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Review Article

State-of-the-Art Developments of Acoustic Energy Transfer

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Acoustic energy transfer (AET) technology has drawn significant industrial attention recently. This paper presents the reviews of the existing AETs sequentially, preferably, from the early stage. From the review, it is evident that, among all the classes of wireless energy transfer, AET is the safest technology to adopt. Thus, it is highly recommended for sensitive area and devices, especially implantable devices. Though, the efficiency for relatively long distances (i.e., >30 mm) is less than that of inductive or capacitive power transfer; however, the trade-off between safety considerations and performances is highly suitable and better than others. From the presented statistics, it is evident that AET is capable of transmitting 1.068 kW and 5.4 W of energy through wall and in-body medium (implants), respectively. Progressively, the AET efficiency can reach up to 88% in extension to 8.6 m separation distance which is even superior to that of inductive and capacitive power transfer.

1. Introduction

In 1921, Nikola Tesla demonstrated a capacitive coupling powering system to turn on an electric bulb that was wirelessly sandwiched between two capacitor plates [1]. That was the first public demonstration of wireless power transfer (WPT). Earlier, Tesla described the technical development of WPT in 1914 [2, 3]. He provided sufficient proof for WPT to be a real and elegant way of future wireless powering. Unfortunately, the advancements made by Tesla were not conveyed by the researchers until the 1980s [4–6]. After 1980, the WPT started to experience its anticipated growth, however, rather as wireless communication. In fact, the wireless mobile communication which was pioneered by Tesla about 100 years ago revolutionized the electronics industry within three decades after the kick-off commercialization [7]. Expectedly, the idea of WPT in the context of high-level power transfer came to our modern technology as a sequence. As a result, since 2000, the development of WPT has been continued by means of serious research. Now, WPT is an active area for both research and commercial centric approach. WPT offers several benefits, such as cord and battery elimination, connector removal, integration of application boundary, and modificationless system extension. Hence, WPTs are considered as a promising future oriented industry. In fact, in a recent work, the focus was to charge 30 smart phones (1 W) or five laptops (2.4 W) simultaneously within 50 cm surrounding wireless area [8]. This experience indicates the rapid development trends of WPTs.

So far, WPT has four active branches—namely, inductive, capacitive, microwave, and acoustic WPT [9]. Additionally, optical WPT is emerging as a subclass of electromagnetic WPT. Among all these, inductive WPT is widely practiced and commercially available [10]. This WPT is enriched with high efficiency, high power (30 kW), and relatively long distance power transfer capability [11–13]. It is recently reported that 5 to 7-meter separation distance between receiver and transmitter is achieved by inductive WPT [14, 15]. Nevertheless, inductive WPT suffers from the coupling misalignment and penetration losses [16]. Capacitive WPT, on the other hand, is still in the developing stage of research and development. Unfortunately, the inverse property of capacitance with respect to distance limits the separation and efficiency of this WPT. However, for short distance (<1 mm) it can achieve high power (>1 kW) transfer with reasonable efficiency [17–20].

Microwave WPT can provide very high efficiency and wide propagation area as well, due to their high energy density penetration [21–23]. Again, optical WPT is capable of transmitting energy over long range (>km) [24, 25]. However, optical WPT can offer 40–50% efficiency because of the two-step conversion process, while microwave WPT can achieve 80–90%. Moreover, the line of sight imposes a drawback for optical WPT whereas the microwave WPT suffers from the generation of microwaves [26, 27].

Acoustic energy transfer (AET), unlike the aforementioned WPTs, transfers power by propagating energy as sound or vibration waves. The propagated energy then collected by a receiver which converts the vibration energy to useful electrical energy [28]. To do so, piezoelectric conversion termed as piezoelectricity is practiced so far. The scope of this paper includes an overview of the existing acoustic based energy harvesting technologies for low power applications. The attempt to trace the trend of this WPT is particularly focused in this paper by reviewing year-by-year sequential developments.

The remainder of this paper is organized as follows: Section 2 discusses the preliminary of AET technology. Section 3 presents the existing AETs since the very beginning of the introduction. Later, Section 4 presents the findings of this review in several parameter contexts and Section 5 relates to the remaining challenges. Lastly, Section 6 concludes this paper with some prospective future agendas.

2. Acoustic Energy Transfer (AET) Technology

The first demonstration of the piezoelectricity was discovered by P. Curie and J. Curie back in 1880 [29]. However, that demonstration was limited to the electricity generation in respect to an applied stress. Later in 1881, along with Gabriel Lippmann, Curie brothers confirmed the converse effect of piezoelectricity. Thus, the mechanical to electrical and electrical to mechanical conversion was established [30]. Since then, this reversely convertible effect has been a key to many modern technologies [31, 32]. Mason attached significant contribution in the sequence of piezoelectric developments by providing a generalized equivalent circuit which has been widely used up to date [33]. Piezoelectricity has been used in power sources, sensors, actuators, piezoelectric motors, reduction of vibrations and noise, fertility treatment, surgery, and more [34].

2.1. Fundamental Outline of AET. The existence of the AET is not new; in fact, the history of using acoustics is as old as the musical instruments. However, the twofold application of the AET to transmit power specifically is new. As mentioned earlier, AET has two-sided operation, the transmitter (primary side) and receiver part (secondary side). The transmitter processes a given energy, mainly electrical power through a converter, and executes the effect of it by vibrating

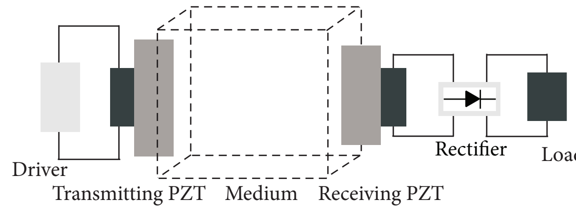


Figure 1: Fundamental schematic of AET technology.

the active area [35]. It can be termed as effective electrical to mechanical conversion. The vibration immediately creates a resonance in the incorporated medium area and propagated in omnidirectional fashion (either air for open influence or material for other cases that varies depending on the type). The propagated power is then collected by a receiving transducer and converted to useful electrical power [36]. Figure 1 presents the basic methodology of AET. It is important to mention that the medium can be air, metal, in-body, or even liquids.

2.2. Benefits of AET. AET can be advantageous in several manners. Most important of all, it uses sound or vibration as energy propagation medium. Hence, it is considered as the safest WPT compared to others. In addition, it does not suffer from misalignment and possesses higher penetration depth (10–20 cm in tissue) due to the frequency range below 10 MHz. Additionally, there are several conditions where electrical power or signal needs to be transmitted through an enclosed metallic wall. Conditionally, the use of electromagnetic radiation or RF is not appreciable in this situation for their attenuation impact. For instance, to sense the pressure leak and to avoid the infection of the container of the Mars Sample Return Mission, it requires wireless sensors. There is another incident where the solution is required to communicate with the crews in a marine structure without affecting its configuration. Again, in a nuclear plant where the physical access is prohibited or in modern composite materials (carbon-fiber epoxy) that are used in military or aircrafts or packaging of food or beverage, for these cases AET is more appropriate due to its nonelectromagnetic features [37–40]. Furthermore, AET is not restricted to the frequency band and energy propagation direction. Hence, AET is highly suitable for liquid or liquid based environment (animal tissue, flesh) [41, 42]. Therefore, AET is suitable for both wall-through and in-body power transfer.

3. Developments of AET

The first attempt to transmit wireless energy through acoustic technique was proposed by Cochran et al. in 1985 [43]. In this proposal, acoustic energy was transferred to an internally fixed plate inside body to treat the bone. The earlier proposals, respectively, tend to use the invasive treatment which are not convenient. A PZT-5 material based 36 × 6 × 1 mm internal fixation plate was fabricated and operated under 1–10 MHz frequencies. The experiment successfully showed the potential of AET. The in vivo experiment confirmed 600 mV output voltage and up to 100 μA average output current with 10 mW of the peak power density.

Later, the experiment was conveyed for practical implementation [44]. From the experiment it was found that an ultrasonic transducer with frequency of 2.25 MHz, 10–20 V of input, and output of >10 mW/cm^2 can generate up to 20 μA with rectification. In some cases, the generated current exceeds 1 mA range. However, both of the aforementioned works focused on the internal healing purposes. Nevertheless, since then, numerous attempts are being taken to harvest wireless energy by AET.

A wall-through power transfer and data communication was introduced by Connor et al. in 1997 [45]. In that method, two coaxially aligned piezo transducers (primary and secondary) were attached as face-to-face fashion; between them a solid wall was placed. A driver circuitry was applied to generate ultrasonic vibrations by the primary PZT and propagated through the wall. The vibration was collected by the secondary PZT and converted back to electrical power. To maintain the simultaneous power delivery, a MOSFET was placed to the secondary PZT. The ON-OFF state of the MOSFET influenced the acoustic impedance of the secondary PZT and that effect is collected by the primary PZT. Hence, it maintained the constant power and data delivery. However, the statistical data were not included. This work was later followed by two closely related works [46, 47].

Two crucial works were done on this acoustic projection by Kawanabe et al. and Suzuki et al. in 2001 and 2002, respectively [48, 49]. In these works, they showed that the acoustic energy transfer (AET) is highly suitable for in-body implants. For the first work, they introduced wearable device prototype which has a one-chip microcomputer to verify the size and energy consumption statistics of the device. This prototype was able to transmit data by acoustic wave with 250 kbps in bidirectional fashion that is equivalent to that of system using electromagnetic waves. On the other hand, the later work focused on both transmitting power and information. To achieve that, the proposed design consisted of two piezo oscillators; one of them collects information from a living body and delivers it to the outside receiver. Maximum 20% efficiency was achieved by both of the proposals in a 30 mm separation distance, using 1 MHz optimal frequency. Successively, a prototype of 36% efficiency was developed by the next year [50].

In 2003, Hu et al. proposed a system model to transmit energy through metal wall [51]. The work examined the feasibility of transmitting power through a sealed wall or armor. Till now, the work is considered as the basic analytical investigation through wave equations for elastic thickness-stretch mode. This investigation used mathematical modeling to form the proposal. From the numerical analysis, it is evident that the output voltage can reach over 0.6 V and 0.4 V with load impedance of 10 Ω and 40 Ω, respectively. However, this work did not consider the effect of diffraction for wave propagation. In addition, the trade-off between head and tails mass is not beneficial in the context of loss. Hence, the practical implementation of the proposal is difficult to achieve.

In corporation with aforementioned model, Sherrit et al. proposed a developed model for feed-through applications [52]. This electromechanical model permits both wireless data and power transmission in a sealed container. The model extends the effect of the dielectric, piezoelectric, and mechanical losses in the considered sealed wall. In addition, the earlier model by Hu et al. was simulated by following the parameters mentioned. However, to prove the practical validation of the proposal, the model was resimulated by considering Motorola 3203HD material properties and investigating PZT-8 for thickness data. In fact, in the following year, the real prototype was developed to evaluate the practical feasibility [53]. From the simulated investigation it is evident that approximately 70% efficiency can be achieved by the proposal. However, the practical prototype could only account for maximum of 53% efficiency. The authors concluded that 100 W electricity can be transmitted with 0.2 m diameter plates. Nevertheless, the efficiency can be improved by increasing the mechanical loss factor of the considered wall.

In 2007, several works on the wall-through power transmission were projected [54]. Among these, [55] accounts for maximum 88% efficiency in a 38 mm to deliver 100 W of electricity. In extension, Bao et al. and Sherrit et al. improved the earlier proposal by transmitting 1 kW power through metallic wall [56, 57]. They have transmitted the power with significant efficiency as well which is 87-88% by using 24.5 kHz frequency. However, [58] achieved maximum 35% efficiency, whereas no statistical data were included in [59].

To deliver power in conductive envelopes, Kluge et al. [54, 60] introduced and examined a similar model to Sherrit et al. A metallic envelope of 5 mm thickness was used as the wall to outside in power and data transfer. The model was capable of transmitting 30 mW of power with 80% efficiency and 1 kb/s of data in the thickness mode at 741 kHz to 3 MHz. Additionally, accelerated life testing was performed for 800 hours at 100°C to test the long term performance of the system which can validate the targeted investigation value of 100,000 hours [61].

Hu et al. presented a solution to transmit energy through a thin metal wall using two isolated piezoelectric transducers [62, 63]. They considered several normalized boundary conditions and solved the open circuit and closed circuit stage of the proposal with synchronized switch harvesting on inductor (SSHI). In extension, the authors modeled a storage circuit considered for inner use of a sealed vessel. From the analysis, it is evident that the peak output power can meet the barrier of over 6 W. However, the complexity of adding a rectifier in nonlinear analysis is avoided here.

Yang et al. [64] suggested a theoretical analysis to transmit energy through a three layered elastic wall and configured 3D linear piezoelectricity equation to 1D equation. By numerical analysis, they proved the functionality of the proposal. For evaluation, they used pure resistor and complex impedance as load. From the investigation, they suggested that fundamental resonant frequency may not offer the best output but rather depends on several performance criteria. Again, as material, iron, aluminum, and lead were considered for designing the model. The materials showed different characteristics which affected design performances along with the load impedance of the output circuit.

Neasham et al. [65, 66] suggested a system to transmit power and data up to 80 mm thick steel marine vessel walls. They introduced electromagnetic acoustic transducers (EMATs) to resolve the limitation of PZT transducer in corroded and contaminated surfaces. The system offered 10 mW power transmission with 0.25% efficiency where the expected efficiency can be increased to 1% through 25 mm steel wall.

For implantable devices, it requires to satisfy several issues. Firstly, the device and containing package have to be biocompatible. Again, the device should be able to harvest energy in the biological environment. And lastly, the receiver of the package should be efficient to transform acoustic energy to electric energy. In summary, the offered package has to be not harmful at all. In 2010, P.-J. Shih and W.-P. Shih designed a fabricated AET model for implementable device [67]. To offer the biocompatible features, they used cohesive gel as package material. Additionally, to extract energy in the biological environment, Young's modulus of the package material was ensured to be lower than that of muscular tissue. Aluminum was selected due to the light weight for the antenna material. The device (cubic package) was designed with the dimensions of $10 \times 10 \times 5.5\,\mathrm{mm}^3$, with the radius of 5 mm (spherical package). The dominant frequency of 35 kHz was selected to crop the best performance. In a nondelivery mode, the device can recharge a 25 μJ battery by 18.1 min with power range of 1.23 mW. Nevertheless, this paper described top to bottom fabrication process with considerable results.

A relative comparison between ultrasonic and inductive wireless power transfer was presented by Denisov and Yeatman in 2010 [68]. The two techniques were modeled and evaluated by simulation. From the simulation results, it is evident that for smaller distance between transmitter and receiver, inductive wireless power transfer performs 81% efficiency while acoustic energy transfer accounts for only 39%. These efficiencies were counted for larger receiver size; however, for smaller size, ultrasonic WPT draws 8.8% and 0.2% compared to 3.4% and 0.013% efficiencies of inductive wireless power transfer. The latter efficiencies are for a tiny receiver of 10 mm. Herein, in the context of transmitter-receiver distances, ultrasonic wireless power transfer shows better results. However, the results were not confirmed in practical environment.

Ozeri and Shmilovitz showed the feasibility of AET to transmit power over 40 mm range distances [69] with level up to several hundreds of mW. To do so, they designed a circular piezo transducer of 15 mm in diameter and 3 mm in thickness. They set acoustic impedance of 30.7 MRayls, matching layer of $1.82\,\mathrm{g/cm}^3$, and Young's modulus of 23 GPa. From the experiment, 27% power transfer efficiency can be achieved at 673 kHz operating frequency with power density of less than $94\,\mathrm{mW/cm}^2$ in the lossy environment. In addition, receiver power control circuit can deliver 88.5% rectification efficiency.

In the very next paper in the same year, Ozeri et al. proposed the improved version of the aforementioned power transfer model [70]. They tuned the operating frequency to 650 kHz and increased the penetration depth to 50 mm from 40 mm. They kept the power level unchanged but remodeled the device dimension to 15 mm diameter and 5 mm thickness. The tuned arrangements provided better performances. It increased the transfer efficiency to 39.1% with 5 mm distance, while possessing 17.6% at 40 mm distance with 45 mW power level. Additionally, power rectification efficiency was also increased to 89% to the implanted load side.

Transmitting energy through air is one of the highly difficult challenges, mainly, due to the infinite resistance property of the open air. However, it has interesting and constructive applications, specially, in mobile devices charging, reducing the weight of the cable slabs, and, most importantly, in biomedical low power implants. Roes et al. intended to solve this challenge by using ultrasound to convey energy through open air [71]. They modeled the system dimensions and calculated effect of attenuation, total achievable energy transfer efficiency. The investigation suggested that maximum 53% efficiency is achievable with the operated model. However, the measured efficiency is as low as 16%. Again, the achieved output power was within microwatt range, 37 μW, due to the low capability of the applied transducer.

Shigeta et al. presented a fundamental Mason's equivalent circuit based power transfer technique by using a commercial transducer [72]. This work was the extension of the earlier work reported in [73] and intended to use under water conditions. The maximum losses caused by the transducer due to the acoustic reflection between the transducer and water impedance are mismatched. By ANSYS simulator the system model was designed and evaluated. The operating frequency of 1.2 MHz was selected with a matched input impedance of 50 Ω. It is shown from the evaluation that the transmission efficiency can be improved up to 50.4–54.5%. A 4.4 μW ultrasonic based receiver circuit was designed with transmission capability over free air at 43 kHz operating frequency [74]. The operating range of the device was recorded 8.6 m which is maximum so far. 65 nm CMOS technology was used to fabricate the prototype of 0.6 V.

An interesting attempt was proposed by Maleki et al. to operate an implantable microoxygen generator (IMOG) by ultrasonic power [75]. Hence, AET was used as the power source. The proposal was modeled and fabricated accordingly. The authors presented in vitro, ex vivo, and in vivo properties of the proposed system. An ultrasonic transmitter with a dimension of 1.2 mm × 1.3 mm × 8 mm was operated by a sinusoidal wave 50 V_{p-p} produced maximum output current at resonance frequency of the PZT which is 2.3 MHz for in vitro characterization. However, 6 V output can be achieved even within transmitter-receiver distances of 40 cm, while in vivo properties can deliver 20 μA current compared to 300 μA current of ex vivo properties. However, in general, the proposal can meet current generation of 150 μA with overall physical dimension of $12.48\,\mathrm{mm}^3$.

The potential to drive a piezoelectric component by delivering wireless power was investigated by Bhuyan et al. [76]. The proposal was validated by theoretical and experimental evaluation. From the evaluation, it was shown that maximum 2.72 mW power can be achieved with 0.0174% energy conversion efficiency in respect to the input power of 15.58 W and electrode area of 2500 cm^2. The piezoelectric active area of 40 mm^2 was considered with the electrical load of 1365 Ω at 782 kHz operating frequency, whereas the worst case power scenario occurred at approximately 773.2 kHz operating frequency. A similar pattern was proposed by Larson and Towe, but to stimulate the nerve wirelessly [77]. The developed prototype was able to generate current over 1 mA at 1 MHz operating frequency. The prototype was implanted in a test rat body and successfully showed the potential to harvest energy with 10–150 mW/cm^2 energy density.

To get benefited from the combined configuration of inductive and ultrasonic ones, Sanni et al. proposed a multitier interface for deeply implantable devices [78]. The inductive part of the system was designed with a carrier frequency of 2 MHz along with a driver and envelope detector circuit. The piezo subsystem contains a driver circuit, power, and signal conditioner circuits. This model can transfer 5 W power within 10 mm distances with an efficiency of 83%. However, for liquid conditions, the model can transfer 29 μW power within 70 mm distances with 1% efficiency.

In the very next year, Ashdown et al. introduced an ultrasonic based full duplex communication through wall [79, 80]. A 25.4 mm diameter piezo transducer was used with resonant frequency of 1 MHz. In the context of power delivery, the results did not confirm any conclusion rather than focusing on the data transmission. Later, Kural et al. demonstrated an ultrasonic based power delivery approach based on guided piezo plate waves [81]. This proposal can transmit 12.7 mW power through a 1.5 mm thick aluminum wall within 54 cm distance range which is considered to be a long distance in this particular projection. This long range is possible due to the 2D (guided) instead of 3D (omni) wave propagation. The optimum operating frequency was set to 35 kHz for 20 V_{pp} input while the transducer length was varied from 40 to 80 mm. However, the system efficiency lies within 7.5% against 170 mW input power which can be improved by using higher driving voltage. This work was the extension of the earlier reported work of guided ultrasonic wave [82].

Leadbetter et al. proposed a power and signal delivery system for implanted hearing aids [83]. 1-3 composite formulation was used to develop the proposal composite of lead magnesium niobate-lead titanate of dimension 1.2 mm × 5 mm [84]. The model was tested in water environment with a loaded transducer of 950 Ω under operating frequency of 1.07 MHz. 60% better efficiency was offered by this model which accounts for power transfer efficiency of 45%. In the same proceedings, a biocompatible transducer was introduced by Lee et al. using ultrasonic resonance method [85]. The manufactured transducer was of 50 mm diameter. The experiment was conducted under two types of medium, water and tissue with penetration depth of 20 mm to 50 mm. In water medium, the transducer performed with 55% efficiency at 243 kHz operating frequency within a 10 mm distance which drops down to 35% at 100 mm distance. However, in tissue environment at 290 kHz driving frequency, the proposal carried 21% and 6.5% efficiencies within 23 mm and 34 mm skin depth, respectively. The output power of 2.6 mW was acquired with 18% efficiency in respect to 250 kHz frequency.

In recent times, specifically from 2014, research in acoustic energy harvesting technology has experienced significant advancements. An ultrasonic based approach was modeled by Denisov and Yeatman to harvest energy directly from ultrasound rather than using a piezoelectric mechanism [86]. The key to do that is using micromechanical settings of a receiving membrane, coupled to a discrete oscillator. The membrane occupied area of 0.5 mm^2, thickness of 15 μm, and height less than 55 μm and operated by an external propagated wave of 200 kHz. The device was tested under separations of 0–30 mm, driving voltage of 10–20 V_{pp}, and vibration amplitude of 9.6–9.9 μm and the mechanical amplification is in the range of 240–250. However, the work was an extension of their earlier work [68].

Kim et al. investigated an electromechanical interrogation scheme to be used in implantable devices [87]. To allow the usage, a pressure sensitive inductor coil was used in the fabricated prototype and tested under in vitro and in vivo circumstances. The dimension of the prototype was set to 40 mm length and 8 mm diameter. The active resonant frequency of >350 Hz was considered for usable transmission within 15 cm separation. In addition, the transducer consumed 11.7 W of power to generate 1 $\mu W/mm^2$ output power. However, 16 μW can be generated using 40 mm^2 active piezo area with a maximum efficiency of 1.4×10^{-7}. At the same time, Leung et al. developed a prototype based om AET system specifically for conductive media [88]. This prototype was able to transfer 62 W power through a 70 mm thick aluminum block with 74% efficiency, when operated at the resonant frequency of 28 kHz. However, the marginal efficiency lies within 85% to 63%, depending on the pickup unit (combination of transducer and rectifier circuit) usage.

Mazzilli et al. acquired 105 mm separation distances for transmitting power wirelessly with 2.3% system efficiency without the load application [89]. However, the efficiency dropped down to 1.6% when a phantom model was attached. The active transducer area was defined as 30 mm × 96 mm for transmitter and 5 mm × 10 mm for receiver and operated with 1 MHz operating frequency. Besides, Shahab et al. designed an energy harvesting model to produce acoustic energy [90]. A spherical source was used to propagate wave energy which was collected by a piezoelectric bar. The dimension of the bar was of 6 mm diameter, operated in 33-*mode* of piezoelectricity and receiver and transmitter separation of 20 mm. The open circuit resonance frequency was 47.7 kHz whereas short circuit possessed 31.4 kHz.

In the same year, 2014, Lee et al. demonstrated an ultrasonic WPT by using piezoelectric composite transducer [91]. The system was intended to be used for powering brain-machine interface system. The resonance frequency was set to 250 kHz for both transmitter and receiver, whereas the measured one was about 280 kHz. From the experiment, it was shown that 55% and 50% efficiencies are achievable within 1 mm and 20 mm distances, respectively, in water medium. In case of animal tissue, the applied input power was recorded as 15.5 mW and the achieved output power was 2.6 mW in response. Hence, the overall accomplished system efficiency was about 18% within 18 mm separation distances. Again, 85 mm separation distances were achieved by Shmilovitz et al. for a noninvasive process [92].

Feng et al. introduced a complete system to harvest passive ultrasonic energy through conductive environment [93]. The prototype of the system was examined by System-on-Chip (SoC) implementation in 0.5 μm CMOS technology. The SoC die area was 3 mm × 3 mm. The prototype transducer and system occupied 380 mm^2 and 10 mm^2 area, respectively. This device was able to transfer energy through 2 mm thick aluminum wall using 13.56 MHz operating frequency while consuming 22.3 μW input energy. At the same time, Fang et al. investigated the feasibility of delivering wireless energy to an implanted device with the receiver separation of more than 10 cm away from the tissue surface [94]. The use of a commercial off-the-shelf (COTS) which is a 3.5 MHz diagnostic ultrasound technology was encouraged here. The transducer of 0.6 mm thickness, area of 1.1 cm^2, and operating frequency of 3.4 MHz was set as device dimension. From the interrogation results, it is seen that the highest recorded voltage was 5.7 V found within 5 mm separation with a load of 10 Ω. However, received power reduced to less than 1 μW when the separation of 100 mm was applied. The omnidirectional powering by ultrasonic wave was focused by Song et al. [95]. Frequencies of 1.15 and 2.3 MHz were selected to operate the transducer with peak acoustic intensity of 720 mW/cm^2. Different receiver sizes employ distinguished received power. 2.48, 8.7, and 12.0 mW of electrical power were achieved from $1 \times 5 \times 1\,mm^3$, $2 \times 2 \times 2\,mm^3$, and $2 \times 4 \times 2\,mm^3$ sized receivers, with efficiencies of 0.4%, 1.7%, and 2.7%, respectively, within 20 cm distance.

Lee et al. designed ultrasonic transmitter and receiver with the size of 30 mm diameter and 3 mm height [96]. Experimental efficiency of 22.6% was achieved through the 10 mm skin tissue with 150 mW of transferable power against a load of 60 Ω. The maximum efficiency was available at the operating frequency of 1.05 MHz where 1 MHz was the resonance frequency. A 60% efficiency is acquired by Leung and Hu by simulation modeling [97]. The model successfully demonstrated 2 W of power transfer through a 5 mm thick metal wall, using a 28 kHz piezoelectric transducers to employ the conversion. Shahab et al. presented a spherical acoustic approach to model a free-free transducer [98, 99]. The analytical model can transmit power to 30.2 mm separation distances. The peak power of 0.0294 $mW/(cm^3/s^2)$ and 0.0314 $mW/(cm^3/s^2)$ is recorded at 75 kHz and 79 kHz against the applied load of 150 kΩ and 1.5 MΩ.

Recently, a hybrid implantable ultrasonic based transducer is reported by Charthad et al. [100]. They developed a prototype of 4 mm × 7.8 mm package size including a 2.5 mm antenna. The proposal can support 100 μW of load power while consuming 34.1% power. As a very latest work, a complex microelectromechanical system is proposed by Jang et al. for implant applications based on acoustic approach [101]. In another recent work, 33% of overall system performance is found from an ultrasonic WPT system [102].

The findings from the aforesaid development report are summarized in Table 1. In between 1985 and 2015 publication year, the articles are reviewed. Several research databases are used to find the reviewed papers on the specific projection. Namely, IEEE explorer, Sciencedirect, IOP, and SPIE are used most frequently. For rational comparison, several parameters are taken into account. Among them, efficiency, power level, and device area are considered as mostly imperative.

4. Discussion

From the aforementioned empirical review, it is clear that the main application of the AET is in powering wall-through systems and implants (implantable biomedical devices for better clarification). For wall-through systems, the maximum transferred power is found to be 1.068 kW which is practically capable of powering ten 100 W electric bulbs [56]. Surprisingly, the maximum transfer efficiency of 88% is also achieved by this work. However, the separation distance is quite small which is 5 mm. Nevertheless, this work already became the threshold for benchmarking further works. In the context of transmitter-receiver distance, the maximum value obtained is 8.6 m with 4.4 μW of delivered power [74]. In addition, 37 μW power is obtained through 1 m separation with 53% efficiency [71]. However, the value stands for air-through instead of metal-through power transfer which is 70 mm in maximum. Titanium and aluminum are the preferred material to be used as the separation wall.

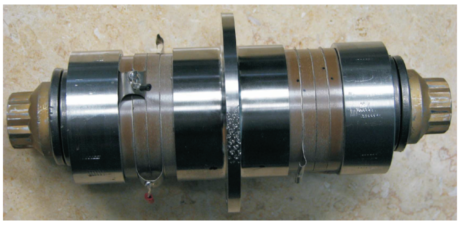
Implantable biomedical devices usually require low power to function, mainly lying within the mW power range. Hence, most of the researches are focused on this power limit. However, maximum transferred 5.4 W power is found in this projection with 36% efficiency. As the required active area to propagate energy is small, therefore, the separation distance is relatively small, and maximum 400 mm is found as separation distance. The efficiency of the proposals can reach up to 50–81% for theoretical designs but, however, dropped down to 45% for practical implementations.

Device size is a crucial parameter to satisfy for both transfers: wall-through and implants. However, device size can be compromised for the first one and thus can be bulky if necessary. Yet, smaller size is much preferred. For implants, it is necessary to be a small device and as tiny as possible for receiver end. So far, less than 10 mm^2 is a preferable size for the implanted receiver end. Beside the size, the vibration mode of the piezo plate is also important to determine. Thickness vibration is the dominant one so far for the vibration mode. Hence, it can be applied for several criteria, based on power demand. However, several attempts of radical vibration mode are applied lately as well.

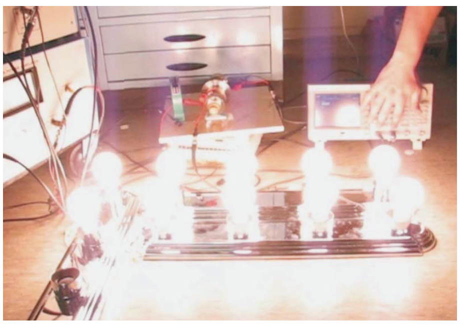
Different range of frequencies are used to design the previously proposed AETs based on the type of applications. High efficiencies are usually used for wall-through transfers. Usually it takes the range of tens of kHz to 13 MHz. Naturally, intermediate frequencies are used for implant systems. However, unlikely, one attempt of power transfer to implants

Table 1: Deployment of the existing AET systems.

References	Year	Frequency	Vibration mode	Active range	Efficiency%	Power level	Device area	Application
Cochran et al. [43]	1985	2.25 MHz	Not specified	Not specified	Not specified	60 mW	$36 \times 6 \times 1\,mm^3$	Implants
Cochran et al. [44]	1988	2.25 MHz	Not specified	Not specified	Not specified	40 μW–3.2 W	$5 \times 5 \times 0.9\,mm^3$	Implants
Kawanabe et al. [48]	2001	Not specified	Not specified	30 mm	20	Not specified	Not specified	Implants
Suzuki et al. [49]	2002	1 MHz	Not specified	40 mm	20	2.1 W	$30\,mm^2$	Implants
Suzuki et al. [50]	2003	100 kHz	Thickness	Not specified	36	5.4 W	$87 \times 134 \times 20\,mm^3$	Implants
Hu et al. [51]	2003	Not specified	Thickness	Not specified	Not specified	Not specified	Not specified	Wall-through
Sherrit et al. [53]	2006	Not specified	Thickness	2.5 mm	53	100 W	Not specified	Wall-through
Kluge et al. [54]	2007	741 kHz	Thickness	5 mm	80	30 mW	Not specified	Wall-through
Arra et al. [58]	2007	840 kHz	Not specified	5–105 mm	21–35	30–87 mW	Not specified	Implants
Bao et al. [55]	2007	755 kHz	Not specified	3.4 mm (Ti)	88	100 W	Not specified	Wall-through
Bao et al. [57]	2008	24.5 kHz	Not specified	4.76 mm (Ti)	87-88	1 kW	Not specified	Wall-through
Sherrit et al. [56]	2008	Not specified	Not specified	5 mm (Ti)	87-88	1.068 kW	Not specified	Wall-through
Shigeta et al. [73]	2009	4.2/3.15 MHz	Thickness	70 mm	0.35	0.8 mW	Not specified	Implants
P.-J. Shih and W.-P. Shih [67]	2010	35 kHz	Not specified	30–70 mm	Not specified	1.23 mW	$10 \times 10 \times 5.5\,mm^3$	Implants
Denisov and Yeatman [68]	2010	>1 MHz	Not specified	10 mm	81, 39	Not specified	Not specified	Implants
Ozeri and Shmilovitz [69]	2010	673 kHz	Thickness	40 mm	27	1 W	$9.75\,mm^2$	Implants
Ozeri et al. [70]	2010	650 kHz	Thickness	5 mm	39.1	100 mW	$137.44\,mm^2$	Implants
Mazzilli et al. [126]	2010	1 MHz	Thickness	50 mm	Not specified	≈3 mW	$30 \times 1.55\,mm^2$	Implants
Roes et al. [71]	2011	20.46 kHz	Not specified	1 m	53	37 μW	Not specified	Air-through
Shigeta et al. [72]	2011	1.2 MHz	Thickness	Not specified	50	Not specified	$41.36\,mm^2$	Implants
Maleki et al. [75]	2011	2.3 MHz	Thickness	30–400 mm	Not specified	≈300 μW	$1.2 \times 1.3 \times 8\,mm^3$	Implants
Bhuyan et al. [76]	2011	782 kHz	Thickness	40 mm	0.0174	2.72 mW	$40\,mm^2$	Not specified
Larson and Towe [77]	2011	1 MHz	Thickness	120 mm	Not specified	23 mW	$41.36\,mm^2$	Implants
Sanni et al. [78]	2012	200 kHz	Radical	70 mm	1	8 mW	Not specified	Implants
Yadav et al. [74]	2013	43 kHz	Not specified	8.6 m	Not specified	4.4 μW	$1.2\,mm^2$	External
Sanni and Vilches [107]	2013	200 kHz	Radical	80 mm	0.2	976 μW	$10\,mm^2$	Implants
Kural et al. [81]	2013	35 kHz	Not specified	540 mm (Al)	7.5	12.7 mW	$46 \times 21 \times 0.25$ mm	Wall-through
Leadbetter et al. [83]	2013	1.07 MHz	Not specified	Not specified	45	Not specified	$12 \times 5\,mm^2$	Implants
Lee et al. [85]	2013	250 kHz	Not specified	23 mm	21	≈2.6 mW	Not specified	Implants
Kim et al. [87]	2014	>350 Hz	Not specified	150 mm	10^{-7}	16 μW	$40 \times 8\,mm^2$	Implants
Leung et al. [88]	2014	28 kHz	Not specified	70 mm (Al)	74	62 W	Not specified	Wall-through
Mazzilli et al. [89]	2014	1 MHz	Thickness	105 mm	1.6	28 mW	$5 \times 10\,mm^2$	Implants
Lee et al. [91]	2014	280 kHz	Not specified	18 mm	18	2.6 mW	$122.5\,mm^2$	Implants
Shmilovitz et al. [92]	2014	720 kHz	Thickness	85 mm	Not specified	35 mW	$15 \times 3\,mm^2$	Implants
Feng et al. [93]	2015	13.56 MHz	Not specified	2 mm (Al)	Not specified	22.3 mW	$3 \times 3\,mm^2$	Wall-through
Fang et al. [94]	2015	3.4 MHz	Not specified	100 mm	Not specified	1 μW	$1.1\,cm^2$	Implants
Song et al. [95]	2015	1.15–2.3 MHz	Not specified	200 mm	2.7	12 mW	$2 \times 4 \times 2\,mm^3$	Implants
Lee et al. [96]	2015	1.05 MHz	Not specified	10 mm	22.6	150 mW	$30 \times 3\,mm^2$	Implants
Leung and Hu [97]	2015	28 kHz	Not specified	5 mm	60	2 W	$30 \times 3\,mm^2$	Others
Shahab et al. [98]	2015	79 kHz	Not specified	30.2 mm	Not specified	Not specified	Not specified	Ambient
Charthad et al. [100]	2015	30 MHz	Not specified	<100 mm	Not specified	100 μW	$4 \times 7.8\,mm^2$	Implants

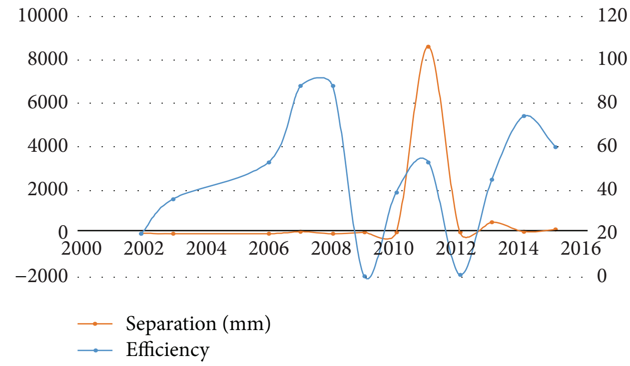


(a) 1 kW power transfer through metal wall [56]. Reproduced with author permission, ©NASA 2008. All rights reserved

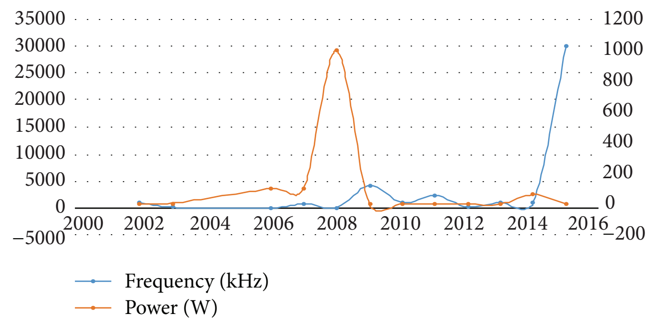


(b) 88% efficiency is achieved, transmitting 1 kW of power [57]. Reproduced with permission, ©SPIE 2008. All rights reserved

Figure 2: Implemented wall-through AETs. (a) 1 kW energy through metal wall; (b) power delivery setup.



(a) Efficiency versus separation distance



(b) Frequency versus received power

Figure 3: Advancements in AET in the context of efficiency, separation distances, frequency, and power in respect to years.

has used maximum 30 MHz frequency. Nevertheless, the preferable frequency range for implants is 1.3 MHz and below. The details of the review are presented in Table 1. Additionally, some implemented AETs are illustrated in Figure 2. The findings from the review can be summarized in brief in Table 2 while a comparison among three WPTs is presented in Table 3.

In Figure 3, the advancements of the AETs are presented. Efficiency, produced power, and separation distance are considered as indicating parameters in respect to years. To simplify the presentation, the values are counted according to the years while the power, separation distances, and efficiencies are used accordingly. From the figure, it is clear that high frequencies cannot guarantee high efficiency or high separation distances. In fact, the maximum 30 MHz frequency offered 60% efficiency with 2 W power in the receiver end. It is interesting that the maximum efficiency of 88% is found for both 24.5 kHz and 840 kHz frequencies. These two frequencies also produced maximum power of 1 kW and 100 W. The frequency trend in Figure 3(b) suggests that less than 1 MHz is the preferable frequency range which possesses better performances. In addition, Figure 4 confirms that the *less than* MHz frequency range is highly suitable for better efficiency and power.

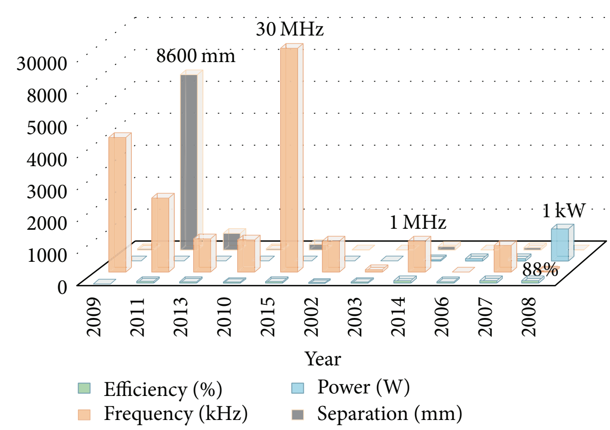


Figure 4: Overall summary of the AET evaluation (values are taken from lower to higher power accordingly).

5. Existing Challenges

AET, as a new technology, has a number of issues to be addressed. According to the previous discussion on this projection, the existing challenges in the AETs can be defined as follows.

5.1. Reflections. A propagated sound wave is significantly affected by the reflection and, hence, results in the spatial resonance and causes energy loss. This incident is particularly important to be considered for AET, as it limits the optimal location of the transmitter and receiver. Therefore, the optimal configuration of the transducer needs to be chosen

Table 2: Summary of the review.

AET type	Frequency (min–max)	Active range (max)	Efficiency % (max)	Power level (max)
Wall-through	24.5 kHz–13.56 MHz	1 m	88	1.068 kW
Implants	35 kHz–30 MHz	400 mm	45	5.4 W
Others	20.46 kHz–782 kHz	8.6 m	20	2 W

Table 3: Comparison of WPTs.

WPT type	Frequency (min–max)	Active range (max)	Efficiency % (max)	Power level (max)
Acoustic	20.46 kHz–30 MHz	8.6 m	88	1.068 kW
Inductive	10.2 kHz–27 MHz	7 m	91	30 kW
Capacitive	20 kHz–15 MHz	1 mm	94.3	1.03 kW

carefully to reduce the effect of diffraction, attenuation, and reflection losses.

5.2. Efficiency. As mentioned, for wall-through power transfer, the efficiency reached 88%. However, for implantable devices it still lies within 45%. Again, the generated value of current in the receiver side is very low compared to voltage generation. Hence, a converter can utilize the total power generation. However, this step offers additional circuitry and increased size. Nevertheless, guided sound waves can increase the efficiency which also limits the position of the transmitter and receiver.

5.3. Heating. Generated heat in the devices is another concern to aid as the long term effect may be not favorable. However, for low power application the heat generation lies within the tolerable limit.

5.4. Effects of Prolonged Exposure. One additional effect of AET that needs to be studied carefully is the possible effect of prolong exposure to ultrasound. So far, there is no clear evidence of effect on this particular projection [103–105]. However, it is predicted that the long term exposure to the acoustic waves may cause significant damage to the human tissue [106]. The cavitation and thermal effects influence this damage. Specifically, the cavitation effect affects the skin cells. Thermal effect, conversely, causes temperature increment near or at the bones. Directed sound beam is the condition for both cases. Therefore to avoid the possible consequences, it is recommended to follow the safety regulatory instructions from ultrasound diagnostic devices which are the closest to this application. According to the instructions, the safety can be generalized by mechanical index (MI) and thermal index (TI) which imply acoustic intensity lower than 94 mW/cm^2 (in the tissue) and limit operating frequency to 100 kHz [92]. However, for generalization no clear instructions are available so far.

There are several papers which have discussed challenges of the AET considering different applications [50, 107–125]. However, again, these works did not claim any clear and precise conclusion, especially, for the prolonged exposure of the devices.

6. Conclusions

The trade-off between safety considerations and performance of the WPTs limits the boundary of the WPT topologies. Hence, it became the focus point of current research trend in this particular area. At this point of consideration, AET can be a strong alternative for low power and small gap applications. Based on the previous literatures, AET can perform far better and safer when the generation of the electromagnetic field is not allowed. In addition, the device size is smaller compared to the other WPTs, in the context of power and separation distances. Interestingly, AET has already performed above 1 kW power range and achieved 88% efficiency and for deep tissue implants, it can deliver power to 400 mm depth which is sufficient. However, still the received power can be improved, which in turn increases the efficiency and reliability of the device.

Compared to inductive or even capacitive WPT, AET is still in very early stage of deployment. However, AET can be considered highly potential for the future generation WPTs, as it draws the industrial consideration in recent times, specifically, in the biomedical applications for the safety features, as implantable devices or biocompatible devices or even for body sensor networks.

The reviews of the previously proposed AETs are presented in this paper. To propose an acoustic based novel power delivering system is the future agenda of this work.

Competing Interests

The authors declare that there is no competing interests regarding the publication of this paper.

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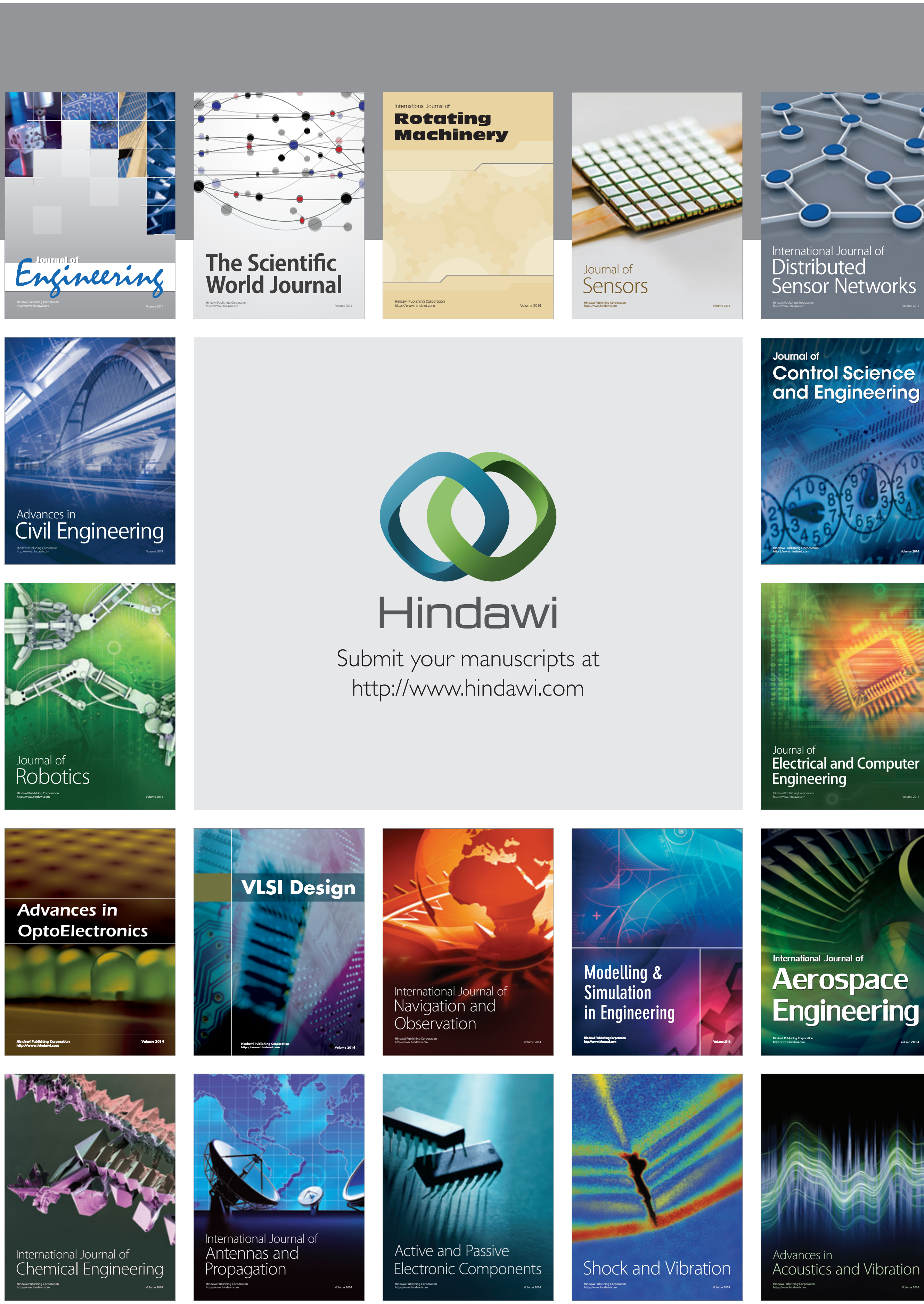
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