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Research Article

A Study on Performance of the Acoustic Energy Transfer System Through Air Medium Using Ceramic Disk Ultrasonic Transducer

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Abstract

Acoustic Energy Transfer (AET) system is a type of contactless transmission of energy that uses ultrasound waves or vibration to transmit energy. The AET works in several mediums such as metal, air, water and even able to work through living tissues. This study investigates the performance of AET through the air by using ceramic disc ultrasonic transducer, specifically for low power applications. A multiple input-output transducer is designed in this study. The simulation and experimental works are carried out and the obtained results are analysed accordingly. Based on the experimental results, the power converter generates 40 kHz frequency and obtained 1.071 mW transmitted power. The multiple transceiver design offers higher output power which is 7.24 mW.

Key words: Acoustic energy transfer, ultrasonic transducer, contactless energy transfer, piezoelectric resonator, inductive power transfer

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Contactless Energy Transfer (CET) has emerged as an inventive new technology that creates possibilities to supply mobile devices with electrical energy without the connection of wire. Elimination of cables or connectors in most of CET applications has increased its reliability especially to a critical system such as in aerospace, biomedical, multi-sensors and robotics applications. Recently, various established technologies of CET systems are developed and investigated widely. These technologies include the current technology of Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT) and optical coupling energy transfer[1].

The IPT system is the most recently used in contactless energy transfer system. It uses coupled of the electromagnetic field coil. The achievement of this IPT system has been proven in many applications such as being built in electric vehicles, mobile phones and various types of battery charging system[2-4]. However, there is a major drawback of this electromagnetic coupling method, where the transmissions distance is relatively limited, causing the efficiency to decrease rapidly with increasing distance. It contributes to reduction of transmission strength in electromagnetic fields. Waffenschmidt and Staring[5] stated that the inductive power transmission in a larger space is very inefficient and not practical due to high conduction losses. Additionally, over a conductive medium, these systems cannot transfer power effectively.

The CPT systems convey energy via high frequency resonant power electronic converter that is connected to two primary metal plates. This system is quite similar with capacitive concept of energy transfer but it uses capacitance coupling. The CPT system has been successfully implemented in some miniature devices[6,7], however, they share the same problem as experienced in IPT, which is low efficiency over a large distance.

Meanwhile, optical coupling energy transfer systems operate correspondingly to far-field electromagnetic and microwave energy transfer. The optical power beam and photovoltaic diodes are created by laser diodes and transform it into electrical power and therefore it is able to deliver a large amount of energy[7,8]. However, diffraction losses that occur internally in this approach lead to low efficiency when operating over a long distance.

Acoustic Energy Transfer (AET) is an emerging new method of transferring energy wirelessly which exploits vibration or ultrasound waves. The AET is still in its early phases and has seen very little development as compared to IPT[9]. Even though the other CET system was established earlier years ago, AET has advantages in some traits. As it propagates through vibration, it can transmit energy through a metal medium where IPT and CPT fail to achieve. The metal walls have a shielding effect which limits the coupling of electromagnetic fields and induces eddy currents in the metal resulting in high losses. However, an AET system would not face such difficulties due to the absence of electromagnetic fields. Several developments proved that AET can sustain its competency across a conductive propagation medium and obtain larger distance of transmission[10]. In biomedical application, presence of electromagnetic fields will cause side effects and it is controlled under medical regulation[11]. Absence of electromagnetic fields has made AET more practical to be used in biomedical applications and is applied in a miniaturized size[12]. Other than that, acoustic velocity in human tissues used bymedical imaging application produces a very small wavelength. This makes AET an attractive method to energize implanted micro-devices wirelessly and allowing reasonable directional transmission since the transducers of overall dimensions are used as few millimeters[13].

There are numbers of publication on AET that have been applied for biomedical, through-wall living tissue and metal application. To the authors' knowledge, there are very few publications that discussed AET through the air. In spite of this, proves that AET through air is possible to be achieved[10]. Theoretical calculation of achievable AET through air has been discussed by Roes *et al.*[14]. This study focuses on the development of AET through the air using ceramic disk transducer that is driven by a push-pull power converter. A multiple transceiver is used in this study to identify how it impacts the system performance.

MATERIALS AND METHODS

AET system: A typical AET system consists of primary and secondary unit where both sides comprise of ultrasonic piezoelectric transducer and are separated by a transmission medium, as shown in Fig. 1. The main important elements that we can classify in this system are power converter and rectifier, transmission medium and transducer. Power converter and rectifier will take part in transmitting and receiving energy using desired ultrasonic transducer. Meanwhile, the transmission medium determines how the wave propagates.

Principle of operation: The AET system is based on sound waves or vibration and is basically applied using an ultrasonic transducer. At the primary unit, power converter is used to

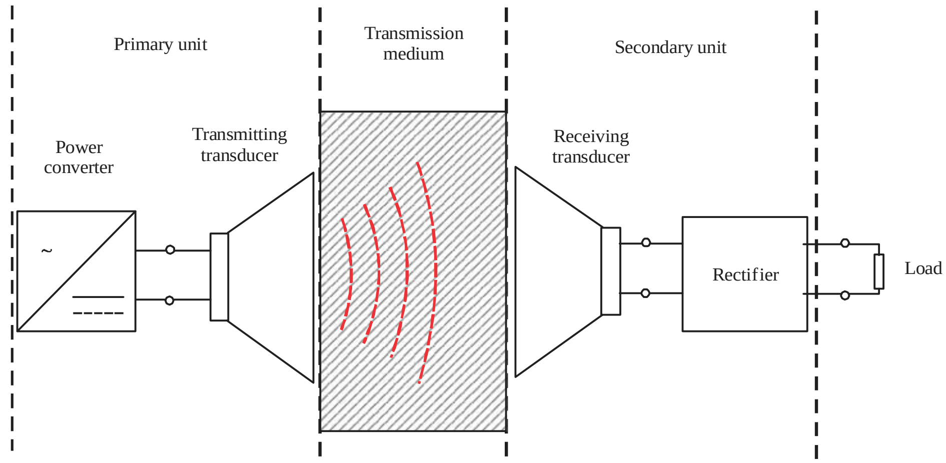

Fig. 1: A typical AET system that consists of 3 parts; primary unit, transmission medium and secondary unit

drive the amount of power needed by the primary transducer. The primary transducer will transform electrical energy into pressure or acoustic wave. It generates waves in the form of mechanical energy and propagates through a medium. The primary transducer should be driven at a specific frequency and is normally represented in a sinusoidal waveform to obtain the best performance that is matched with the propagation medium. In this study, a push-pull power converter is used to drive power to the transducer.

The secondary transducer is placed at a point along the path of the sound wave for the inverse process of converting back into electrical energy. In other words, this acoustic wave is picked up by the secondary transducer at a specific frequency and converts the mechanical energy back to the electrical energy. It then can be used for powering up an electrical load. The sine wave is also produced at the secondary transducer. In order to produce sinusoidal wave, the circuit of the primary unit should consist of a DC-AC converter and an AC-DC rectifier is needed at the receiving unit.

Wave behaviour: Transmission medium is a part where the sound wave is being propagated between the transmitting and receiving transducers. There are some phenomena that affect the transmission; attenuation, diffraction and reflection of the sound waves[12]. These phenomena contribute to the loss mechanism for an AET system since it changes the characteristic of the sound wave. Attenuation is reduction of signal strength during transmission and is measured in decibel. Diffraction refers to various phenomena which occurred when a wave encounters an obstacle. It is described as the apparent bending of waves around small obstacles and the spreading out of waves past small openings. Meanwhile, reflection is a change in direction that a wave experiences when it bounces off of a barrier between two kinds of media. An important idea that needs to be considered in determining the medium for transmission is material acoustic impedance. Acoustic impedance specifies how much sound pressure is generated by the occurrence vibration of the medium at a desired frequency. The medium which the wave propagates through will have its own acoustic impedance[15]. The characteristic acoustic impedance of a material is the product of its density and the velocity of propagation of sound in the material[16].

The unit for acoustic impedance is in Mrayl, which is equivalent[17] to Pa sec cm^{-1}, kg sec^{-1} m^{-2} and N sec m^{-1}. Acoustic impedance of a material can be defined as the product of its material density (ρ) and acoustic material velocity (c).

Acoustic impedance in most metals is approximately 45 Mrayl and it is not much different compared with piezoelectric material which is approximately 30 Mrayl, whereas there is a large mismatch between piezoelectric and air. This suggests that more power will be received with a metal medium compared to air medium for a given input power. Reflection is one of the wave behaviors that change the direction of the wave when it bounces off a barrier between two kinds of media. This phenomenon can be avoided by using a good match of impedance[18]. For applications in which there is an obvious mismatch between the medium and the acoustic impedance of the transducer, matching layers could reduce the reflection[16]. Another concern in modeling the medium is determining the acoustic interface, which is a reflection in the middle of two materials that have different acoustic impedances. Some amount of energy is reflected and the rest will be transmitted across the boundary when sound strikes an acoustic interface at normal incidence[19].

Ultrasonic transducer: Piezoelectric materials could generate electrical energy from the pressure and mechanical energy from an electric field. Hu *et al.*[20] agreed that transducer material gives different damping effect. Therefore, the material of the transducer contributes to the system performance. Piezoelectric materials with high transduction efficiency would be advantageous to be used. One of the types of transducer is a ceramic disk transducer. Ultrasonic ceramic disk transducer is capable to transform acoustic energy to mechanical energy and then to electrical energy or vice versa. This type of transducer employs unique construction featuring higher sensitivity, wider bandwidth and smaller size as compared to conventional transducer. Figure 2 shows that, the transducer utilized compound vibrator, which is a conical aluminum resonator with a connector bonded at the center of the piezoelectric elements of the bimorph type, consisting of oppositely polarized material in a sandwich construction.

When an ultrasonic signal is applied to the compound vibrator, conical resonator begins to vibrate effectively because of its shape and drive the piezoelectric resonator at its central part according to the frequency of the signal. As a result, the compound resonator generates a high electrical signal from the piezoelectric resonator. Furthermore, the formation of standing waves inside the case results in a higher electrical voltage. If the resonant frequency of this compound resonator corresponds to the frequency of the ultrasonic wave being applied, then the electrical voltage generated from the piezoelectric resonator is at a maximum level.

RESULTS AND DISCUSSION

This study consists of the results of the AET performance, which is tested using different conditions. The test is to analyze the factors that influence wave behavior that affected the energy transfer efficiency and power transfer capability. The experiments covered three sections, which are firstly, analyzing the optimum frequency, followed by the setup of AET system using push-pull converter and rectifier and finally, applied using multiple transducers.

Experimental of basic AET system: The initial experiment is executed to find the optimum value of the transducer to transmit energy. The chosen ultrasonic transducer is 16 mm multicomp ceramic disk transducer. This transducer is connected to the function generator and oscilloscope. The function generator is used to generate some amount of

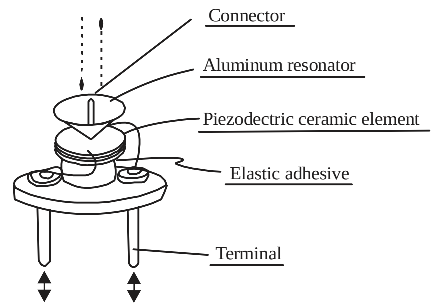

Fig. 2: Topology of ceramic-film ultrasonic transduce

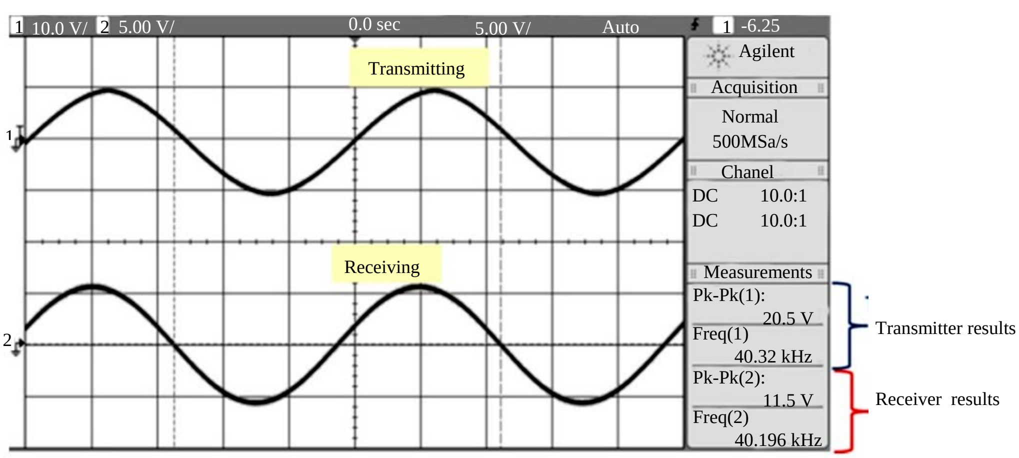

Fig. 3: Result of transmitting voltage from function generator

power and frequency. The frequency value has varied to see where the optimum value of the transducer based on the signal shown on the oscilloscope. The distance of both transmitting and receiving transducer is constant which is 20.0 mm. The results of the optimum frequency that is shown in the oscilloscope are as in Fig. 3. The results show the waveform of the transferred voltage where it is a maximum at frequency 40.19 kHz. The overall result of the variable frequency vs transfer voltage amplitude can be seen in Fig. 4.

The result shows that, at this ≈40 kHz value, the energy can be transferred at a maximum level. The obvious changes of frequency would rapidly decrease the transfer voltage and affect the performance of the system. This experiment proves the theoretical explanation that the resonance frequency of the system should match with the transducer's optimum frequency to obtain high efficiency of energy transfer. The result is then will be used to set up a push-pull power converter that produces some amount of voltage that can transfer using the same frequency.

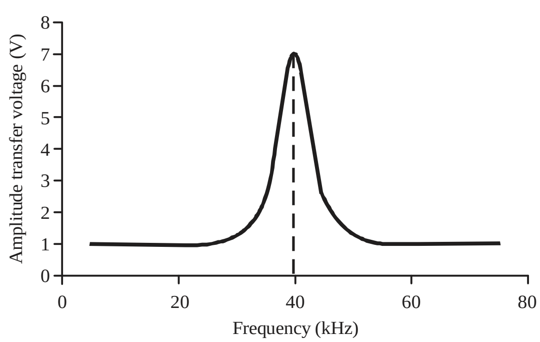

Fig. 4: Amplitude vs frequency of the AET initial experiment

Single transceiver AET system: The arrangement of the power converter, transducers and rectifier for single transceiver AET System has been carried out as shown in Fig. 5. The DC input voltage that is supplied to the push-pull converter circuit is 5 V and connected to the ultrasonic transducer as a transmitter. The secondary ultrasonic transducer is placed opposite and perpendicular to the transmitting transducer with air gap 20.0 mm. A simple bridge rectifier is used in the secondary unit to convert the received AC voltage to DC voltage.

From the result in Fig. 6, the frequency obtain by the transmitter is 40.92 kHz, which is in good condition to transfer power. The receiving signals also show that the transmitter and receiver can transfer energy even though only almost 45% of the Vpp voltage were received. However, the value shown in the oscilloscope is in AC voltage. The received voltage has been converted to the DC voltage using rectifier with different value of load and measured using a digital multimeter. The power obtained at the output is shown in Fig. 7.

Figure 8 shows the output power result when the distance of the air gap is increased. The alignment of the transducer's position is constant. In a certain limit, the output power will be decreased as the air gap distances increased.

Since the energy is transferred by wave propagation, the initial distance would not affect the performance of the system as long as the alignment of both transducers is not changed. Due to this fact, an AET system should be arranged where both transducers are opposite to each other in a line, otherwise the efficiency will drop off rapidly.

Multiple transceiver AET system: The experiment also covers the study on the performance of the system if multiple

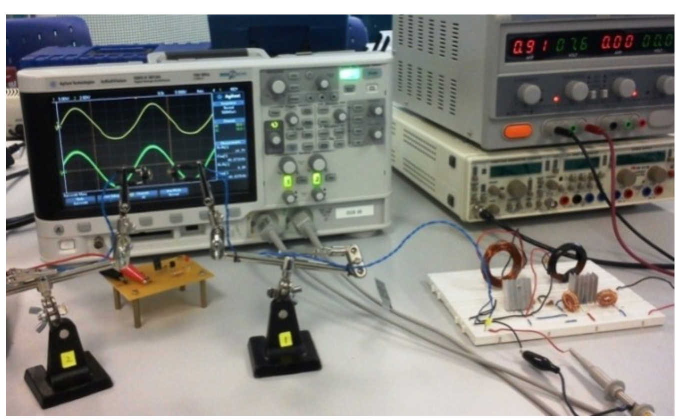

Fig. 5: AET system experimental setup shows AET basic system using push-pull power converter transmits energy through the air medium

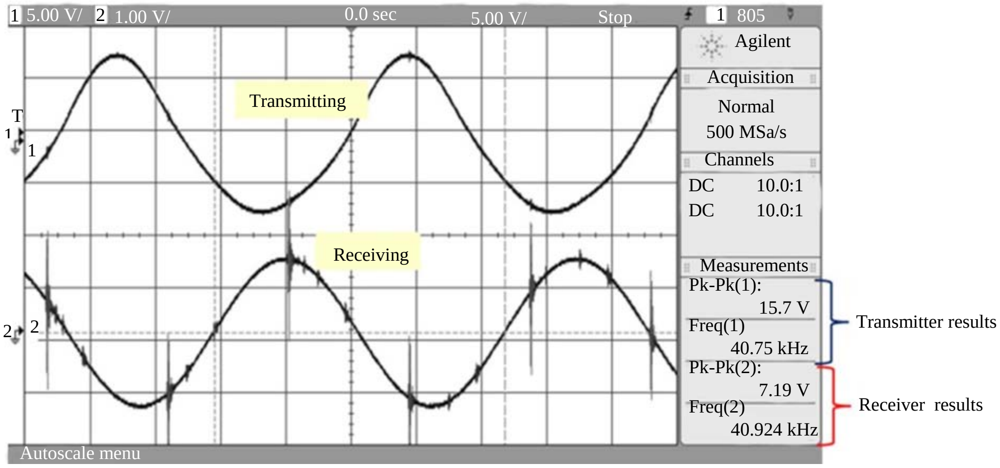

Fig. 6: Result of push-pull power converter on AET

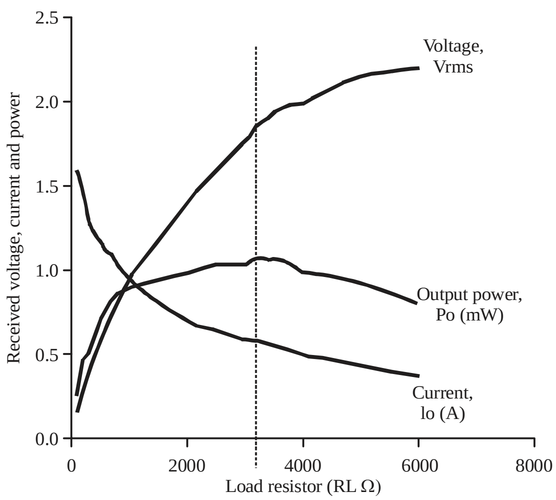

Fig. 7: Optimal power transfer ratio increases with an increase in load resistance. The most optimum value is at 3.3 kΩ load resistances where 1.071 mW power is obtained

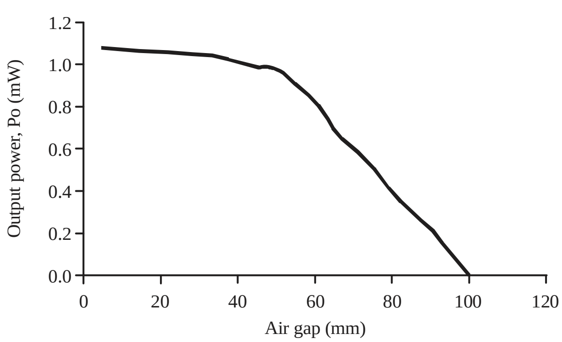

Fig. 8: AET system with different air gap between transducers

input-output of the transducer is used. The arrangement of the system is shown as in Fig. 9. The ultrasonic

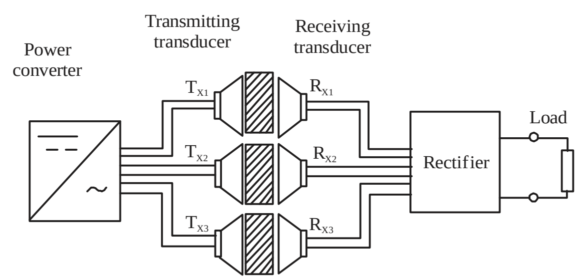

Fig. 9: Multiple input-output AET system block diagram

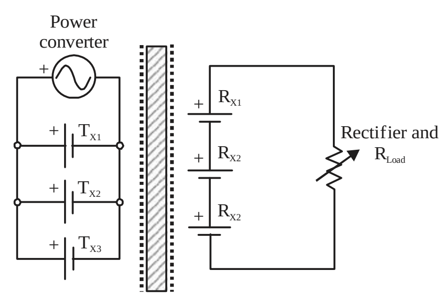

Fig. 10: Connection of multiple transmitters, T_x in parallel and multiple receivers, R_x in series

transducers will be placed double or triple paired in both sides, transmitter and receiver.

All the transmitting transducer is connected to the power converter in parallel connection. This will make the transmitting transducer transmit equal power from the converter in each transmitting transducer. The receiving transducer connected to the rectifier in series connection, thus the input of the transducer will get maximum value of power to the load. The schematic of the connection can be simplified as in Fig. 10.

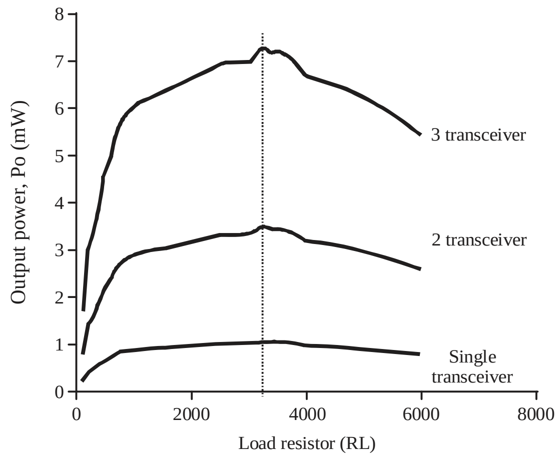

Fig. 11: Result of multiple input-output AET system. The maximum power of the system is 1.07 mW for single transceiver, 3.47 mW for two transceivers and 7.24 mW for three transceivers

The results in Fig. 11 show that the output power is increased when multiple transceivers is used. This result shows that the development of AET system using multiple transceivers has achieved better than the single transceiver using the same transmitted power.

CONCLUSION

Development of the AET system through the air medium using a push-pull converter has been analyzed in this study. The system achieves to transfer 1 mW power using a single transceiver. The air medium is quite challenging to be used for transferring energy through compared to the other medium such as metal and conductive media. However, the efficiency of the system was increased, which is 7.24 mW power when 3 transceivers is used. The arrangement of multiple transceivers actually replicates the power of one transceiver to double or triple power depends on the system design. Thus, this system could save more power and lead to energy saving where the small input power generated can be expanded to a larger power at the receiver. The push-pull converter also works well as the frequency generated match with the transducer's optimum frequency. For future development, it is suggested the high output power of the transmitter is proposed so the receiver will possibly receive high power.

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