ICIC Express Letters
Part B: Applications
Volume **7**, Number **2**, February **2016**

ICIC International ©2016 ISSN 2185-2766
pp. **469–474**

APPLICATION OF INDEPENDENT COMPONENT ANALYSIS TO IMPROVEMENT OF SIGNAL-TO-NOISE RATIO IN OPTICAL WAVE MICROPHONE

Hiroyuki Kawakami, Takashi Samatsu and Yoshito Sonoda

Graduate School of Industrial Engineering
Tokai University
9-1-1, Toroku, Kumamoto 862-8652, Japan
4bijm001@mail.tokai-u.jp; samatsu@tokai-u.jp; ysonoda@ktmail.tokai-u.jp

Received July 2015; accepted September 2015

Abstract. *An approach to signal-to-noise ratio improvement for an optical wave microphone is presented. In the optical wave microphone, ultra-weak diffraction light, which results from phase modulation by a sound wave, is converted to an electrical signal by a photodetector. The diffraction light pattern has two intensity peaks with opposite temporary phase, which are generated at the increasing and the decreasing density gradients of a sound wave, respectively. Differential detection of these by using a dual photodiode is effective to increase the signal intensity. In this study, we adopted an independent component analysis to the two signals in order to improve the signal-to-noise ratio. In the next stage, this method is to be applied to measurement of body-sounds related to the disease and mental stress.*

Keywords: Optical wave microphone, Laser, Independent component analysis, SN ratio

1. **Introduction.** Stethoscope is the most common way to diagnose disorder through sounds from human bodies such as heart beat, breathing, and digestion. Recently there is a study identifying the amount of stress using such sounds [1], which requires microphones to be placed on the thoracic or abdominal part of the body for measurement on a constant basis. Such microphones adopt an oscillation membrane, which is oscillated by a sound and transforms it into an electrical signal. Since its sensor part is a solid object, there are various restrictions and disadvantages such as the disturbance in a sound field caused by a microphone itself, or the matter of the membrane durability.

In contrast, an optical wave microphone can directly detect a sound by a laser beam without disturbing airflow and sound field. In this method, ultra-weak diffraction light generated by a sound wave entering into the laser beam is detected and converted to electrical signal. It has a large bandwidth from audio to ultrasonic waves and can also detect the high sound pressure. Though it can solve various problems of the oscillating membrane microphone [2-4], the Signal-to-Noise (SN) ratio of it still needs to be improved to realize a standard microphone.

Since two diffracted lights in reversed phase appear from a probing laser beam in an optical wave microphone, these can be detected simultaneously by using a split type photodiode. Then, Independent Component Analysis (ICA) [5,6] is used in this study to separate original sounds and noises from two electrical signals in order to improve the SN ratio. Also, the ICA output signal is compared with the signal obtained by the difference detection of two signals [7] to evaluate its performance. The theory of the optical wave microphone is described in Chapter 2, and an experimental result and consideration to an obtained result is described in Chapter 3. The last chapter is a conclusion of this study.

2. Optical Wave Microphone.

2.1. Principle and theory. The fundamental principle and theory of the optical wave microphone have been already established [2], but an abstract is shortly introduced in this chapter to explain the background of research and to use the theoretical equation in the later discussion for experimental results.

Figure 1 shows abstract of the model for theoretical analysis. When an incidence probing laser beam crosses a sound wave, diffraction light waves are generated and propagate with and in the penetrating beam through the Fourier optical system and reach the detection plane, which is set in the back focal plane of a receiving lens. The diffracted light is homodyne-likely detected there by using the penetrating laser light as a local oscillating power. In such a condition, the intensity of diffracted light of higher orders and multiple diffractions are much smaller than that of the first order diffraction light and can be neglected. In the practical machine, the electrical output from a photo detector includes both the DC component and the AC component relating to diffraction light Doppler-shifted by sounds. The DC component is removed in the electric circuit and only the 1st AC component is used. The spatial intensity of diffraction light signal for the theoretical model shown in Figure 1 is given by the following equation [3,4].

$$I_{ac} = I_0 \Delta\varphi_0 \exp\left(-u^2\right) \left[\exp\left\{-(u-\theta)^2\right\} - \exp\left\{-(u+\theta)^2\right\}\right] \cos\omega_a t \tag{1}$$

where $I_0 = \left(2P_0/\pi w_f^2\right) \exp\left[-2(y_f/w_f)^2\right]$ [W/m^2], $\Delta\varphi = k_i(\mu_0 - 1)\Delta Z \Delta p/\gamma p$, μ_0: refractive index of air, γ: specific heat ratio, ΔZ: width of sound, p: atmospheric pressure, Δp: sound pressure, k_i: wave number of laser light, ω_a: angular frequency of sound wave, P_0: laser power, $u = x_f/w_f$: the normalized x-coordinate in the back focal plane, $\theta = k_a w_0/2$: the normalized wave number, k_a: wave number of sound wave, w_0: radius of laser beam waist in sound incident region, w_f, x_f, y_f: radius of the beam cross section, x-coordinate and y-coordinate in the observing plane, respectively.

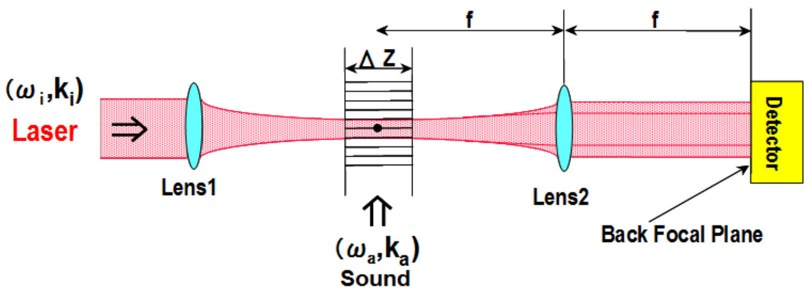
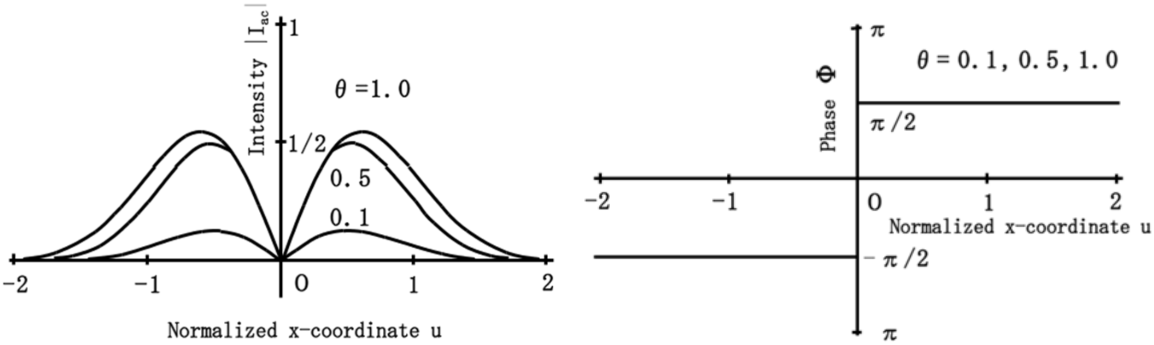


FIGURE 1. Optical setup for theoretical analysis

Based on the equation, numerical calculations of the diffraction pattern are carried out, in which a visible laser was assumed as a probing laser beam. Figure 2 shows examples of spatial distributions of the intensity and the phase of the diffraction light pattern. The spatial profile of diffracted light pattern (I) oscillating at the sound frequency has two peaks, where spatial positions do not change with frequency in the audio-wave or the low frequency ultrasonic band. On the other hand, the temporal phase difference (Φ) between the right and left diffraction patterns oscillating at ω_a is π, as shown in Figure 2 (right).

2.2. Experimental setup. A laser diode (685nm, 28mW) is used as the light source. The laser beam diameter at the sound detection region is 4mm and the spot size (diameter) at the observing plane is 2.4mm. A sound wave (5kHz) vertically enters to the laser beam. The sound pressure is set to 100dB on the center axis of the laser beam. Diffraction signal light produced by the sound wave propagates through the optical receiving system and then is detected by a photo-detector together with penetrating laser light, which is



(a) Spatial intensity profile (b) Spatial phase profile

FIGURE 2. Theoretical profiles of diffracted light distribution

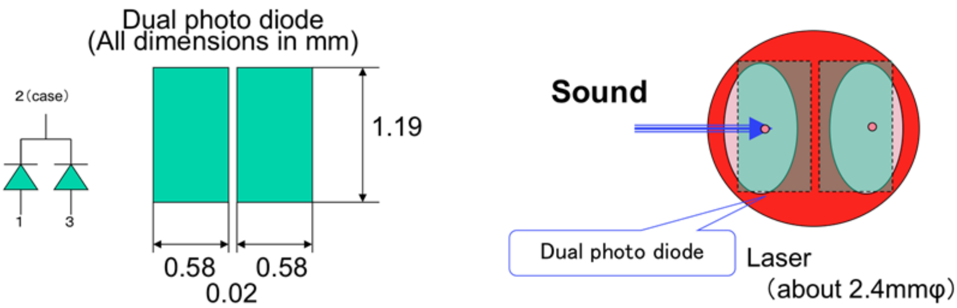


FIGURE 3. Shape of detecting plane of dual photo diode

used as a local power of heterodyne detection. In this experiment, the photo-detector is the divided dual photo diode with two elements, as shown in Figure 3. The distance between both elements is 0.02mm. Cathode edges of both elements are electrically connected (short-circuited), as shown in the circuit figure. Two signals in reversed-phase can be obtained when each element receives the both side diffraction lights separately, and then output of the dual detector is input to a differential amplifier.

3. **Experimental Result and Discussion.** Fast ICA [6] is adopted for signal processing. Under the condition that multiple signal sources are each statistically independent, ICA is recommended as one of the Blind Source Separation; a statistical method that estimates a signal source only by using data observed with a sensor while its signal transmission characteristic to a sensor is unknown. Figure 4 shows the image of blind source

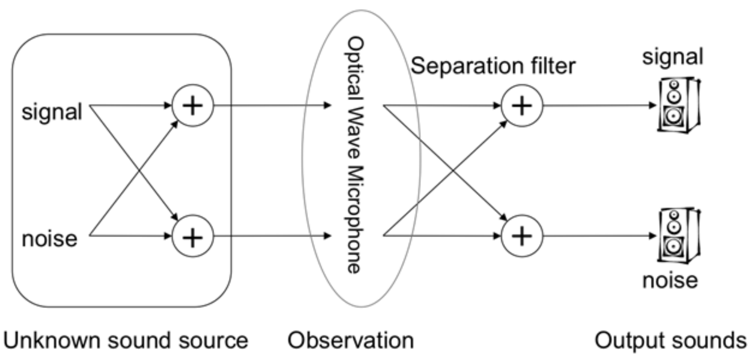
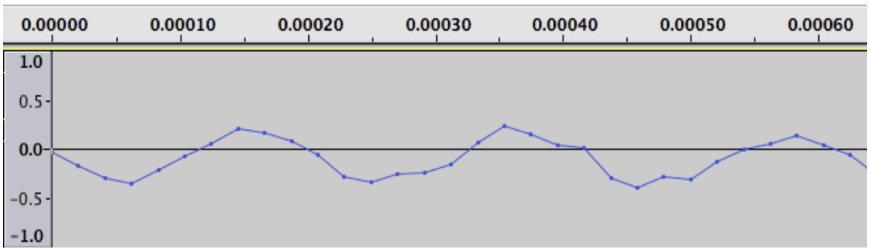


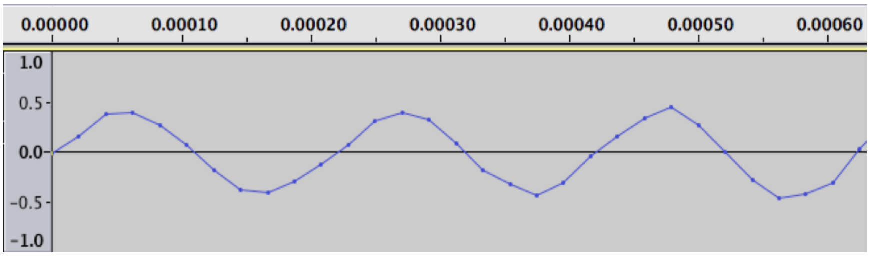
FIGURE 4. Blind source separation using an optical wave microphone

separation using an optical wave microphone. As mentioned in the prior section, an optical wave microphone can measure two diffracted lights; two sounds, with one laser. Signal and noise components are separated using this characteristic.

Figure 5 shows part of two signals observed with an optical wave microphone when single sound is input at 100dB of sound pressure and at 5kHz of frequency. Reversed phase is shown as mentioned in the prior section. Since the device used in this study had difficulty in adjusting beam diameter and the dual photodiode used was multi-purpose, positions of the diffracted light and the diode do not match. Although the amplitudes of the two signals were tried to be adjusted, there was a limitation in mm-scale adjustment.

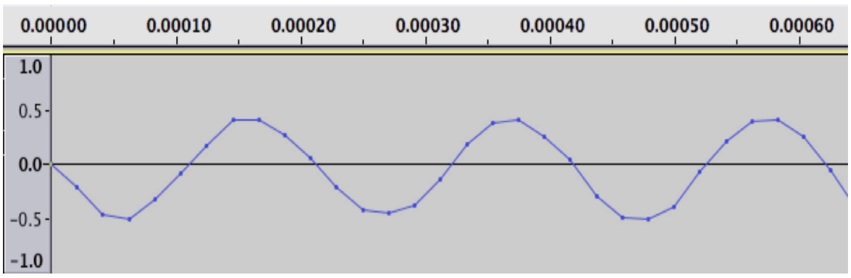


(a)

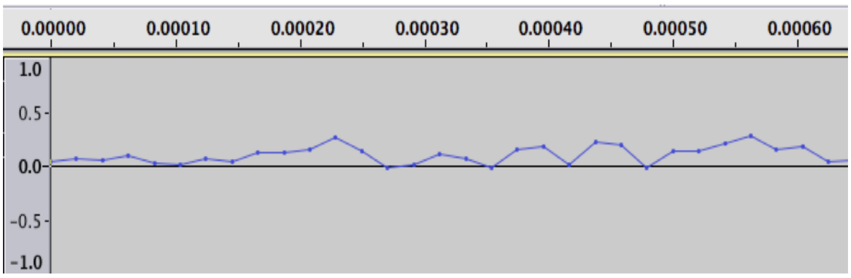


(b)

FIGURE 5. Two signals observed with optical wave microphone (with input signal at 100dB, 5kHz)



(a)



(b)

FIGURE 6. Signal separated using ICA (with input signal at 100dB, 5kHz)

Figure 6 shows the result of ICA using a signal measured with an optical wave microphone as an input signal. Sine wave shown in Figure 6(a) is much clearer than that in Figure 5, and a lot of noise components can be expected according to Figure 6(b). Figure 7 shows a differential detection wave of a signal measured with optical wave microphone. In this microphone, a signal in reversed phase is observed on a measurement plane while a noise applied in a position near the measurement plane is expected to be the component in the same phase. By reversing one of the signals and combining both signals offset the noise component in the same phase, and it could lead to SN ratio improvement. As same as Figure 6(a), sine wave which is clearer than input signal is shown in Figure 7.

Figure 8 shows the result of spectrum analysis on the signals measured with optical wave microphone (Ch1, Ch2), original signal component separated by ICA, and differential detection signal. 200Hz high-pass filter is used against the noise generated in the low frequency area due to the characteristic of optical wave microphone and problems unique to the measurement device. Therefore, all signals show local peak at around 200Hz. In all areas at 200Hz or higher, SN ratio is improved by about 10dB in both ICA and differential detection methods. Furthermore, ICA succeeds in removing noise about 5dB larger than differential detection near 300Hz-1kHz, suggesting that ICA is more effective than differential detection for SN ratio improvement. In the next stage, we try to remove noise, especially in low-frequency area, to improve the total SN ratio.

Along with this, we will try to develop another measurement device using an optical fiber sensor as shown in Figure 9 [8]. In this measurement system, the length of a fiber sensor part is very short within 50mm and the reference local power is not needed. It has a high degree of flexibility in installation as a stable detection technique measuring sounds from a human body.

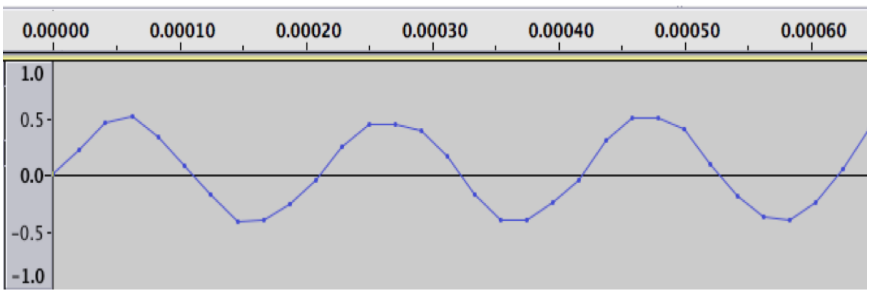


Figure 7. Differential detection signal (with input signal at 100dB, 5KHz)

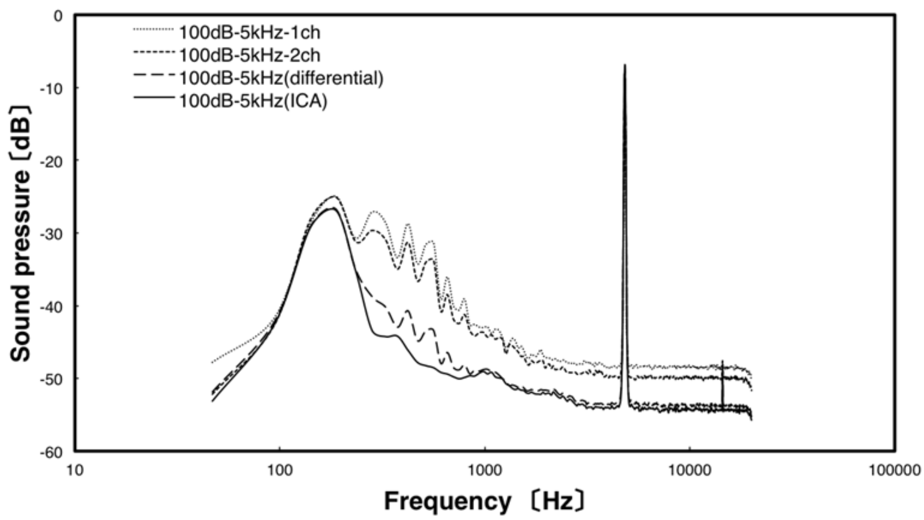


Figure 8. Result of spectrum analysis (with input signal at 100dB, 5KHz)

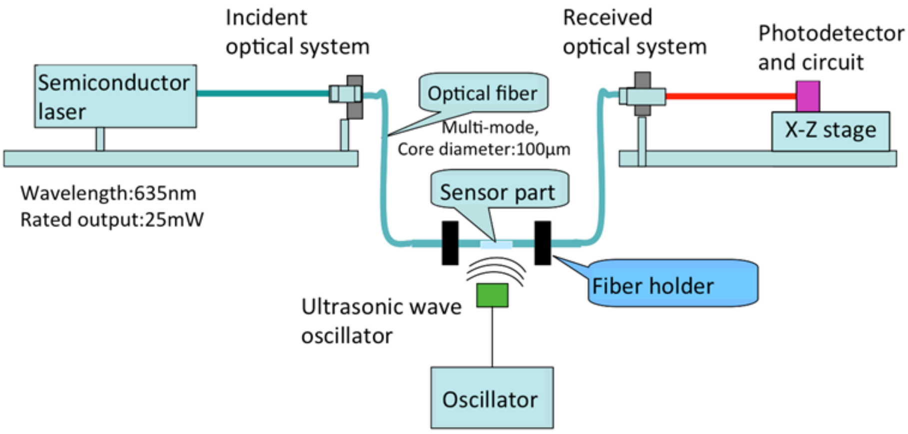


Figure 9. Optical wave microphone with optical fiber sensor

4. **Conclusions.** In this study, the ICA is applied to the signal processing of the optical wave microphone to improve the SN ratio. The SN ratio is improved by about 10dB in the audio frequency areas, and by 15dB near 300Hz-1kHz, and also the reasonable and good result is obtained for the differential detection method. In the present experiment, the laser beam diameter at the detection plane was not matching with the size of the dual photodiode. The better result will be obtained by matching these.

Acknowledgment. The authors acknowledge the supports of the Grant-in-Aid for Scientific Research (C) (No. 22560429) from Japan Society for the Promotion of Science.

REFERENCES

[1] H. Miwa, Heart rate and respiratory rate measurement using body-sound, *Journal of Robotics and Mechatronics*, vol.23, no.3, 2011.
[2] Y. Sonoda and M. Akazaki, Measurement of low-frequency ultrasonic waves by Fraunhofer diffraction, *Jpn. J. Appl. Phys.*, vol.33, no.5B, pp.3110-3114, 1994.
[3] Y. Sonoda, Direct detection of acoustic waves by laser light diffraction and proposals of the optophone, *Proc. of the 16th Int. Cong. on Acoust. and the 135th Meet. of Acoust. Soc. America*, vol.1, pp.427-428, 1996.
[4] J. W. Goodman, *Introduction to Fourier Optics*, 3rd Edition, Roberts & Company Publishers, 2005.
[5] P. Comon, Independent component analysis, a new concept? *Signal Processing*, vol.36, no.3, pp.287-314, 1994.
[6] A. Hyvarinen and E. Oja, A fast fixed-point algorithm for independent component analysis, *Neural Computation*, vol.9, no.7, pp.1483-1492, 2006.
[7] T. Samatsu, M. Iwahara and Y. Sonoda, Optical information processing system in optical wave microphone for improvement of SNR, *ICIC Express Letters*, vol.4, no.6(B), pp.2323-2328, 2010.
[8] T. Samatsu and Y. Sonoda, Development of optical wave microphone with optical fiber sensor, *ICIC Express Letters*, vol.8, no.4, pp.1187-1192, 2014.