A PRIMARY LEVEL ULTRASONIC POWER MEASUREMENT SYSTEM DEVELOPED AT NATIONAL INSTITUTE OF METROLOGY, THAILAND

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ABSTRACT

The total output power from a medical ultrasound transducer has to be measured due to various reasons but in general they are related to assessment of performance and safety of equipment. The objective of this work was to develop a primary level ultrasonic power measurement system to establish standards for ultrasonic power measurement in Thailand. This system is being set up at the National Institute of Metrology, Thailand (NIMT) and it will be capable of determining the ultrasonic output power in the frequency range from 1 MHz to 20 MHz, and in the power range from 1 mW to 20 W. The implementation of the system utilizes a radiation force balance technique based on the method recommended in IEC 61161. Three ultrasound transducers with three different resonance frequencies, 1 MHz, 5 MHz and 10 MHz were used as an ultrasound source to test the performance of the developed system. The results of the measurements from the developed primary system are presented in comparison with those measured from the commercial ultrasound power meter (UPM). It is shown that the measurements yielded results that were consistent and the developed system is currently able to determine the ultrasonic output power in the frequency range from 1 MHz to 10 MHz, and in the power range from 1 mW to 500 mW. Current efforts are being made to focus on evaluating the measurement uncertainty for each component of the system, testing the frequency measurement range of the system up to 20 MHz and extending the power measurement region of the system to 20 W.

1. INTRODUCTION

Medical diagnostic ultrasound has become the primary noninvasive imaging modality because it does not employ ionizing radiation such as X-rays and also provides real-time information of the anatomical structures. In addition to diagnostic applications, the applications of ultrasound energy for therapeutic treatment purpose such as High Intensity Focused Ultrasound (HIFU) have also grown significantly in the past few years [1-6]. However, ultrasound exposure in general may introduce undesirable biological effects such as thermal or mechanical effects when the exposure takes place at levels which can be harmful to tissue [7, 8]. Therefore, the ultrasonic power produced at the output of medical ultrasound devices must be determined and strictly regulated. In addition, there are still other reasons for making ultrasonic power measurements, for examples, to ensure the most effective exposure levels used during patient treatment, to allow consistent application and intercomparison of treatment regimes and to ascertain whether the device is performing satisfactory [8]. Various procedures are available for determining the ultrasonic output power such as the radiation force balance technique [9-11], the use of piezoelectric hydrophones [12], acousto-optic [13], thermoacoustic [14] and ultrasonic power through electroacoustic efficiency of transducers [15]. However, the radiation force balance technique has been selected to use in this work because this technique can be carried out easily and the measurement ranges can cover all commercial ultrasound equipment in both therapeutic and diagnostic applications.

Radiation force balance is a measurement technique to determine the total output power of an ultrasound transducer using the time-average force exerted by an acoustic field on an object (target). The radiant power is directly proportional to the total radiation force (weight) on the target. The measurement principle is as follows: the ultrasound beam to be measured is directed on to a target and the radiation force that the field exerted on the target is measured by determining the difference of the force on the target with and without ultrasound. In practice, the ultrasound source is alternately switched on and off. The choice of the time intervals (typically of the order of 15 s to 35 s) and of the number of switch-on-switch-off cycles (typically between one and eight) depends on the specific measurement situation [10]. The measured radiation force could then be converted to the ultrasound power values with the help of the theory in [16-20].

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In view of the above, it is clear that there is a well defined need for a measurement of the total output power from an ultrasound transducer. However, there is currently no primary level ultrasonic power measurement system to use as a standard in Thailand. Consequently, this paper describes a development of a primary level ultrasonic power measurement system using a radiation force balance technique based on the method recommended in IEC 61161 [21] to establish standards for ultrasonic power in Thailand. This system will be capable of determining the ultrasound output power in the frequency range from 1 MHz to 20 MHz, and in the power range from 1 mW to 20 W. The implementation of the developed system is described below along with the results of the preliminary testing.

2. STATEMENT OF THE CONTRIBUTION/METHODS

In order to verify the performance of our developed primary system, the output powers were measured from the same ultrasound source with two different systems. The first system is our developed primary measurement system described in details in Section A, whereas, the other system is the Ultrasound Power Meter (UPM), Model UPM-DT-1 (Ohmic Instruments, Maryland, USA) presented in Section B.

2.1 Developed primary system

The measurements of the total ultrasonic output power were performed by our developed primary system using a set-up as shown in Figure 1 and the photograph of this system are also presented in Figure 2. The system consists of the following parts:

(1) Water bath: A custom-made water bath was built from acrylic resin. Its diameter and height are 150 mm and 160 mm, respectively. The ultrasound transducer under test was placed and sealed in the base of the water bath, which was filled with degassed water to diminish cavitation probability.

(2) Ultrasound transducer: Three unfocused ultrasound transducers from Olympus NDT Inc., Waltham, MA, USA with operating resonance frequencies of 1 MHz, 5 MHz and 10 MHz were used as an ultrasound source to test the performance of the developed system. The diameter of these transducers is 12.7 mm.

(3) Function/Arbitrary waveform generator: The radio frequency (RF) signal was generated in the frequency range from 1 MHz to 10 MHz by a function generator (Agilent 33250A) to be used as an input signal to the ultrasound transducer. In addition, this RF voltage had to be adjusted to ensure that the ultrasonic output power from the transducer could be set to be from 1 mW to 500 mW.

(4) Power amplifier: The RF signal generated from the function generator was magnified by a 50 dB power amplifier (Amplifier Research 75A250A)

(5) Digital osscilloscope: The output voltage from the power amplifier to the ultrasound transducer was monitored in real time using a digital oscilloscope from Tektronix model DPO7054.

(6) Electrobalance: The radiation force was measured by a precision electrobalance model CC50 (Sartorius, Germany), with 1 μg of readability and 51 g maximum load capacity. The weight measured from the electrobalance was then transferred to a computer via a serial port.

(7) Target: The target was made from Ham A acoustic absorber material (Precision Acoustics, Dorset, UK) in a circular shape with a diameter of 50 mm. Its thickness is 14 mm. The target was then suspended in the degassed water using a 0.2 mm nylon wire over the ultrasound transducer and was connected to the electrobalance. It is also good to note that the face of the transducer source should be parallel to the absorbing target.

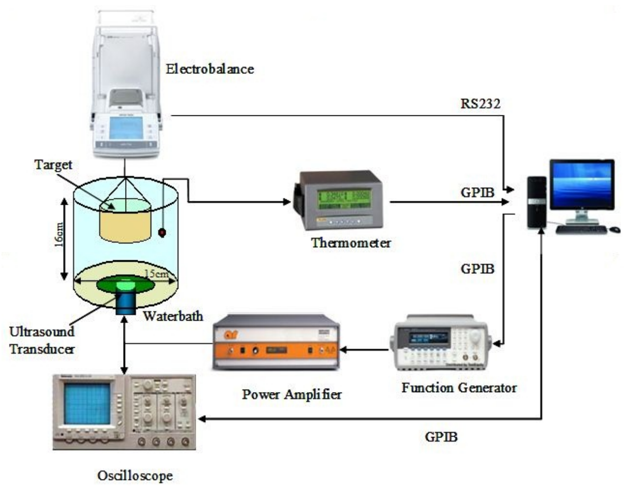

Fig.1: *Schematic diagram of the developed primary level ultrasonic power measurement system.*

(8) Temperature measurement system: The water temperature in the water bath was monitored in real time using a thermometer (Fluke, Chub-E4), and the measured data were then transmitted to the computer via a GPIB connection. Since the velocity of the ultrasound waves is a function of the water temperature, the measured water temperature is then utilized as an input to calculate the ultrasound velocity using the formula attributed to "Greenspan and Tschiegg [22]".

(9) Alignment system: The placement of the water bath was controlled by 3 axis stepper motors. The precision of the XYZ stepper motors of the alignment system is 0.025 mm per step, which allows the displacement from one position to another position of the transducer very accurately. In this work, the ultrasound transducer was positioned about 2 mm

away from the absorbing target in order to measure the ultrasonic power at the surface of the transducer source.

(10) Data acquisition and control system: The measurement sequence, such as changing the distance between the transducer source and the target, collecting temperature data from the thermometer, obtaining weight data of the target from the electrobalance and calculating the total output power from the transducer under test, was performed by a custom-made LabVIEW 8.5 virtual instrument (VI) program presented in Figure 3.

As already mentioned, our developed system was carried out using radiation force balance technique. When the absorbing target, which was connected to the analytical balance by the thin nylon wire, was irradiated by ultrasound waves from the ultrasound transducer, a radiation force generated at the target was measured by the electrobalance in mass units and could be converted to the ultrasonic power value in watt units using the help of the theory in [17-20]. For plane waves, the relationship between the measured radiation force (?mg) and the ultrasonic power (P) can be expressed by the following equation:

$$P = \frac{\Delta m \cdot g \cdot c(t)}{1 + R^2} \tag{1}$$

where P is the ultrasonic power, Δm is the deviated weight caused by the radiation force, g is the gravity (9.78297034 m/s^2), $c(t)$ is the velocity of ultrasound waves in water as a function of the water temperature (t) and R is the reflection coefficient of the target.

During this work, the reflection coefficient of the target (R) was assumed to be very small and could be negligible. The effect of the reflection coefficient of the target (R) will be accounted later when the measurement uncertainty is evaluated. Therefore, the equation 1 could be rewritten as equation 2.

$$P = \Delta m \cdot g \cdot c(t) \tag{2}$$

In order to obtain the deviated weight caused by the radiation force (?m) in equation 2, the ultrasound transducer was turned ON and OFF every 30 seconds for 7 cycles. Typically, the electrobalance would take a few seconds to stabilize after a sudden change in the radiation force caused by turning the ultrasound source ON and OFF. During this stabilization time, water continued to evaporate and so the weight of the target still decreased. Figure 4 shows the drift in the deviated weight measured from the electrobalance. This drift was occurred mainly through the gradual evaporation of water in the target. Therefore, accurate power measurement results could not be obtained by simply observing the weight change in the displayed values as these contained contributions from the radiation force and weight loss. Approximation and extrapolation methods must be used to compensate for the drifts by averaging the change in mass at turn ON and turn OFF. This would help to reduce an underestimation in the calculated output power. The deviated weight caused by the radiation force (?m) in equation 2 could then be calculated from the differences in the extrapolated values.

Fig.2: *Photograph of the primary level ultrasonic power measurement system developed at the National Institute of Metrology, Thailand (NIMT)*

2.2 Ultrasound Power Meter (UPM) System

The measurements of the total ultrasonic output power were also carried out via the Ultrasound Power Meter (UPM), Model UPM-DT-1 (Ohmic Instruments, Maryland, USA) with three unfocused ultrasound transducers from Olympus NDT Inc., Waltham, MA, USA at the operating resonance frequencies of 1 MHz, 5 MHz and 10 MHz.

The principle of this commercial ultrasound power meter (UPM) is also based on the radiation force balance method. The measurement was performed using a position clamp to hold the ultrasound source in degassed water above a conical reflecting target as shown in Figure 5. The ultrasound energy passes through the water to reflect off the target and then is absorbed by the rubber lining. The radiant power is directly proportional to the total downward force (weight) on the target. This weight is transferred through the target support assembly to the electromechanical load cell inside the scale and then converted to the power value (in watts) via a computer controlled feedback loop inside the system.

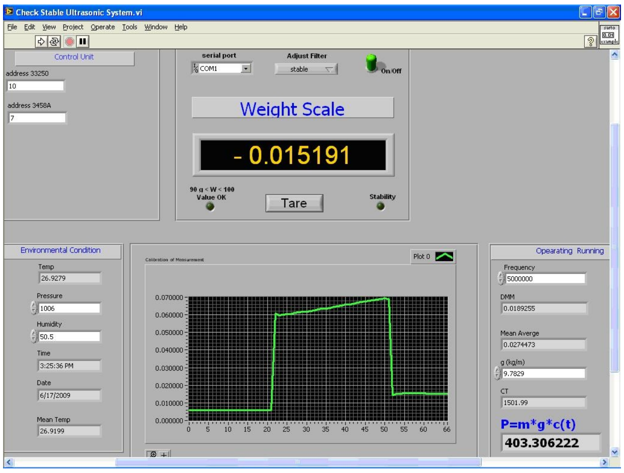

Fig.3: *Custom-made LabVIEW program used to determine the total output power from the ultrasound transducer*

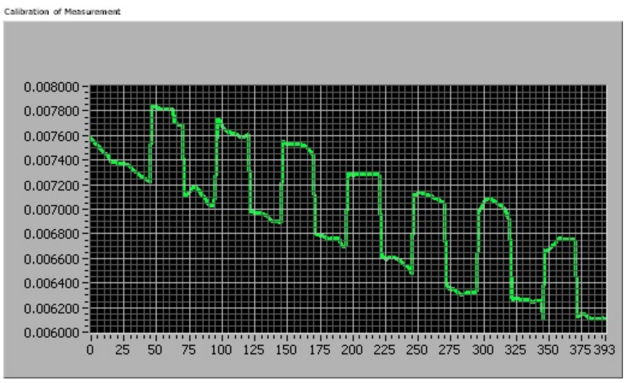

Fig.4: *Example of drift in the deviated weight measured from the electrobalance due to the buoyancy change of the target, and its compensation by the approximation and extrapolation methods.*

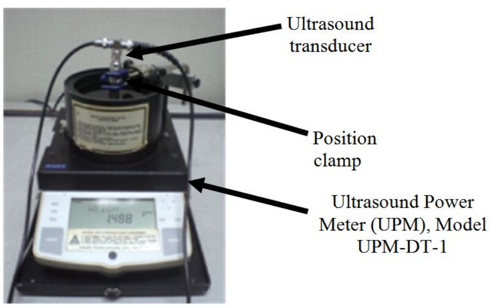

Fig.5: *The experimental set-up for the ultrasonic power measurement using the Ultrasound Power Meter (UPM), Model UPM-DT-1 (Ohmic Instruments, Maryland, USA).*

3. RESULTS

The ultrasonic output power measurements were carried out using a specific procedure based on the method recommended in IEC 61161 and the preliminary results measured from the primary system developed at National Institute of Metrology, Thailand (NIMT) for 11 nominal output power values (1mW, 10mW, 20mW, 40mW, 60mW, 80mW, 100mW, 200mW, 300mW, 400mW and 500mW) using three unfocused ultrasound transducers (Olympus NDT Inc., Waltham, MA, USA) with operating resonance frequencies of 1 MHz, 5 MHz and 10 MHz are shown on Tables 1, 2 and 3, respectively. Those results are presented together with the results measured from the commercial ultrasound power meter (UPM).

It is good to mention here that humidity, atmospheric pressure and ambient temperature were also monitored during each measurement.

Table 1: *PRELIMINARY RESULTS OF THE TOTAL OUTPUT POWER MEASURED FROM 1 MHZ ULTRASOUND TRANSDUCER*

Normainal Power (mW)	Average Radiation Power (mW) from 1 MHz Ultrasound Transducer	
	Developed Primary System	Ultrasound Power Meter (UPM)
1	1.06±0.24	-
10	10.13±0.54	10±0.82
20	19.62±0.40	19±1.63
40	40.13±0.92	41±1.03
60	60.75±0.50	59±1.03
80	76.27±0.84	77±1.63
100	98.90±0.77	98±0.82
200	192.21±2.42	193±2.42
300	298.72±1.73	295±2.34
400	377.82±4.88	380±2.19
500	483.83±8.31	487±5.16

Table 2: *PRELIMINARY RESULTS OF THE TOTAL OUTPUT POWER MEASURED FROM 10 MHZ ULTRASOUND TRANSDUCER*

Normainal Power (mW)	Average Radiation Power (mW) from 10 MHz Ultrasound Transducer	
	Developed Primary System	Ultrasound Power Meter (UPM)
1	1.06±0.19	-
10	12.45±1.22	11±1.10
20	22.72±0.75	24±2.19
40	41.15±0.82	43±1.63
60	64.38±1.03	65±1.03
80	85.38±2.5	86±2.94
100	108.35±2.42	111±3.01
200	216.07±5.24	219±5.47
300	320.32±2.00	325±9.07
400	399.68±2.43	405±8.55
500	506.07±3.71	510±12.69

4. DISCUSSIONS

To ensure compliance with the traceability requirements [21], the validity of our developed sys-

Table 3: *PRELIMINARY RESULTS OF THE TOTAL OUTPUT POWER MEASURED FROM 5 MHZ ULTRASOUND TRANSDUCER*

Normainal Power (mW)	Average Radiation Power (mW) from 5 MHz Ultrasound Transducer	
	Developed Primary System	Ultrasound Power Meter (UPM)
1	1.46±0.21	-
10	10.64±0.73	10±0.73
20	24.89±0.82	25±1.03
40	41.46±0.60	40±0.82
60	60.92±0.57	59±1.63
80	80.12±0.70	77±1.63
100	99.66±0.59	99±3.20
200	200.29±1.43	201±2.76

tem was also previously confirmed as presented in [5, 6] by comparing the measurement results of the total output power from our developed primary system at the National Institute of Metrology, Thailand (NIMT) with those measured from the commercial ultrasound power meter (UPM) and those provided by the National Physical Laboratory (NPL, UK) using the primary standard. However, the validation in [5, 6] was carried out using only a continuous-wave 3.5 MHz ultrasound check source (Precision Acoustics, Dorset, UK) as an ultrasound source to measure 3 nominal ultrasonic output power values (10mW, 100mW and 1000mW). Therefore, in order to improve the performance testing of the developed system this work shows the measurement results from our developed system in comparison with those from the commercial ultrasound power meter (UPM) using three ultrasound transducers at three different frequencies (1 MHz, 5 MHz and 10 MHz) for 11 nominal output power values (1mW, 10mW, 20mW, 40mW, 60mW, 80mW, 100mW, 200mW, 300mW, 400mW and 500mW) and it is shown that the power measurements from our developed system yielded results that were reproducible and consistent with those measured from the commercial ultrasound power meter (UPM). To investigate the reproducibility of the measurement system, the measurements were repeated for six times by resetting the transducer, the water bath and the target completely. Therefore, the results presented on Tables 1, 2 and 3 are the average data of six measurements for each nominal output power. In addition, these results will soon be compared with the results measured from the primary system developed at the National Metrology Institute of Japan (NMIJ) to enhance the verification of our developed system.

Note: The ultrasonic output powers from the 10 MHz transducer at the nominal output power of 300mW, 400mW and 500mW could not be presented on Table 3 since in order to generate those ultrasonic output powers it is required to use the excitation voltage to the 10 MHz transducer higher than the voltage limitation of the transducer that can withstand. Therefore, high power ultrasonic transducers are being prepared to replace these ultrasound sources.

5. CONCLUSION

In conclusion, the total output powers of the ultrasound transducers were successfully determined using our developed measurement system. It is expected that the primary level ultrasonic output power measurement service at the National Institute of Metrology, Thailand (NIMT) will soon be fully functional. The current system is able to determine the ultrasonic output power in the frequency range from 1 MHz to 10 MHz, and in the power range from 1 mW to 500 mW. However, our ultimate goal is to develop a system capable of measuring output power up to 20 W and in the frequency range up to 20 MHz since these measurement ranges will cover all commercial ultrasound equipment in both therapeutic and diagnostic applications.

Current efforts are being made to focus on evaluating the measurement uncertainty for each component of the system, testing the frequency measurement range of the system up to 20 MHz and extending the power measurement region of the system to 20 W.

6. ACKNOWEDGMENT

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