Ultrasonics 50 (2010) 340–346

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Short Communication

Design of an ultrasonic sensor for measuring distance and detecting obstacles

Jongkyu Park [a,*], Yub Je [b], Haksue Lee [b], Wonkyu Moon [b]

[a] Department of Mechanical Engineering, Changwon National University, 9 Sarim-dong Changwon, Gyeongnam 641-773, Republic of Korea
[b] Department of Mechanical Engineering, Pohang University of Science and Technology, San 31 Hyojadong Nam-ku, Pohang, Gyungbuk 790-784, Republic of Korea

ARTICLE INFO

Article history:
Received 6 May 2009
Received in revised form 6 September 2009
Accepted 17 October 2009
Available online 22 October 2009

Keywords:
Ultrasonic sensor
High directivity
Parametric array
Continuum model

ABSTRACT

This paper introduces a novel method for designing the transducer of a highly directional ultrasonic range sensor for detecting obstacles in mobile robot applications. The transducer consists of wave generation, amplification, and radiation sections, and a countermass. The operating principle of this design is based on the parametric array method where the frequency difference between two ultrasonic waves is used to generate a highly directional low-frequency wave with a small aperture. The aim of this study was to design an optimal transducer to generate the two simultaneous longitudinal modes efficiently. We first derived an appropriate mathematical model by combining the continuum model of a bar and countermass with the compatibility condition between a piezoelectric actuator and a linear horn. Then we determined the optimal length of the aluminum horn and the piezoelectric actuator using a finite element method. The proposed sensor exhibited a half-power bandwidth of less than ±1.3° at 44.8 kHz, a much higher directivity than existing conventional ultrasonic range sensors.

1. Introduction

As various kinds of robots have been developed to replace human works, sensing technology to give environmental information has also attracted a fair of amount of critical attention. Ultrasonic range sensors have been recently used for range detection and obstacle recognition in robots because of their low price, high efficiency, and relatively simple structure. While ultrasonic waves have better directivity than low-frequency waves in general, they are attenuated more rapidly [1,2]. This means that the directivity and working distance cannot be improved simultaneously if only one working frequency is used. Therefore, the directivity related to the spatial resolution as well as the working distance should be placed at their analytic center. Polaroid-type sensors of Murata and SensComp are commercially available for robot, although most products use a single working frequency of 40 kHz and have a half-power beamwidth (HPBW) of 20° as shown in Fig. 1 [3–6]. This means that the beam is about 1 m wide at a distance of 5 m from the sound source. If one object is close to another inside the beam, both will be recognized as a single object. Therefore, the objective of this research was to develop an ultrasonic sensor with a high directivity of less than 5° while maintaining the same working distance as existing commercial products. Specifically, this paper focuses on the method for designing the driving and amplification portions of the transducer.

In this research, we used a modified version of Gallego-Juarez's stepped plate as a transmitter, and a microphone as a receiver [7–12]. The original stepped plate had components for wave generation, amplification, and radiation. Its main characteristic is that ultrasound of a single frequency can be amplified and produced efficiently from an energy perspective by adding steps of a half wavelength of sound in air to the large radiating plate. However, this required a modification to generate dual-frequency waves to use a parametric acoustic array. As dual-frequency waves (primary waves) with sufficiently high amplitude propagate, a difference frequency wave (secondary wave) is generated due to the nonlinear effect of the media in air [13–17]. While commercially developed parametric acoustic array systems such as Woody Norris' company, Joseph Pompei and Sennheiser have been focused on a loudspeaker to generate audible sounds, the main point of this study is that ultrasonic waves are used as a media detecting objects. Therefore the used primary radiating frequencies are 80 kHz and 120 kHz [18]. It is necessary to generate high-amplitude primary waves with two frequencies to achieve the design objective, and adjusting the two resonance frequencies requires a novel design method. The parametric acoustic array makes it possible to improve the directivity of the ultrasonic range sensor without reducing its working distance.

The first step was to develop and verify the method for obtaining an optimal design of the generation and amplification portions of the transducer to generate the two simultaneous longitudinal

* Corresponding author. Tel.: +82 55 213 3608; fax: +82 55 275 0101.
E-mail address: chong@changwon.ac.kr (J. Park).

0041-624X/$ - see front matter
doi:10.1016/j.ultras.2009.10.013

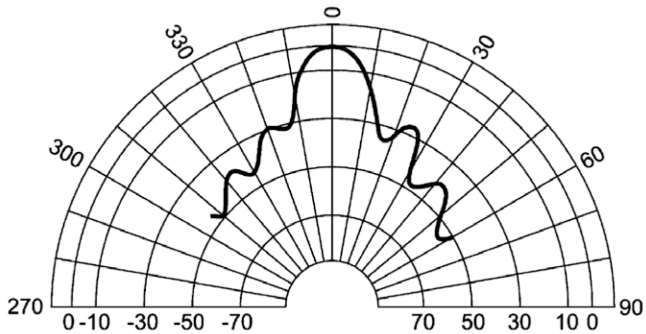

Fig. 1. Directional pattern of a commercially available Polaroid sensor [3]. The HPBW of the sensor is almost 20 degree.

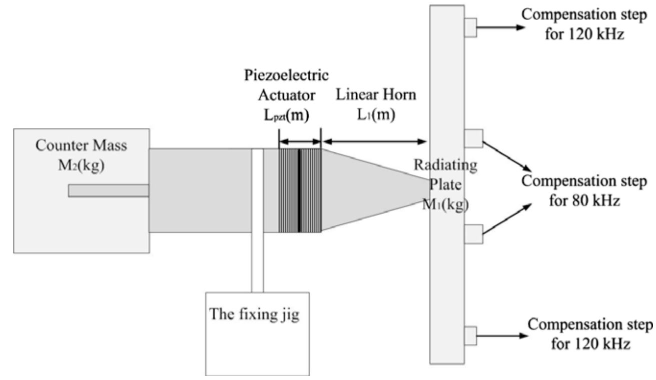

Fig. 2. Schematic diagram of the ultrasonic sensor. This sensor is composed of a radiating plate, a linear horn, piezoelectric ring actuators, and counter mass.

modes efficiently. We derived an approximate analytical continuum model using the Mathematica commercial software package. The graphical output of this model was used to analyze the effect of various design parameters and determine the boundaries of the system solution. Each design parameter was then determined by applying the compatibility condition between the aluminum bar and the piezoelectric actuator. Finite element analysis provided the final design solution. This model was verified through several experiments using a prototype of the ultrasonic sensor based on the design.

2. Design procedure

This research used Gallego-Juarez's stepped-plate transducer because of its low fabrication cost and its suitability for generating intense waves for use in parametric array. The plate makes it possible to radiate the acoustic wave in phase by placing steps with a half wavelength of sound in air at nodal lines of the plate [7–12]. The stepped-plate transducer was composed of three parts: the radiating section, the wave amplification section, and the wave generation section.

The generation and amplification sections had to be modified to generate dual-frequency waves because they were originally designed only for a single frequency. Because the plate design was based on the assumption of a free boundary condition, a countermass was attached to the end of the transducer to ensure that the two modes had the same node point.

Fig. 2 shows a schematic diagram of our stepped plate. Prestressed PZT ceramic rings with opposite polarizations were used as the transducer material. The vibration from the PZT rings was amplified by a linear horn and transferred to the radiating plate. The radiating plate with a stepped profile generated high-intensity ultrasound.

The design procedure can be summarized as the following procedure. First, a difference frequency of 40 kHz was selected; this is the same as the working frequency of conventional ultrasonic sensors. The optimal primary frequencies were selected to be 80 and 120 kHz for efficient generation of the difference frequency wave. The diameter of the driving parts was determined to be one quarter of the 80-kHz wavelength for longitudinal modes. Then, two piezoelectric disk actuators (C21; Fuji Ceramics Company) were used for wave generation [19]. This transducer used a linear horn as a wave amplification component because of its amplification ratio, ease of fabrication, and stability of stress concentration.

The radiating section (i.e. stepped plate) was modified to generate dual-frequency waves because the existing stepped plate proposed by Gallego-Juarez et al. is suitable for single-frequency wave generation. The step position and height are adjusted to compensate for the flexural vibration resulting at the two frequencies of 80 kHz and 120 kHz. The axisymmetric mode with three nodal circles (i.e., the third axisymmetric mode) was selected for generation of the 80-kHz wave and the axisymmetric mode with four nodal circles (i.e., fourth axisymmetric mode) was selected for generation of the 120-kHz wave. The stepped profile was designed using the following method. Let λ be the wavelength of the 120 kHz ultrasonic wave. Subsequently, the steps should have the height of $\lambda/2, 3\lambda/2, 5\lambda/2, \ldots$ to phase compensation of the 120 kHz vibration. For an 80 kHz ultrasonic wave, the wavelength is $3\lambda/2$. The step height required to compensate an 80 kHz wave is $3\lambda/4$. Therefore, after the compensation at 80 kHz is achieved by the steps of height $3\lambda/4$, the compensation at 120 kHz can be achieved by the steps of height $3\lambda/2$ with less influence to the 80 kHz radiation. Fig. 3 shows the plate with the resulting stepped profile for the generation of the dual-frequency waves.

3. Mathematical model and simulation

There are several restrictions when using two frequencies. First, there is a size constraint in that the transducer must be as short as possible to fit into the robot. The following algorithm was used to derive the optimal length for the operation of the

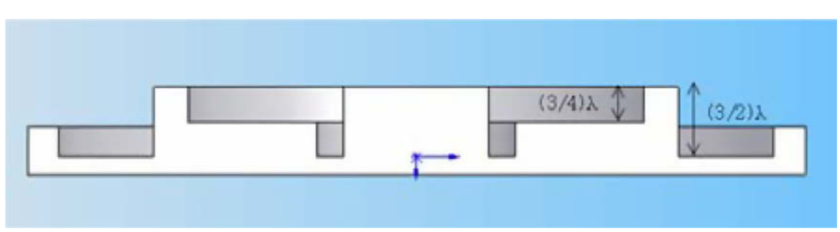

Fig. 3. The plate with the stepped profile for the generation of the dual frequency waves.