Ghasemi, Negareh, Walker, Geoffrey R., & Broadmeadow, Mark A. H.
(2015)
Real time maximum power conversion tracking and resonant frequency modification for high power piezoelectric ultrasound transducer. In
The 11th IEEE International Conference on Power Electronics and Drive Systems (PEDS 2015), 9-12 June 2015, Sydney, Australia.

IEEE PEDS 2015, Sydney, Australia
9 – 12 June 2015

Real Time Maximum Power Conversion Tracking and Resonant Frequency Modification for High Power Piezoelectric Ultrasound Transducer

Negareh Ghasemi, Geoffrey R. Walker and Mark A. H. Broadmeadow
School of Electrical Engineering and Computer Science
Queensland University of Technology
Brisbane, Australia
Email: n.ghasemi@qut.edu.au

Abstract- **piezoelectric ultrasound transducers are commonly used to convert mechanical energy to electrical energy and vice versa. The transducer performance is highly affected by the frequency at which it is excited. If excitation frequency and main resonant frequency match, transducers can deliver maximum power. However, the problem is that main resonant frequency changes in real time operation resulting in low power conversion. To achieve the maximum possible power conversion, the transducer should be excited at its resonant frequency estimated in real time. This paper proposes a method to first estimate the resonant frequency of the transducer and then tunes the excitation frequency accordingly in real time. The measurement showed a significant difference between the offline and real time resonant frequencies. Also, it was shown that the maximum power was achieved at the resonant frequency estimated in real time compare to the one measured offline.**

I. INTRODUCTION

High power piezoelectric transducers have gained significant importance in different applications (including biomedical and industrial applications) due to their ability of converting mechanical strains into useful electrical power and vice versa [1-3]. To achieve the desired energy conversion performance of the transducer, it is highly important to excite it at its main resonant frequency. The main resonant frequency is usually determined as a frequency at which the transducer impedance has the lowest amplitude and maximum power is delivered by the transducer [4, 5]. However, the main resonant frequency of the transducer is changed due to environmental and structural variations during operation. Undesirable resonant frequency variations lead to inefficient energy conversion and increase the power consumption especially in the case of high power ultrasound transducer.

Several excitation methods have been proposed to drive high power ultrasound transducers with high quality signals such as linear power supplies and multilevel converters [6, 7]. Multilevel converters draw more attraction in high power biomedical and industrial applications [8, 9] where generating a sinusoidal excitation signal at high power and high voltage using a linear power supplies is not a practical solution [10]. However, applying a distorted excitation signal deteriorates the energy conversion performance of the transducer and increases power dissipation [11-13]. Therefore, an excitation signal with low distortion is highly required to avoid poor energy conversion and power consumption increment.

Each piezoelectric transducer has multiple resonant frequencies, at which the amplitude of the transducer impedance decreases. The lowest magnitude of the impedance corresponds to the main resonant frequency of the transducer, at which the highest possible efficiency of energy conversion is achieved. The fundamental frequency of the excitation signal is usually tuned according to the main resonant frequency of the transducer to achieve optimal energy conversion. However, the resonant frequencies of the transducer including the main one are changing during real time operation. Undesirable change of the main resonant frequency inevitably reduces the energy conversion efficiency. Therefore, it is very important to estimate this frequency in real time and tune the excitation frequency accordingly.

Different methods have been proposed to measure the impedance of ultrasonic transducers in order to estimate their resonant frequencies. These methods are classified as frequency domain and time domain measurement methods [14, 15]. To measure the impedance of ultrasonic transducers in frequency domain, vector network analyzer is commonly used[16]. Time domain measurement methods are based on the ratio of the voltage and current of the transducer measured in real time. For this type of measurement, transducer can be excited at different single frequencies using multiple single frequency signals or at multiple frequencies using rectangular signals (e.g. pulses) [14, 17, 18]. Also, different models have been presented to tune the excitation frequency close to the main resonant frequency of an ultrasound transducer using additional components such as variable capacitive loads and inductors [19-21]. Utilizing more components impose more cost and complexity to the system.

This paper proposes a simple, fast and efficient method to achieve optimal energy conversion performance of a high power piezoelectric transducer. It defines the main resonant frequency based on the maximum power calculated in real time. The operating frequency of the system was kept updated according to the estimated resonant frequency. After estimating the main resonant frequency, the driving frequency is adjusted accordingly to enhance the transducer energy

978-1-4799-4402-6/15/$31.00 ©2015 Crown

conversion performance. Such an adjustment would result in maximum energy conversion possible. In order to examine the proposed method in different experimental conditions, the transducer is driven by two different signals, sinusoidal and multilevel signals. To generate a sinusoidal signal, a signal generator and a linear amplifier are utilized. Also, a sixteen level modular multilevel cascade converter is developed to generate a high voltage and high power excitation signal.

II. EXPERIMENTAL PROCEDURE

A high power ring-shaped piezoelectric transducer with several dominant resonant frequencies, mostly below 90 kHz, is applied for experimental evaluation. To illustrate the difference between the resonant frequency of the transducer measured before and during real time operation, at first, the impedance frequency response of the transducer is measured by a network analyzer (R&S ZVL3) when the transducer is not energized by an external power supply. From the network analyzer result, the main resonant frequency of the transducer is 70.95 kHz at which the transducer impedance has the lowest amplitude.

Fig. 1 shows the impedance frequency response of the transducer. In order for maximum power delivery the transducer should be excited at 70.95 kHz. However this frequency changes during real time operation of the transducer so a real time measurement method is required to estimate the resonant frequency during the transducer operation. To do so, the transducer is excited over a wide range of frequencies (20 kHz- 90 kHz). At each stage of frequency sweeping, the voltage and current of the transducer are measured in real time then the impedance and the power of the transducer are calculated. The frequency at which maximum power is delivered (impedance amplitude is minimum) is the main resonant frequency of the transducer.

Structural and environmental variations such as temperature changing and also the excitation signal changes influence the energy conversion performance of the transducer. Therefore, a repetitive algorithm is required for the real time resonant frequency estimation and operation frequency adjustment. Based on this algorithm, the maximum power is always delivered as the resonant and the operating frequencies are regularly updated.

For real time resonant frequency estimation in this paper, the transducer is excited by two different signals:

1) *Sinusoidal signal*
2) *Multilevel signal*

1. *Sinusoidal Excitation Signal*

In this experimental test, the transducer is excited by a 60Vpp sinusoidal signal generated by a Picotest 50MHz function/arbitrary waveform generator and amplified by a linear power amplifier OPA549. The operating frequency is changed between 20 kHz and 90 kHz with 1 kHz step size, and at each stage the voltage and current signals are captured using a RIGOL DS1204B oscilloscope. MATLAB R2014b software is used for Fast Fourier Transform (FFT) analysis and calculating correspond power at each stage. According to the real time experimental results, the main resonant frequency of the transducer changed is estimated as 70.85 kHz. To highlight the advantage of the proposed method, the values of the power delivered at 70.85 kHz and 70.95 kHz are extracted from the experimental results and shown in Table I.

According to test results shown in Table I, it is obvious that the resonant frequency of the transducer is changed during its operation as the maximum power is delivered at 70.85 kHz rather than 70.95 kHz (network analyzer result).

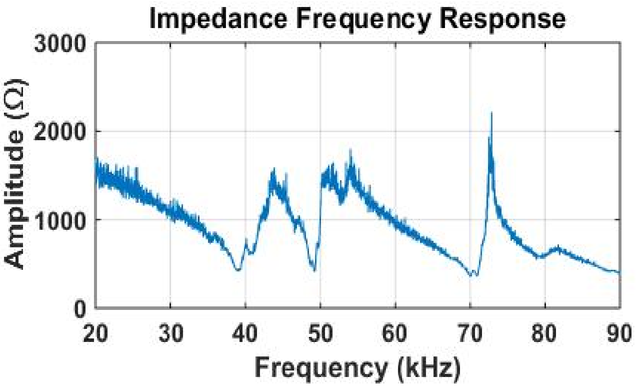

Fig.1. Impedance frequency response of a piezoelectric transducer (measured offline)

TABLE I

REAL TIME MEASUREMENT RESULTS (SINUSOIDAL EXCITATION)

Resonant Frequency	F=70.95 kHz (Estimated offline)	F=70.85 kHz (Estimated in real time)
Minimum Impedance Amplitude	|Z|=829.226 Ω	|Z|=706.62 Ω
Calculated Power	P =0.516 W	P=0.578 W

2. *Multilevel Excitation Signal*

To further evaluate the advantage of proposed method in efficient energy conversion, for the second experimental test a sixteen level modular multilevel cascade converter is developed and will be used to excite the transducer by a 180 Vpp 16-level waveform. A field-programmable gate array (FPGA) is used to generate sampled pulse width modulation (PWM) drive signals. The implemented hardware setup is depicted in Fig.2. The frequency of the excitation signal is varied between 20 kHz to 90 kHz. At each step, the power generated by the transducer is calculated based on the voltage and current of the transducer measured during real time operation. FFT is applied to both voltage and current signals in order to compute the efficient power delivers at each frequency.

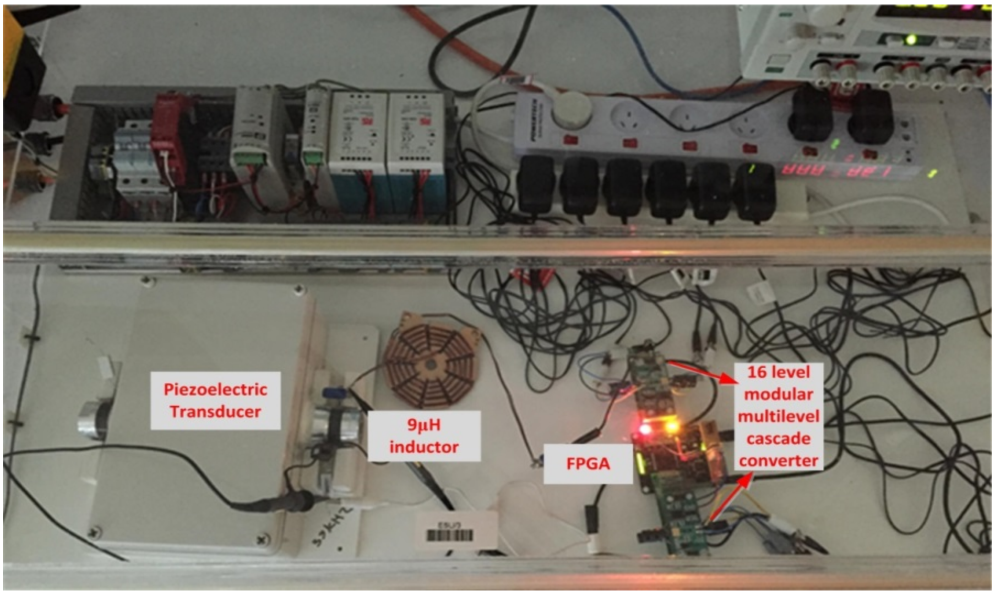

Fig.2. Experimental setup of the multilevel cascade converter

The main resonant frequency of the transducer is then estimated according to the minimum impedance and the maximum generated power.

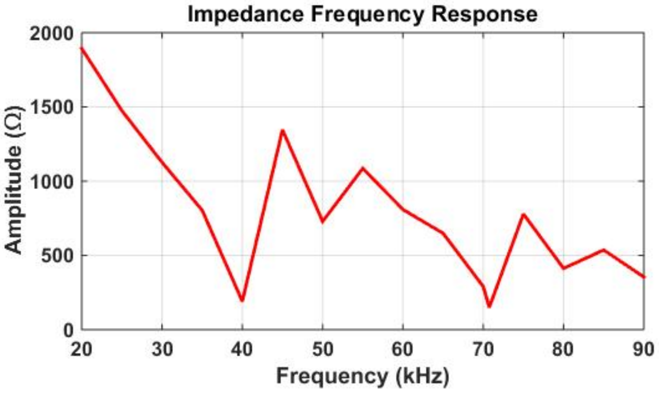

Fig.3. Frequency response of the transducer (measured in real time)

As it is shown in Fig.3, the impedance of the transducer changes during real time operation compared to Fig.1 which represents the transducer impedance measured offline. This impedance variation results in resonant frequencies shifting.

Table II presents the results of the second real time resonant frequency estimation method. Based on these results, it is obvious that the main resonant frequency of the transducer changed to 70.75 kHz in real time as the maximum power, 27.906 W is delivered at this frequency.

The comparison between the power delivered at 70.75 kHz and 70.95 kHz reveals that when the excitation frequency is adjusted based on the main resonant frequency of the transducer measured in real time (70.75 kHz), the transducer delivers 27.906 W while if the excitation frequency is adjusted to 70.95 kHz (network analyzer result), 11.26 W is delivered by the transducer. This is a critical issue for some ultrasound applications at which the maximum power should be delivered by transducers.

TABLE II

REAL TIME MEASUREMENT RESULTS
(MULTILEVEL EXCITATION)

Frequency	F=70.95 kHz	F=70.85 kHz	F=70.75 kHz
Minimum Impedance Amplitude	|Z|=359.5 Ω	|Z|=159.97 Ω	|Z|=145.13 Ω
Calculated Power	P =11.26 W	P =25.317 W	P=27.906 W

Also, the results of Table II show that the transducer impedance behavior is affected by the excitation signal changes. According to the test results presented in Table I, when a 30 V sinusoidal signal is applied to excite the transducer the maximum power is delivered at 70.85 kHz. However, if 90V 16-level excitation signal is applied, the maximum power is delivered at 70.75 kHz. Such a difference can be due to the effect of output filter (9 µH inductor), the change in excitation signal as well as the effect of ambient testing conditions.

For any of these experimental tests, once the main resonant frequency is estimated, the operating frequency of the system is then changed manually to achieve efficient system operation. All presented experimental results prove the capability of the proposed method in real time resonant frequency estimation and maximum power tracking.

III. CONCLUSION

A fast and efficient method was proposed to estimate the resonant frequency of a high power piezoelectric transducer in real time in order to achieve maximum possible energy conversion. According to the experimental results, it was shown that resonant frequency of the transducer changes during its real time operation. Moreover, it was shown that for efficient energy conversion, the transducer should be excited at its main resonant frequency. Compared to other resonant frequency tracking methods, the advantage was that maximum power was delivered in real time while no additional components were used. Despite the fact that the frequency adjustment was carried out manually using signal generator and FPGA, in future works, this can be done with a closed loop control system using Digital Signal Controllers (DSC). New generations of DSCs are fast enough to be used for power calculation, resonant frequency estimation and the operating frequency adjustment.

REFERENCES

[1] A. A. Vives, *Piezoelectric Transducers and Applications*. DE: Springer-Verlag, 2008.

[2] B. J. O'Daly, E. Morris, G. P. Gavin, J. M. O'Byrne, and G. B. McGuinness, "High-power low-frequency ultrasound: A review of tissue dissection and ablation in medicine and surgery," *Journal of Materials Processing Technology,* vol. 200, pp. 38-58, 5/8/ 2008.

[3] T. J. Kamierski and S. Beeby, *Energy Harvesting Systems: Principles, Modeling and Applications*: Springer Science + Business Media, 2011.

[4] L. Apc International, *Piezoelectric ceramics: principles and applications*. Mackeyville, PA: APC International, 2002.

[5] N. Ghasemi, S. Queensland University of Technology, and F. Engineering, "Improving ultrasound excitation systems using a flexible power supply with adjustable voltage and frequency to drive piezoelectric transducers," Dissertation/Thesis, 2012.

[6] C. Kauczor and N. Frohleke, "Inverter topologies for ultrasonic piezoelectric transducers with high mechanical Q-factor," in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, 2004, pp. 2736-2741 Vol.4.

[7] N. Ghasemi, F. Zare, A. A. Boora, A. Ghosh, C. Langton, and F. Blaabjerg, "Harmonic elimination technique for a single-phase multilevel converter with unequal DC link voltage levels," *IET Power Electronics,* vol. 5, pp. 1418-1429, 2012.

[8] A. Heidarkhan Tehrani, P. Davari, S. Singh, and A. Oloyede, "Sterilizing tissue-materials using pulsed power plasma," *Journal of Materials Science: Materials in Medicine,* vol. 25, pp. 953-964, 2014/04/01 2014.

[9] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, W. Bin, *et al.*, "Recent Advances and Industrial Applications of Multilevel Converters," *Industrial Electronics, IEEE Transactions on,* vol. 57, pp. 2553-2580, 2010.

[10] S. C. Tang and G. T. Clement, "A harmonic cancellation technique for an ultrasound transducer excited by a switched-mode power converter," *IEEE Trans Ultrason Ferroelectr Freq Control,* vol. 55, pp. 359-67, Feb 2008.

[11] N. Ghasemi, F. Zare, P. Davari, C. Langton, P. Weber, and A. Ghosh, "Power electronic converters for high power ultrasound transducers," in *Industrial Electronics and Applications (ICIEA), 2012 7th IEEE Conference on*, 2012, pp. 647-652.

[12] F. Lanza di Scalea, H. Matt, and I. Bartoli, "The response of rectangular piezoelectric sensors to Rayleigh and Lamb ultrasonic waves," *The Journal of the Acoustical Society of America,* vol. 121, pp. 175-187, 2007.

[13] G. R. Walker, N. Ghasemi, M. A. H. Broadmeadow, and G. F. Ledwich, "A high cell count cascade full bridge converter for wide bandwidth ultrasonic transducer excitation," in *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*, 2014, pp. 2140-2146.

[14] G. K. Lewis and W. Olbricht, "Cost-effective broad-band electrical impedance spectroscopy measurement circuit and signal analysis for piezo-materials and ultrasound transducers," *Measurement Science and Technology,* vol. 19, p. 105102, 2008.

[15] D. M. Peairs, G. Park, and D. J. Inman, "Improving Accessibility of the Impedance-Based Structural Health Monitoring Method," *Journal of Intelligent Material Systems and Structures,* vol. 15, pp. 129-139, 2004.

[16] D. Huijuan, W. Jian, Z. Hui, and Z. Guangyu, "Measurement of a piezoelectric transducer's mechanical resonant frequency based on residual vibration signals," in *Information and Automation (ICIA), 2010 IEEE International Conference on*, 2010, pp. 1872-1876.

[17] J. S. Kim, K. Choi, and I. Yu, "A new method of determining the equivalent circuit parameters of piezoelectric resonators and analysis of the piezoelectric loading effect," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* vol. 50, pp. 424-426, 1993.

[18] P. Davari, N. Ghasemi, F. Zare, P. O'Shea, and A. Ghosh, "Improving the efficiency of high power piezoelectric transducers for industrial applications," *IET Science, Measurement and Technology,* vol. 6, pp. 213-221, 2012.

[19] J. M. Renno, M. F. Daqaq, and D. J. Inman, "On the optimal energy harvesting from a vibration source," *Journal of Sound and Vibration,* vol. 320, pp. 386-405, 2009.

[20] W.-J. Wu, Y.-Y. Chen, B.-S. Lee, J.-J. He, and Y.-T. Peng, "Tunable resonant frequency power harvesting devices," 2006, pp. 61690A-61690A-8.

[21] J. Twiefel, B. Richter, T. Hemsel, and J. Wallaschek, "Model-based design of piezoelectric energy harvesting systems," 2006.