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Long-range measurement system using ultrasonic range sensor with high-power transmitter array in air

Sahdev Kumar *, Hideo Furuhashi

Department of Electrical and Electronics Engineering, Aichi Institute of Technology, 1247 Yachigusa, Yakusa-Cho, Toyota 470-0392, Japan

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ABSTRACT

A long-range measurement system comprising an ultrasonic range sensor with a high-power ultrasonic transmitter array in air was investigated. The system is simple in construction and can be used under adverse conditions such as fog, rain, darkness, and smoke. However, due to ultrasonic waves are well absorbed by air molecules, the measurable range is limited to a few meters. Therefore, we developed a high-power ultrasonic transmitter array consisting of 144 transmitting elements. All elements are arranged in the form of a 12 × 12 array pattern. The sound pressure level at 5 m from the transmitter array was >30 dB higher than that of a single element. A measuring range of over 25 m was achieved using this transmitter array in conjunction with a receiver array having 32 receiving elements. The characteristics of the transmitter array and range sensor system are discussed by comparing simulation and experimental results.

1. Introduction

In the past few decades, ultrasonic sound has attracted considerable attention owing to its potential use in advanced technologies such as biomedical applications and various nondestructive inspection modalities. Ultrasonic wave applications in robotics, amusement, security, and industrial use have been highlighted for amazing benefits of this technology. In particular, ultrasonic transmitting arrays (UTA) are used for beam forming [1–5]. Generally, UTA are also used for directional scanning and obtaining range images. Moreover, ultrasonic range sensors without beam scanning have been investigated. They use only one transmitter element in combination with an ultrasonic receiver array (URA). The distance of objects is calculated using the time-of-flight (TOF) measurement method, and the direction is calculated by delay-and-sum (DAS) operation [6–8]. Such an ultrasonic range imaging system has several advantages over other conventional systems because of its simple construction and ability to maintain a high degree of privacy when monitoring human activities. However, the measurable range is limited to a few meters in air because of high absorption of ultrasonic waves in air. Therefore, here we have focused our attention on improving the measureable range through the development of the UTA.

Some attempts have been made to improve the measurable range using spread spectrum pulse compression techniques, and a range of over 6 m has been reported for a small plate [8]. An important work by Tanaka et al. has been carried out by developing a high-power transmitter via spark discharge [9]. We also proposed an ultrasonic range sensor using the UTA and theoretically investigated its characteristics via computer simulations [10,11]. We have designed and fabricated the UTA with its sound pressure level (SPL) shown as >30 dB higher than that of the SUT [12,13].

In this study, we further investigated the characteristics of the UTA and demonstrate its improved range imaging sensing abilities. The problems of using a transmitter array for an ultrasonic range sensor are clarified by analyzing both experimental and theoretical simulation results [12]. Our results pave the way for the use of our novel UTA structure for future ultrasonic range sensing system applications.

2. Transmitter and receiver arrays

Fig. 1 shows our UTA consisting of 144 elements with diameter 8.6 mm and the inter element spacing was 10 mm. Each element was operated at 40 kHz fundamental frequency. The devices T4010B4 transmitting elements with a directivity of 100° (−6 dB) were used. The modulation pulse width and pulse repetition period were controlled using a personal computer. The operating voltage of the transmitter elements was 30 V peak-to-peak. The transmitter array had a maximum sound pressure of 126 dB at 5 m with a

* Corresponding author.
E-mail addresses: kumarsahdev42@gmail.com (S. Kumar), furuhasi@aitech.ac.jp (H. Furuhashi).

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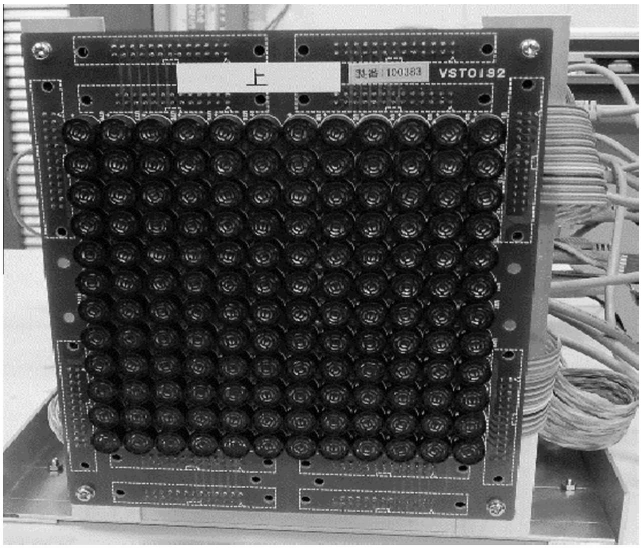

Fig. 1. Developed (12 × 12) ultrasonic transmitter array.

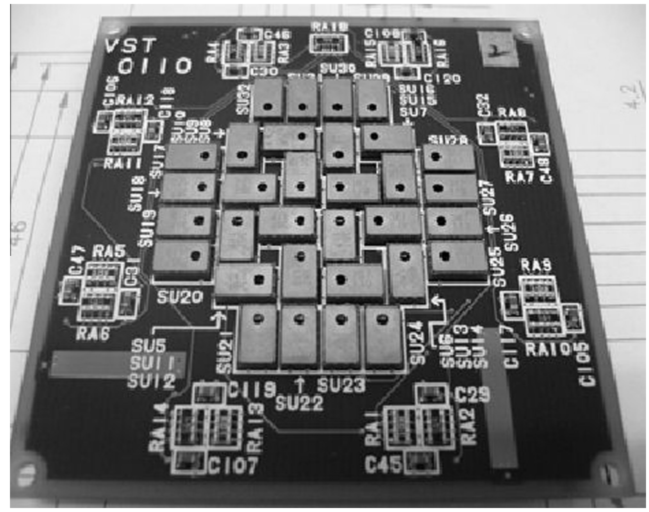

Fig. 3. Developed ultrasonic receiver array.

pulse width of 2 ms. Fig. 2 shows the schematic block diagram of the ultrasonic transmitting system used in this experiment. A 40 kHz signal was modulated to generate ultrasonic pulse of 2 ms using the field programmable gate array (FPGA). The pulse width and pulse repetition period are controlled by the personal computer. The generated signal is converted to analog signal by a D/A converter and amplified it before transmission. The D/A converted signals from each element are equally amplified to keep the same operating conditions for different modulated pulses. The device DAC (AD5415) is used as a converter that has 2 channels of 12 bits resolution each. The analog signals were amplified by operational amplifiers up to 30 V peak-to -peak.

Fig. 3 shows our developed receiver array for range sensing. It comprised 32 receivers (Knowledge Acoustics, SP0103NC3-3; 6.15 mm × 3.76 mm). Fig. 4 shows block diagram of the ultrasonic receiving system. The transmitted ultrasonic sound is received by the receivers after reflection from the object (a plastic board of width 30 cm × height 80 cm). Then received signal is converted to the digital by an A/D converter system using a device TSM-372012 (Interface Corporation). Signal conversion from analog to digital takes place after every 2.5 µs with a resolution of 12 bits. The DAS operations are performed on all direction to determine the 3D positions of target objects using Matlab and Simulink. The whole system (transmitting and receiving) is controlled by a personal computer. The system noise was reduced to its threshold level and range images were obtained by the TOF measurement method.

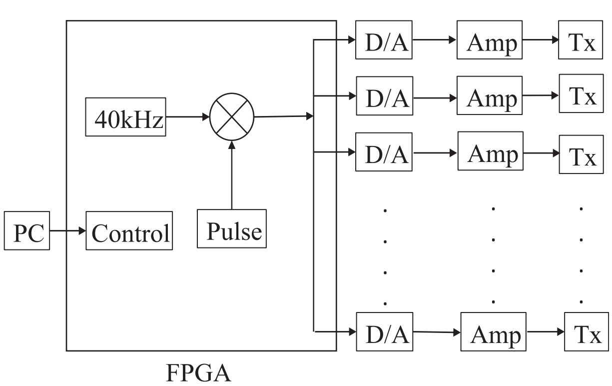

Fig. 2. Schematic diagram of the ultrasonic transmitting system.

3. Modulated pulse response

3.1. Theory

We theoretically analyzed via computer simulations that a transmitter array using n transmitter elements does not always generate n times higher sound pressure [10,11]. The sound pressure of transmitter array for far field was approximately calculated at any point at particular time t using the following Eq. (1)

$$P(x,y,z,t) = D(\theta)A_0\frac{e^{-2\pi i\frac{r}{\lambda}}}{r}\times\sum_{i=1}^{n}\exp\left(-2\pi i\frac{x_i\sin\theta_x+y_i\sin\theta_y}{\lambda}\right)\times\exp\left[-\left\{\frac{2\left(t-\frac{r}{c}+\frac{x_i\sin\theta_x+y_i\sin\theta_y}{c}\right)}{\tau}\right\}^2\right] \quad (1)$$

Here, r is the distance between the center of the array O (0, 0, 0) and observation point Q (x, y, z). θ_x and θ_y are the angles of vector OQ along the yz and xz planes. Wave velocity, wavelength and pulse width are denoted by c, λ and τ, respectively. The positions of the transmitting elements are P_i (x_i, y_i, 0), and n is the number of elements. D(θ) denotes the directivity and A_0 is the output sound pressure of one element.

Although Eq. (1) indicates that the sound pressure in the $\theta_x = \theta$ and $\theta_y = 0°$ directions (where 0° is directly in front of the transmitter) is n times higher than that of a single transmitter, but it is low in the near field of the transmitter array, as calculated theoretically via computer simulations [10]. Such effects appear mainly for short pulses. Here, we experimentally investigate the influence of short pulse modulation on transmitter arrays.

The sound pressure at point Q (x, y, z) at particular time t in near field is calculated using the following Eq. (2) [10]

$$P(x,y,z) = \sum_{i=1}^{n}D(\theta_i)A_0\frac{e^{-2\pi i\frac{r_i}{\lambda}}}{r_i}\times\exp\left\{-\left(\frac{2(t-r_i/c)}{\tau}\right)^2\right\} \quad (2)$$

Here, it is assumed that sound pressure is pulse modulated and all transmitting elements have the same sound pressure amplitude.