XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 - September 4, 2015, Prague, Czech Republic

DESIGN AND FABRICATION OF 1 MHz ULTRASONIC TRANSDUCER FOR TRANSFER STANDARD AT NIMT

Patchariya Petchpong[1], *Yong Tae Kim*[2]

[1] Acoustic and Vibration Metrology Department, National Institute of Metrology (Thailand), Bangkok, Thailand, patchariya@nimt.or.th

[2] Division of Convergence Technology, Korea Research Institute of Standards and Science, Daejeon, Korea, ytkim@kriss.re.kr

Abstract – The fabrication of a single element transducer made from Lithium Niobate ($LiNbO_3$) operating at 1 MHz to 10 MHz is focused on this paper. The air-backed immersion type $LiNbO_3$ transducer is developed to be used as the standard transfer ultrasonic transducer to calibrate the ultrasound power-meter, which is measured the total emitted acoustic power radiated from the medical equipment. To clarify the precision of the acoustic power, the primary standard calibration measurement (radiation force balance, RFB) based on IEC 61161 is used to investigate the fabricated transducer. The geometry of the piezoelectric active element was firstly designed by the prediction of the Krimholtz, Leedom, and Matthaei (KLM) simulation transducer technique. The electrical impedance measurements of the $LiNbO_3$ element, before and after assembling into the transducer, were checked and compared. The results of electrical impedance show that the operating frequency is in the range from 1 MHz to 10 MHz by forming harmonics. The evaluations of total emitted power and radiation conductance of fabricated transducer were also revealed. Results of acoustic power have been responding up to 2.1 watts, which can be assessed within 6% of measurement uncertainty.

Keywords: ultrasonic transducer, radiation force balance, acoustic power, lithium niobate piezoelectric

1. INTRODUCTION

Ultrasonic transducers for medical equipment have increasingly widespread clinical use in a variety of sizes and pattern forms for many applications in the diagnostic, the therapeutic and destructive purposes. Basic safety needs for ultrasonic physiotherapy and diagnostic devices are referred in IEC standards, as for example IEC 60601-2-5 [1], IEC 62359 [2] and IEC 61157 [3], which specify the requirement for acoustics power measurements with the uncertainties. Therefore, the fabricated transducer shall be investigated the acoustic characteristics. The total emitted power of ultrasonic transducer can be determined by use the standard method based on the measurement of the radiation force balance system as recommended in IEC 61161 [4]. The 1 MHz Lithium Niobate ($LiNbO_3$) ultrasonic transducer (S/N: KRISS-1MHz-5LN), which is designed and fabricated at KRISS (Korea Research Institute of Standards and Science), is used to generate the acoustic power and radiation conductance in the RFB calibration system as a reference standard. The frequencies would be various along the resonance frequencies of transducer in 1 MHz to 10 MHz range. In the following parts of this paper, the fabrication technique and the determination of acoustic impedance characteristics will be revealed. Also, the actual realization of the fabricated transducer by RFB method will be illustrated with the associated uncertainty evaluation. Moreover, this transfer standard transducer will be the artifact in the bilateral comparison between National Metrology Institutes (KRISS and National Institute of Metrology **(**Thailand), NIMT) to check the primary standard (RFB) method in the future.

2. EXPERIMENTAL METHOD

2.1. KLM Simulation

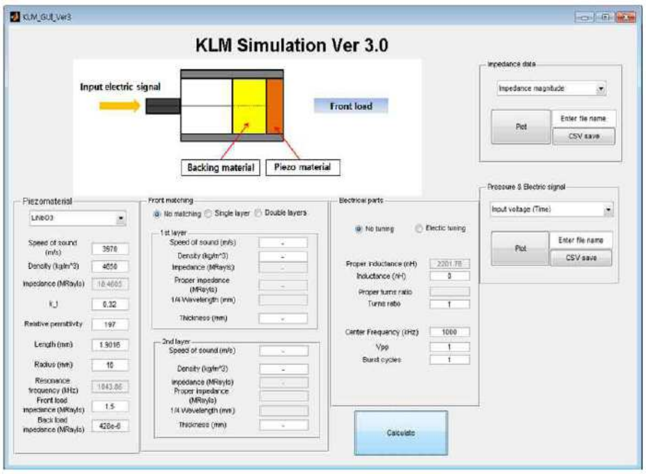


Fig. 1. Graphic user interface of KLM Simulation program.

In order to obtain the desired frequency electrical resonance and the optimize transducer design; the geometry of the piezoelectric active element was performed by the prediction of the Krimholtz, Leedom, and Matthaei (KLM) simulation technique as shown in Fig 1 [5]. The KLM is one of the most widely applied transducer equivalent circuit model to simulations and calculate the optimized values for the matching layers in the transducer design and the acoustic impedance. The significant advantage of the KLM model provides understanding the relationship between the structure of the electrical circuit and the behaviour of the transducer [6,7].

2.2. Fabrication

The air-backed $LiNbO_3$ transducer was designed for this research, usually generating a longitudinal wave. The $LiNbO_3$ single crystal of 20-mm diameter, (36^o rotated Y-cut at 1 MHz, overtone polish, coaxial type chrome-gold electrodes with 17-mm diameter of hot electrode, Boston Piezo-Optics Inc.) was performed as the active element, which transfer of energy between the mechanical and electrical ports for the element transducer. The transducer itself is constructed within a stainless steel casing with a diameter of approximately 30 mm and 60 mm length. A thickness of 1.9 mm of $LiNbO_3$ single circular plate was used to make the transducer at frequency 1 MHz. Its fabrication is presented in Fig 2. The BNC coaxial cable was provided with the top of the transducer for applying voltage.

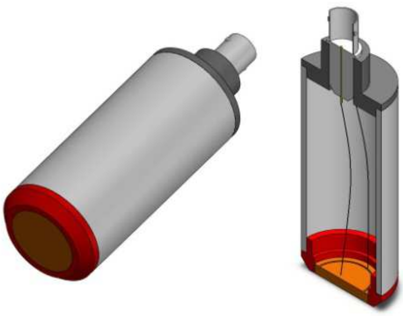


Fig. 2. Fabrication of 1 MHz $LiNbO_3$ Ultrasonic Transducer.

Then, the electrical impedance and conductance of the $LiNbO_3$ element, before and after assembling into the transducer, were investigated and compared using an impedance analyzer. The equipment set up for determining the impedance and conductance measurements of ultrasonic transducer is illustrated in Fig 3. The transducer was attached underneath the water vessel that contained the de-gassed water to match the acoustic impedance with practical condition. The ultrasonic absorber was also used in the propagation medium to avoid the reflections and acoustic standing waves. Then, the measured impedance probe of precision impedance analyzer (4294A, Agilent) was connected to the transducer.

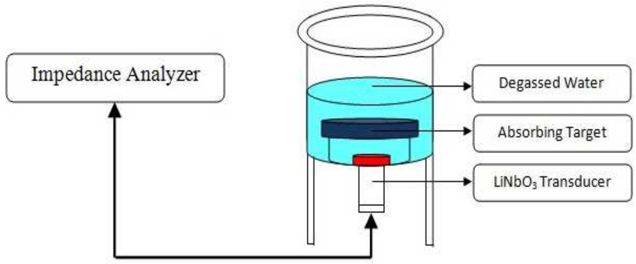


Fig. 3. Establishment of electric impedance measurement of fabricated ultrasonic transducer.

2.3. RFB Method

The Radiation Force Balance (RFB) technique is a well-established method to determine the time-average radiated acoustic power (*P*) from transducer sources as defined in IEC 61161. It is widely recognized and normally used at the national metrology institutes (NMIs) as the primary standard method to realize the ultrasonic power measurement. The absorption scheme is employed in this research to absorb the ultrasonic radiation. The RFB technique is performed under the vessel conditions (Langevin Condition) related to acoustic radiation force theory [4]. The basic calculated time-average output power (*P*) shall be evaluated as the following equation as referred in IEC 61161 (assumed on a plane wave and perfectly absorbing target):

$$P = c \times F \tag{1}$$

Where F is the radiation force acting on the target ($F = \Delta m \times g$); c is the speed of sound in water, Δm is the deviated weight in the measurement when switching on and off of applied voltages to the transducer and g is the gravitational acceleration.

In fact, the correction factor for non-plane wave (Cor_1) is included to determine the acoustic output power. Therefore, each calculated output power at a single distance shall be evaluated as the following equation:

$$P = c \times F \times Cor_1 \tag{2}$$

The correction factor (Cor_1) due to the effects of non-plane field structure (beam divergence) as mentioned in equation 2 is estimated as a function of *ka* in accordance with:

$$Cor_1 = 1 + \frac{0.6531}{ka} \bullet \left(1 + \frac{1.407}{(ka)^{2/3}}\right) \tag{3}$$

Where is the wavenumber and *a* represents the radius of active element of the ultrasonic transducer.

The radiation conductance (*G*) is given by the total time-average acoustic power (*P*) the ultrasonic transducer and the excitation voltage (*V*). The formula is:

$$G = P / V^2 \tag{4}$$

The measuring instruments of ultrasound transducer calibration in the RFB system are established as presented in Fig 4.

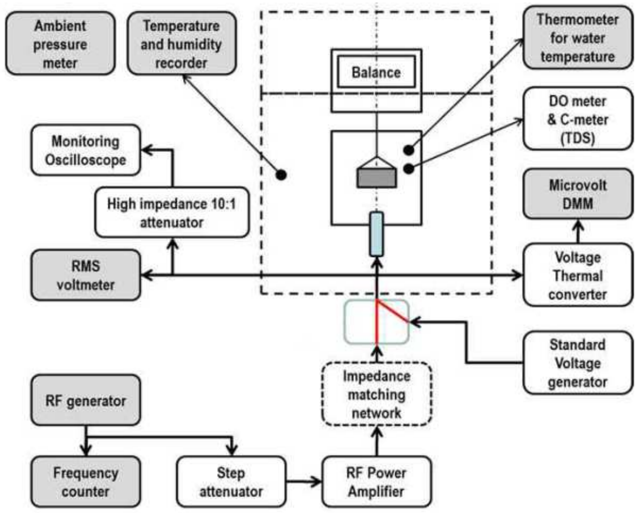


Fig. 4. Diagram of radiation force balance system for the ultrasound power and radiation conductance measurements.

The ultrasonic transducer would be attached and sealed on the center of the water tank. The degassed water shall be used to be the liquid medium in the water tank. It is necessary to be used only deionized and degassed water (dissolved oxygen contents < 4 mg/L, ionizing material contents < 1 mg/L) when determination of the output power above 1 W to avoid the cavitation. The water tank is placed to the middle basement, which can be adjusted the required positions between the transducer and the absorbing target. The water tank shall be covered on top to keep in closed environmental condition in order to avoid the thermal convection currents due to the cooling effects of the evaporation at the liquid surface. The absorbing target shall be suspended with an electronic micro-balance at the middle of the ultrasonic transducer. A temperature sensor should be put into the water tank to determine the temperature of the measuring medium (water) during the calibration process. This is to determine the sound speed in the water used to find the power result.

The RF generator shall be determined the appropriate generated electronic signal of radio frequency (input voltage) to obtain the desired frequency and power ranges of the transducer. The transducer input voltage is controlled using the program controller to the amplifier input voltage, which is monitored by the voltmeter (reading from the thermal voltage converter [8]). The generated waveform shall be amplified by the RF power amplifier to the transducer.

The ultrasonic power shall be investigated from the variation between the force evaluated with and without ultrasonic radiation. In order to estimate the radiation power, the program shall automatically control the turning on and off the RF generator. The turn-on and turn-off times were maintained in 20 s and 100 s, respectively during the three cycle measurements at each distance point. The variations of balance readings (Δm) due to the ultrasonic radiation were recorded. The target distances were varied at 6 different positions. Then, the linear regression was performed to approach the ultrasonic power result at the zero target distance (P_{out}), which is taken from the average results from six reproducibility measurements of various distances. This is to reduce the effects of standing wave. Finally, the calibration measurements of transducer at various frequencies were carried on to determine the radiation conductance (G) and acoustic power (P).

3. RESULTS

3.1. Impedance and Conductance Characteristics

The result of conductance (real value of admittance) measurements of bare Lithium Niobate piezoelectric as shown in Fig 5 was investigated by the impedance analyzer. It presents the fundamental and harmonic frequencies response of the piezoelectric plate before fabricating into the transducer housing. The peaks of conductance by forming harmonics confirm that the Lithium Niobate piezoelectric plate can be operating in the range 1 MHz to 10 MHz. Therefore, this piezoelectric ceramic plate could be selected to assemble on the single ultrasonic transducer for generating ultrasonic power.

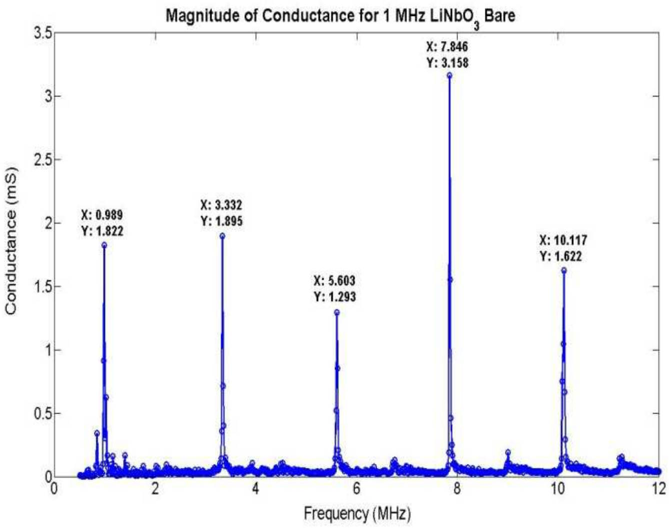
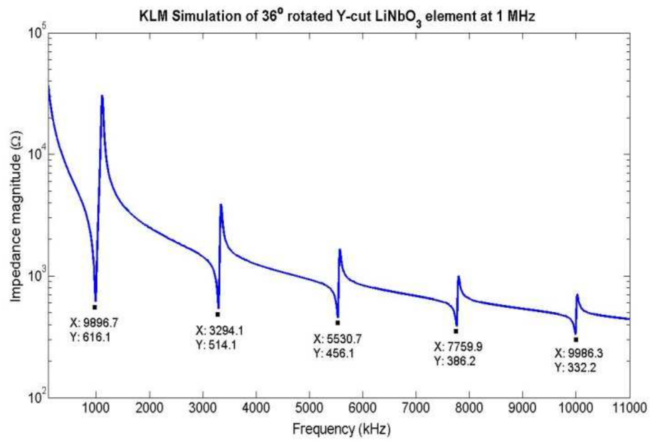


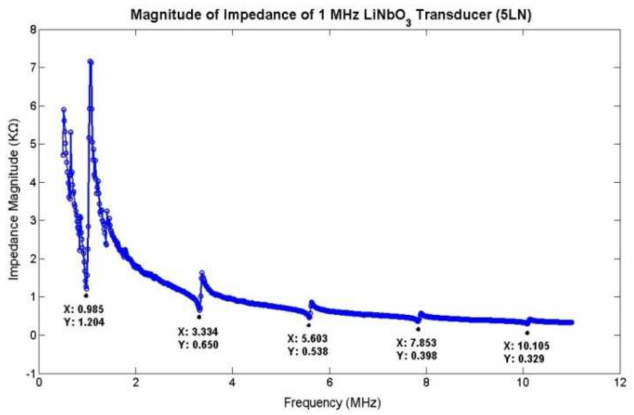
Fig. 5. Relationship between the conductance magnitude and the harmonic frequency of 1 MHz Lithium Niobate piezoelectric circular disk before assembling.

From KLM model prediction, the simulation results of acoustic impedance magnitude and conductance of 36^{o} rotated Y-cut 1 MHz $LiNbO_3$ element related to the various frequencies are displayed in Fig 6(a) and Fig 7(a), respectively.

The fundamental and forming harmonic frequencies of KLM model calculation responding to the impedance magnitude are 0.990, 3.294, 5.531, 7.760 and 9.986 MHz. These frequencies are agreed with the results obtained from the magnitude impedance measurements of fabricated ultrasonic transducer that show at 0.985, 3.334, 5.603, 7.853 and 10.105 MHz as seen in Fig 6(b).

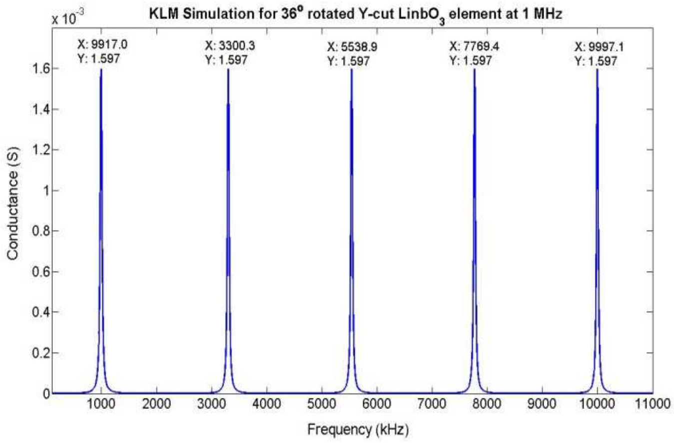


(a)

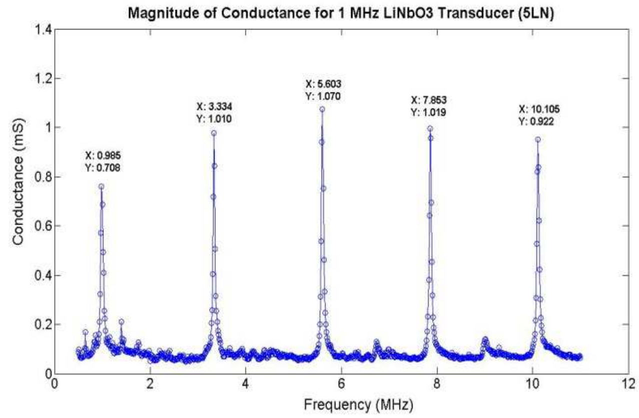


(b)

Fig. 6. Comparison of electrical impedance magnitude of fabricated 1 MHz $LiNbO_3$ ultrasonic transducer: (a) KLM simulation (b) measurement results.



(a)



(b)

Fig. 7. Comparison of radiation conductance magnitude of fabricated 1 MHz $LiNbO_3$ ultrasonic transducer: (a) KLM simulation (b) measurement results.

Figure 6(a) and 6(b) present the comparison of conductance magnitude between the KLM simulation and actual measurement of fabricated 1 MHz transducer. The comparison results indicate the similar frequencies of KLM calculation and measurement responding the conductance values. On KLM calculation graph, the simulated responses of harmonic frequencies for radiation conductance magnitude are at 0.992, 3.300, 5.539, 7.769 and 9.997 MHz, respectively. In addition to, the conductance results obtained from the measurements as presented in Fig 7(b) show the responsibility at 0.985, 3.334, 5.603, 7.853 and 10.105 MHz of forming harmonic frequencies. These frequencies are exactly the same values, which were investigated from the magnitude impedance measurements as shown in Fig 6(b).

In fact, the suitable fundamental and forming harmonic frequencies are investigated from the response amplitude of the relative maximum of radiation conductance at each resonance frequency. Hence, the appropriate operating frequencies to generate the acoustic radiation force of the fabricated 1 MHz $LiNbO_3$ ultrasonic transducer are 0.985, 3.334, 5.603, 7.853 and 10.105 MHz, respectively.

3.2. Evaluation of Acoustic Output Power and Acoustic Radiation Conductance

Table 1 represents the calculation results of evaluation time-average output power and acoustic conductance radiated from the fabricated 1 MHz $LiNbO_3$ transducer (S/N: KRISS-1MHz-5LN). There are various the input voltages (U_{in}) at each nominal frequency (f_N) to obtain the different values (low – high) of radiation output power (P_{out}). In the range of input voltages, four levels, which are 8, 12, 24 and 48 V, respectively had been monitored. These results illustrate that this transducer can be used at multi-frequencies response. The acoustic output power can be determined from 0.036 W upto 2.1 W. The measurement uncertainty is displayed within the coverage factor k = 2 for normal distribution correspond to a coverage probability of approximately 95%. All values are assessed within 6% of expanded uncertainty. This fabricated transducer is more convenient to use as the reference transducer in the range 1 to 10 MHz for radiation power calibration. Moreover, the fabricated transducer is expected to be used as the reference ultrasonic transducer at NIMT.

Table 1. Acoustic output power and radiation conductance of fabricated 1 MHz ultrasonic transducer.

f_N	F	U_{in}	P_{out}	G	U (k=2)
MHz	MHz	V	mW	mS	%
1.0	0.9850	8.0	36.7	0.57	6
		12.0	80.7	0.56	5
		24.1	311.0	0.54	5
		48.0	1306.0	0.57	5
3.3	3.3340	8.01	62.9	0.98	6
		12.0	127.0	0.63	5
		24.0	510.0	0.89	5
		48.0	2034.0	0.88	5
5.6	5.6038	8.0	93.2	1.45	5
		12.0	133.0	0.92	5
		24.0	533.0	0.93	5
		47.8	2114.0	0.93	5
7.9	7.8525	8.01	65.4	1.02	5
		12.1	126.0	0.86	5
		24.0	500.0	0.87	5
		48.0	2001.0	0.87	5
10.1	10.1050	8.0	54.6	0.85	5
		12.0	113.0	0.78	5
		24.0	454.0	0.79	5
		47.8	1811.0	0.79	5

4. CONCLUSIONS

From the magnitude impedance and radiation conductance characteristics obtained by the calculation, the results confirm that KLM model simulation can be used to predict and design the desired transducer perfectly. The air-backed single $LiNbO_3$ ultrasonic transducer was fabricated to be used in the multi-frequencies range. Results of acoustic power have been responding up to 2.1 watts at nominal frequency 5.6 MHz, which can be assessed within 6% of measurement. The 1 MHz $LiNbO_3$ ultrasonic transducer is designed to be used as the reference transducer at NIMT. It can be used in the multi-frequencies at the range 1 to 10 MHz for radiation power calibration. This research is served the NIMT service to extend its capability of the power measurement calibration in the future.

ACKNOWLEDGMENT

One of the authors (P Petchpong) gratefully acknowledges the Ultrasound Metrology section in Center for Medical Metrology of the Korea Research Institute of Standards and Science (KRISS) for providing the capability in education and skill of measurement techniques and for supplying the equipment. This work was financially supported by 2012 Korean NRF (National Research Foundation) Postdoctoral Fellowship Program for Foreign Researchers. The authors are grateful for the support.

REFERENCES

[1] IEC 60601-2-5, “Medical electrical equipment - Part 2-5: Particular requirements for the basic safety and essential performance of ultrasonic physiotherapy equipment”, by International Electrotechnical Commission (IEC), 3rd ed., 2009.

[2] IEC 62359, “Ultrasonics - Field characterization - Test methods for the determination of thermal and mechanical indices related to medical diagnostic ultrasonic fields”, by International Electrotechnical Commission (IEC), 2nd ed., 2010

[3] IEC 61157,”Standard means for the reporting of the acoustic output of medical diagnostic ultrasonic equipment”,by International Electrotechnical Commission (IEC),2nd ed., 2007

[4] IEC 61161, “Ultrasonics –Power measurement- Radiation force balances and performance requirements”, by International Electrotechnical Commission (IEC), 3rd ed., 2013.

[5] Y.T. Kim, H.K. Lee, J.W. Lee and W.S. Ohm, “SPL Prediction of Difference Frequency Sound from a Piezo-Electric Transducer by KLM Model Coupled Parametic Array Technique.”, Proceedings of Korean Acoustical Society 2012, Vol. 31, No” 1, pp. 276-280, 2012.

[6] R. Krimholtz, D.A. Leedom and G.L. Matthaei, “New Equipment Circuit for Elementary Piezoeletric Transducers”, Eletronics Letteres, Vol. 6, No. 13,1970,pp. 398-399.

[7] Deric P Jones, “Biomedical Sensors”, New York: Momentum Press, 2010, pp. 296.

[8] Patchariya Petchpong, Yong Tae Kim and Bongyoung Ahn, “Investigation of RF-Voltage Measurement by the Thermal Voltage Converter in Ultrasound Radiation Force Balance Calibration”, 44th Annual Congress of Korean Society of Ultrasound in Medicine, 24th - 25th May 2013, Seoul, Korea, pp. 308, 2013.