selected to adjust level of the noise. Therefore, the amplitude of the random noise must be adjusted before adding to the simulated sound field. By introducing the constant α to the Signal-to-noise ratio equation we obtain

$$\alpha = \frac{\sum |S_{Data}|^2}{\sum |S_{Noise}|^2} \frac{1}{10^{\frac{SNR_{dB}}{10}}} \tag{13}$$

where S_{Data} is the sound field simulated video, S_{Noise} is the random noise data that were generate and SNR_{dB} is the signal-to-noise ratio level in decibel. After computing α we could control the noise level of the random noise by

$$C_{Noise} = \alpha \times S_{Noise} \tag{14}$$

where C_{Noise} is the control level random noise that we could add it to recieve the simulated video with different level of random noise as shown in Fig. 5 below.

D. Experiment Results

Each type of filter was tested with five different filter bandwidths. The performance result of each type of filter are collected as shown in Fig. 6. In general, the gaussian bandpass filter with 10000Hz filter bandwidth are showing the best performance in SNR level compared to all filters. The gaussian spatial bandpass filter is the only filter that SNR level reaches the 12dB SNR following by Cosine spatial bandpass filter.

In order to reach more insight view of filter performance, the average performance of each filter type in overall filter bandwidth and the SNR level after filtering are applied to each simulated data with different SNR level are shown in Fig. 7. It could be seen clearly that the overall filter performance of the gaussian spatial bandpass are above all the other filter type that are used in this experiment.

V. Conclusion

In conclusion, the spatio-temporal filtering method could be used effectively to reduce the unwanted noise in the PPSI system. The Gaussian spatial bandpass filter is performed best above of all the other filter types that were used in this research paper. It was the only filter that reach the 12dB SNR level and it outperform the other types of filter by more than 3dB SNR.

Also, the spatio-temporal bandpass filter is performed best when the filter has a wider frequency bandwidth. The frequency bandwidth will have dramatical effect on cosine and Ideal bandpass filter. On the other hand, the frequency bandwidth will only have slightly increased in performance on Gaussian and Butterworth filter.

However, we could clearly see that spatio-temporal filter are performed best when the SNR level of the image is low. The filter performance tends to be decreased over the increase SNR level. Also, beware that if the spatio-temporal

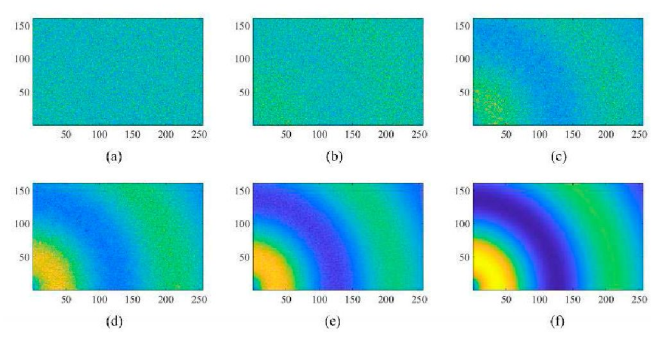

Fig. 5. 10kHz simulated sound field obtain by three-dimensional Green's function with different level of noise. (a) SNR = -20dB, (b) SNR = -10dB, (c) SNR = 0dB, (d) SNR = 10dB, (e) SNR = 20dB, (f) without noise.

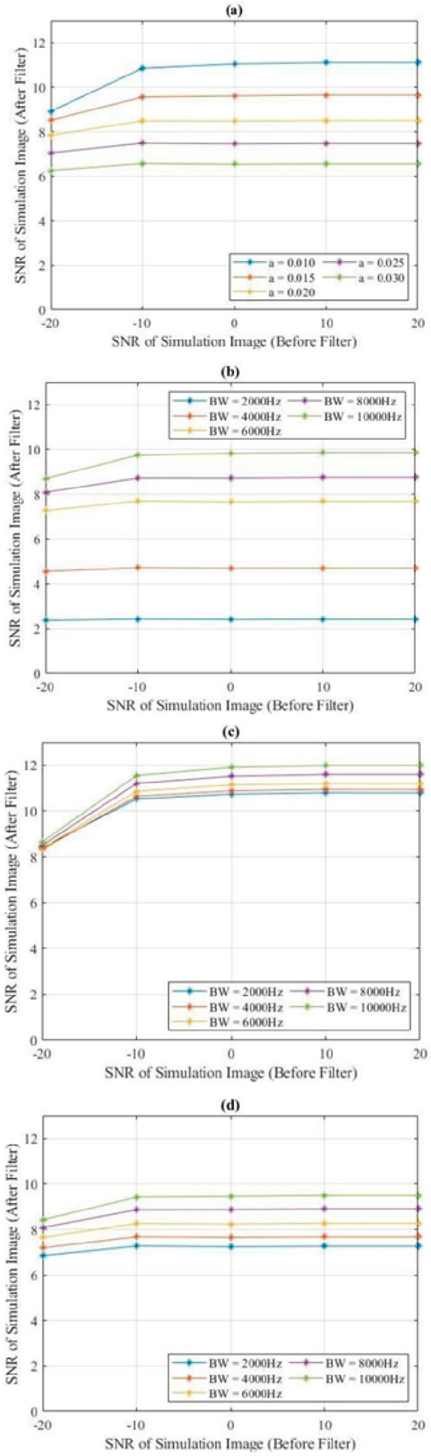

Fig. 6. The SNR level comparison of simulated sound field before and after filtering with different bandwidth of (a) Cosine bandpass (b) Ideal bandpass (c) Gaussian bandpass (d) 3rd order Butterworth bandpass, all center frequency at 10000Hz.

bandpass filter is applied to the data that has a higher SNR level than 10dB SNR, it tends to decrease the SNR level of the output data as it shown in Form Fig. 7(b).

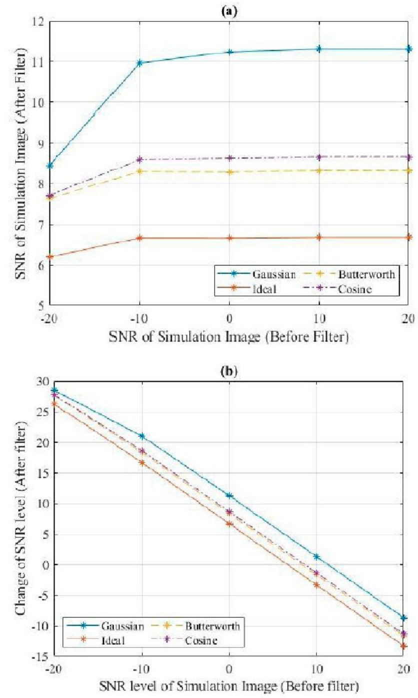

Fig. 7. (a) The SNR level comparison of each type of filter in overall bandwidth (b) The SNR level change after filter were applied to simulate data.

REFERENCES

[1] K. Ishikawa, K. Yatabe, N. Chitanont, Y. Ikeda, Y.Oikawa, T. Onuma,H.Niwaand and M. Yoshii, "High-speed imaging of sound using parallel phase-shifting interferometry," Opt. Express, vol. 24, no.12,pp. 12922-12932, Jun 2016

[2] Y. Oikawa, K. Yatabe, K. Ishikawa and Y. Ikeda, "Optical sound field-measurement and imaging using laser and high-speed camera,"45th Int.Congr. Expo. Noise Control Eng., pp. 258–266, 2016.

[3] K. Ishikawa, K. Yatabe, Y. Ikeda, Y. Oikawa, T. Onuma, H. Niwa andM. Yoshii, "Optical sensing of sound fields: non-contact, quantitative,and single-shot imaging of sound using high-speed polarizationcamera," 5th Jt. Meet. of Acoust. Soc. Am. and Acoust. Soc. Jpn., Nov.2016.

[4] K. Ishikawa, K. Yatabe, Y. Ikeda, Y. Oikawa, T. Onuma, H. Niwa andM. Yoshii, "Interferometric imaging of acoustical phenomena usinghigh-speed polarization camera and 4-step parallel phase-shiftingtechnique," Proc. SPIE, vol. 10328, 103280I, Nov. 2017.

[5] K. Yatabe, K. Ishikawa, and Y. Oikawa, "Simple, flexible, and accuratephase retrieval method for generalized phase-shifting interferometry,"J. Opt. Soc. Am. A, 34(1), 87–96 (2016).

[6] K. Yatabe, K. Ishikawa, and Y. Oikawa, "Hyper ellipse fitting insubspace method for phase-shifting interferometry: practicalimplementation with automatic pixel selection," Opt. Express 25(23),29401–29416 (2017).

[7] N. Chitanont, K. Yaginuma, K. Yatabe, and Y. Oikawa, "Visualization of sound field by means of schlieren method with spatio-temporalfiltering," in 2015 IEEE Int. Conf. Acoust. Speech Signal Process.(ICASSP), April 2015, pp. 509–513.

[8] N. Chitanont, K. Yatabe, K. Ishikawa, and Y. Oikawa, "Spatiotemporalfilter bank for visualizing audible sound field by Schlieren method,"Appl. Acoust., vol. 115, pp. 109–120, 2017.

[9] R. Tanigawa, K. Ishikawa, K. Yatabe, Y. Oikawa, T. Onuma and H. Niwa, "Extracting sound from flow measured by parallel phase-shifting interferometry using spatio-temporal filter" Proc. SPIE 10997,109970R (2019).

[10] H. Schreiber and J.H. Bruning, Phase Shifting Interferometry, chapter 14, pp. 547–666, Wiley-Blackwell, 2006.

[11] Y. Awatsuji, M. Sasada, and T. Kubota, "Parallel quasi-phaseshiftingdigital holography," Appl. Phys. Let., vol. 85, no. 6, pp. 1069–1071,2004.

[12] J. E. Millerd, N. J. Brock, J. B. Hayes, M. B. North-Morris, M. Novak, and J. C. Wyant, "Pixelated phase-mask dynamic interferometer,"Proc. SPIE, vol. 5531, pp. 5531–5531–11, 2004.

[13] D. Malacara, M. Servín, and Z. Malacara, Interferogram, Analysis For Optical Testing (CRC,2005),2nded.

[14] Chitanont N., "Spatial-Temporal filtering for visualzing audible soundfield by Schlieren method", Ph.D. thesis, Waseda University, Tokyo, 2017