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A high-precision angular control system for HIFU calibration

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ABSTRACT

A design of high-precision angular position control system for calibrating high intensity focused ultrasound (HIFU) is presented with alignment procedures. Two independent angular controls are achieved by combining a worm gear and a belt gear system. The proposed system verifies alignment by comparing simulation data and experimental data with three different transducers and two different types of hydrophones. The performance of the proposed system is compared to that of a commercial system. The results indicate that the proposed system provides high precision angular alignment (e.g., <0.01 radians) with robust reproducibility regardless of the hydrophone type.

1. Introduction

Medical uses for ultrasound are no longer limited to simple diagnosis, image-guided surgery such as radio frequency (RF) ablation, or tumor biopsy. In many instances, ultrasound is used therapeutically by increasing the energy level. High intensity focused ultrasound (HIFU), which is also known as focused ultrasound surgery (FUS), is a prime example of high-energy therapeutic ultrasound [1,2]. HIFU systems produce a focused ultrasound field whose intensity can reach over 10,000 W/cm^2 in order to induce localized tissue damage in a short exposure time (i.e., within 100 ms). Tumors can be treated effectively without significant collateral damage to the intervening tissue by adopting a phased array transducer and electronic scanning [2–7].

For safe clinical use of a HIFU system, characteristics of the ultrasound field and the total acoustic power need to be measured accurately. Critical acoustic parameters such as peak compressional pressure, peak rarefactional pressure, 6 dB focal spot size of the transducers, and maximum scanning area are obtained from the ultrasound field measurement. The total acoustic energy applied to the body can be determined from the total acoustic power measurement. In diagnostic ultrasound imaging, standard equipment and procedures are well established for taking the measurements mentioned above [8–10]. Though the basic principles are the same, several factors prevent these methods from being used directly to calibrate HIFU systems [11].

First, ultrasound imaging generally has a pulse duration that is less than five cycles, whereas HIFU uses a long pulse duration that is more than tens of cycles. Therefore, reverberation can significantly affect the total acoustic power measurement. Additionally, a therapeutic transducer has narrow bandwidth allowing both ring up time and ring down time on the order of five to ten cycles. Hence, the reliable minimum pulse duration is generally no less than 20 cycles.

Second, cavitation can occur during measurement due to the high rarefactional pressure ultrasound field. If cavitation occurs, not only is the measurement erroneous, but also the measurement component, such as a hydrophone, may be damaged. Theoretically cavitation occurs approximately at the rarefactional pressure of 100 MPa in pure water, therefore water needs to be purified and degassed to a higher level to avoid cavitation [12].

Third, harmonic components are generated due to strong nonlinear effects. In measuring a nonlinear sound field, a broadband hydrophone is needed to cover all the higher frequency components and allow more precise angular alignment. Since HIFU systems typically use a frequency range of 0.30–3 MHz, the ideal hydrophone must cover the frequency range of 0.10–30 MHz, assuming that the tenth harmonic is the upper limit.

To measure total acoustic power via radiation force balance using a precision weight scale, the angled position of the reflector could be used to avoid reverberation. To avoid cavitation at high rarefactional pressure, deionized water can be used for the field

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measurement under pressurized conditions after the degassing process. An optical hydrophone could be a candidate broadband hydrophone since its sensitivity is virtually independent of frequency [13].

Considering the factors mentioned above that are critical to calibrating HIFU, we present a systematic solution for high-precision angular position control, which can be performed in a laboratory. The angular position control system is based on combined a worm gear and a belt gear. Standard procedures for the appropriate use of this proposed system, and an automated search algorithm for the focal point were developed. The overall system was tested with HIFU for reliable and efficient ultrasound field measurement.

2. Methods

2.1. Angular position control requirements

The accuracy requirement can be calculated using a simple hydrophone model. If we assume that the hydrophone is a line and the angle between the hydrophone and wave front is θ as shown in Fig. 1, the received signal $s(t)$ from the hydrophone is given by the following equation:

$$s(t) = \int_{-r_0}^{r_0} \cos\left(2\pi f_0 t + \frac{2\pi \sin\theta}{\lambda} x\right) dx = \frac{\lambda}{\pi \sin\theta} \cos(2\pi f_0 t) \sin\left(\frac{2\pi \sin\theta}{\lambda} r_0\right) \quad (1)$$

where f_0 is the HIFU frequency, λ is the wavelength, and r_0 is the radius of the active area in the hydrophone. Since HIFU uses a signal tens of cycles long, the single frequency sinusoidal pressure input is a valid assumption in Eq. (1). Considering that the maximum frequency is 30 MHz, as mentioned above, the wavelength will be approximately 50 μm. Additionally, the radius of a commercial hydrophone for medical systems is in the range of 50–1000 μm. Based on the given values, the expected measurement error is calculated and plotted in Fig. 2. As seen in Fig. 2, the angular alignment error should be less than 0.01 radians to achieve a measurement error of 5% with a 500 μm diameter hydrophone. For a measurement error less than 1% with the same hydrophone, the alignment error should be less than 0.005 radians.

The received signal $s(t)$ can be rewritten by Eq. (2) when using a two dimensional hydrophone model.

$$s(t) = \int_{-r_0}^{r_0} w(x) \cdot \cos\left(2\pi f_0 t + \frac{2\pi \sin\theta}{\lambda} x\right) dx \quad (2)$$

where $w(x)$ is a weighting factor according to the shape of the hydrophone. The factor $w(x)$ is $2\sqrt{r_0^2 - x^2}$ for a circular shaped hydrophone of radius r_0, and $\sqrt{\pi} r_0$ for a square hydrophone with

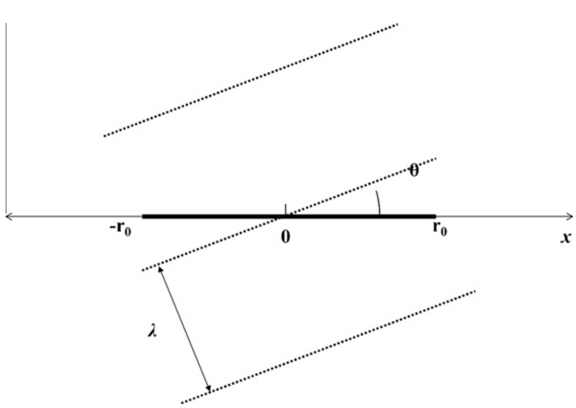

Fig. 1. A simplified hydrophone model.

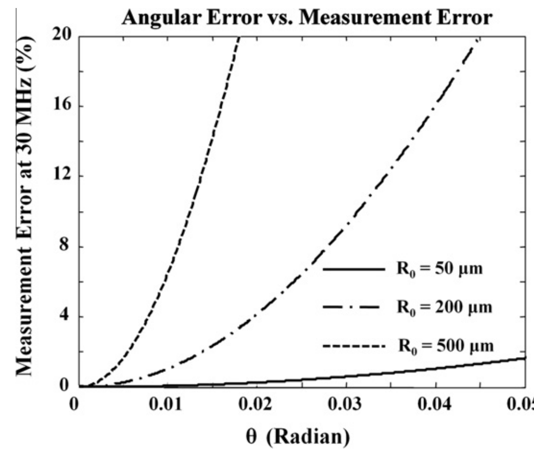

Fig. 2. Hydrophone measurement errors at f = 30 MHz vs. angular alignment errors.

length $\sqrt{\pi} r_0$ given one of the axis of the square hydrophone is parallel to the wavefront. Hence, the angular dependency can be stronger for a rectangular hydrophone than a circular hydrophone. In other words, the sensitivity of a square hydrophone can be affected more by the angular error due to the phase cancelation compared to a circular hydrophone. The signal from the simplified model is identical to the rectangular hydrophone model, except for a constant weighting factor. Therefore, the requirements for the line hydrophone model can be safely applied to general hydrophones.

Additionally, the angular position system has to be versatile enough to accommodate different hydrophones. A membrane hydrophone is relatively transparent to a sound field during measurement, so it can make more accurate measurements and is approximately 10–15 cm in diameter including the supporting structure [14–17]. On the other hand, a needle hydrophone is small at the tip, generally has a better directional response, and has a metal shaft length ranging from 3 to 7 cm [18–20]. A broadband optical hydrophone is also small at the tip, but requires a supporting structure, so the overall dimensions are similar to the needle hydrophone [21–24]. Therefore, the angular position system needs to incorporate different mounting options for various hydrophones.

2.2. Angular position system design and implementation

The field measurement is usually conducted with a 3D motion control system after alignment, as seen in Fig. 3. A manual translation stage (S-120LRC, DPI, Korea) is used for the hydrophone side

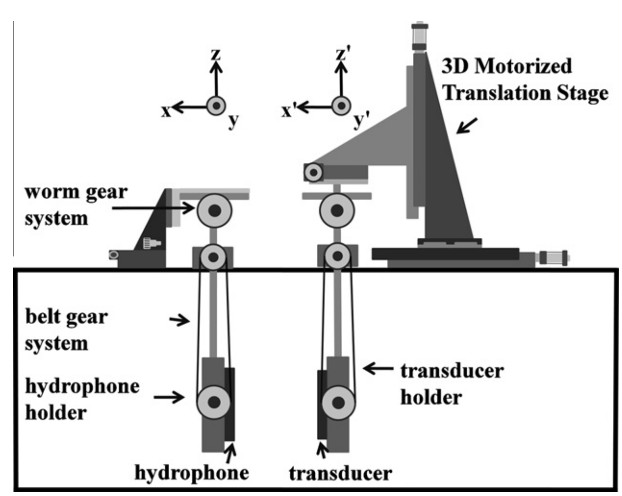

Fig. 3. Schematic of the overall system.