HYBRID ENERGY HARVESTING OF PIEZOELECTRIC AND ELECTROMAGNETIC USING VIBRATION EXCITATION OF BIMORPH CANTILEVER BEAM

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Penuaian tenaga adalah teknik untuk mengumpul tenaga dari kawasan persekitaran dan bertukar menjadi tenaga elektrik. Sebelum ini, perkembangan peralatan elektronik yang berkuasa rendah, hanya bergantung pada bateri sebagai sumber kuasa, namun kuasa bateri boleh mengurangkan kemampuan jangka hayat dalam pengunaan sesuatu peralatan. Oleh itu, kebanyakkan penyelidik mendapati bahawa kaedah penuaian tenaga boleh meningkatkan pengeluaran kuasa bergantung kepada variasi dimensi geometri dan bahan yang digunakan. Objektif utama adalah untuk menghasilkan penuaian tenaga daripada piezoelektrik dan elektromagnetik berdasarkan aplikasi getaran. Dalam kajian ini, pelaksanaan penuaian tenaga dari dua teknologi dianalisis untuk membentuk sistem penuaian tenaga hibrid. Kedua-dua teknologi yang digabungkan dalam sistem ini adalah berkaitan dengan teknologi penuaian tenaga piezoelektrik serta elektromagnet. Model unsur terhingga (FEA) telah dijalankan dengan menggunakan perisian Ansys sebagai alat bantuan untuk membantu menyelesaikan analisis harmonik dan menganalisis rasuk julur piezoelektrik pada dimensi yang pertama dan magnet dianalisis menggunakan analisis electromagnetik serta rasuk optima ditentukan dengan menggunakan analisis penyelesaian pengoptimuman permukaan. Kedua-dua pengeluaran kuasa yang dijana daripada magnet dan piezoelektrik ini kemudiannya digabungkan untuk membentuk satu unit tenaga. Litar penuaian kuasa telah dihasilkan untuk menyimpan pengeluaran kuasa dan membandingkan pengeluaran kuasa arus ulang alik (AC) dan arus terus (DC) menggunakan ujikaji goncangan. Oleh itu, ujikaji goncangan digunakan untuk membuktikan keputusan yang diperolehi dalam analisi dengan eksperimen. Dalam eksperimen, alat pengesan jarak diaplikasi dalam ujikaji ini untuk mengesan pesongan rasuk julur piezoelektrik. Hasil keputusan rasuk pertama mendapati ralat sebanyak 8 peratus diantara voltan yang mengunakan arus ulang alik dengan arus terus. Rasuk julur optima telah dibuktikan bahawa voltan mempunyai ralat pada 3.32 peratus manakala kuasa pengeluaran mendapati dimana ralat peratusan adalah pada 9.74 peratus diantara analisis dan eksperimen. Keputusan Ketumpatan Kuasa Normal (NPD) pada rasuk julur optima iaitu 13.927 kg / m^3 adalah setanding dengan kajian-kajian lain yang dapat diaplikasi dalam sistem penuaian tenaga untuk aplikasi getaran. Selain itu, pembaikan boleh dibuat untuk mengurangkan saiz penuai ini dari 36.5 mm x 19.05 mm hingga 35 mm x 10.24 mm sambil mengekalkan kekerapan semula jadi yang munasabah dan keluaran kuasa. Walau bagaimanapun, rasuk optimum telah mengurangkan saiz dan bukannya mempunyai ketumpatan kuasa normal yang lebih tinggi telah dihasilkan daripada kajian ini. Hasil kajian ini dapat digunakan dengan berkesan untuk meningkatkan prestasi jangka hayat yang lebih baik dan fungsi keupayaan untuk menghasilkan sumber kuasa dari arus ulang alik (AC) dan arus terus (DC).

ABSTRACT

Harvesting energy is the technique for accumulating energy from the surrounding environment and transforming it into electricity. Instead, the evolution of low power electronics, dependencies on battery as a power source that can decrease the lifespan and function capability. Thus, many researchers are finding that energy harvesting method can increase the power output depending on the geometry and material applied. The main objective is to develop energy harvesting of a piezoelectric and electromagnetic system based on vibration excitation. In this project, the implementation of harvesting energy from two technologies to form a hybrid energy harvester system was analyzed**.** These two technologies involve the piezoelectric harvesting energy and the electromagnetic harvesting energy. A finite element model was developed using the Ansys software with the harmonic analysis solver for initial beam and response surface optimization for optimum beam. Both power output generated by the electromagnetic and the piezoelectric is then combined to form one unit of energy. The power harvesting circuit was developed to store the power output instead to use the battery as power source and compared the AC and DC power output using a shaker. Thus, shaker was used as a modal testing to validate the analytical result. Further, it was found that the initial beam result of analytical was validated with experiment result with 8% error for voltage and the power harvesting of AC source was highest compare to DC source. Others, the optimal beam was validated that voltage has 3.32% error while power has 10.86% error between analytical and experiment results. Normalized Power Density (NPD) results of the optimal beam at 13.927 kgs/m^3 are comparable with other literature also can be used in energy harvesting system for vibration application. Additionally, the efforts can be made towards decreasing the size of this harvester from 36.5 mm x 19.05 mm to 35 mm x 10.24 mm while still maintaining a interested resonant frequency and power output. Nevertheless, the optimum beam has minimized size instead of has higher normalized power density was generated of this project. The outcome of this work could be effectively used to improve the better lifespan and function capability performance for generating AC-DC sources.

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ε	Induced current
N	Number of turns
Φ	Magnetic flux
p_ρ	Power density
F	Frequency
A	Input acceleration
R	Load resistance
d	Amplitude
P	Power
V	Voltage
y(t)	Excitation vibration
ω_n	Natural frequency
k	Equivalent stiffness
k_m	Mechanical stiffness
k_p	Electrical stiffness (piezoelectric effect)
ξ_m	Mechanical structural damping ratio
ξ_p	Piezoelectric damping ratio
ξ_{em}	Electromagnetic damping ratio
c	Damping coefficient
c_m	Mechanical damping
c_p	Piezoelectric damping
c_{em}	Electromagnetic damping
σ	Mechanical stress
Y	Modulus elasticity
D	Electric displacement
d	Piezoelectric strain coefficient
E	Electric field
ω	Driving frequency
Yc	Young modulus of piezoelectric material
tc	Thickness of piezoelectric material
I	Current

C	Capacitor reactance
δ	mechanical strain

LIST OF ABBREVIATIONS

AC	Alternating current
DC	Direct current
FEA	Finite element analysis
EMF	Electromagnetic force
EH	Energy harvesting
PZT	lead zirconate titanate
PEH	Piezoelectric energy harvester
EM	Electromagnetic
MEMs	MicroElectroMechanical system
PCB	Printed Circuit Board
NdFeB	Neodymium Iron Boron
SDOF	Single degree of freedom
DOF	Degree of freedom
CAD	Computer aided design
RSO	Response surface optimization
DOE	Design of experimental
DAQ	Data acquisition system
FRF	Frequency response function
FFT	Fast Fourier transform
NPD	Normalized power density
HEH	Hybrid energy harvesting
MOGA	Multi objective genetic algorithm

REFERENCES

Ali, N. M., Mustapha, A. A., and Leong, K. S. (2015). Investigation of hybrid energy harvesting circuits using piezoelectric and electromagnetic mechanisms. *Proceeding IEEE Student Conference on Research and Development, SCOReD*, (c), 564–568.

Alesendro Massaro. (2015). Book Innovative Materials and Systems for Energy Harvesting Applications (VEH).

Ajitsaria, J., Choe, S. Y., Shen, D. and Kim, D. J. (2007). Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation. *Smart Materials and Structures, 16* (2), 447-454.

Ansari, M., and Karami, M. (2015). Energy Harvesting from Controlled Buckling of a Horizontal Piezoelectric Beam. *Smart Materials and Structures*, *24* (11), 964-1726

Anton, S., and Sodano, H. (2007). A review of power harvesting using piezoelectric materials (2003–2006). *Smart Materials and Structures*, *16* (3), 964-1726.

Amirtharajah, R. and Chandrakasan, A.P. (1998). Self-powered signal processing using vibration-based power generation. *IEEE Journal of Solid-State*, *33* (5).

Barbara T. F. (2015). Monthly Energy Review. U.S. Energy Information Administration Office of Energy Statistics U.S. Department of Energy Washington, U.S.

Beeby, S., Tudor, M., and White, N. (2006). Energy harvesting vibration sources for microsystems applications. *Measurement Science and Technology*, *17* (12), 957-1726.

Beeby, S.P., Torah, R.N., Tudor, M.J., Glynne-Jones, P., O'Donnell, T., Saha, C.R. and Roy, S., (2007). A micro electromagnetic generator for vibration energy harvesting. *Journal of Micromechanics and Micro Engineering*, *17* (7), 960-1317.

Benasciutti, D., Moro, L., Zelenika, S., and Brusa, E. (2010). Vibration energy scavenging via piezoelectric bimorphs of optimized shapes. *Microsystem Technologies*, *16* (5), 657–668.

Cepnik, C., Lausecker, R., and Wallrabe, U. (2013). Review of electrodynamic energy harvesters-a classification approach. *Micromachines*, *4* (2), 168-196.

Cepnik, C., Radler, O., Rosenbaum, S., Ströhla, T., and Wallrabe, U. (2011). Sensors and Actuators A: Physical Effective optimization of electromagnetic energy harvesters through direct computation of the electromagnetic coupling. *Sensors & Actuators: A. Physical*, *167* (2), 416–421.

Connolly D., Lund H., Mathiesen B.V., Leahy M. (2011). “The first step towards a 100% renewable energy-system for Ireland,” *Application Energy*, 88, 502-507.

Challa, V.R., Prasad, M.G., Shi, Y. and Fisher, F.T., (2008). A vibration energy harvesting device with bidirectional resonance frequency tunability. *Smart Materials and Structures*, *17* (1), 015-035.

Challa, V., and Prasad, M. (2008). Evaluation of coupled piezoelectric and electromagnetic technique for vibration energy harvesting. *The International Society for Optical Engineering, 12* (7), 277-786.

Challa, V. R., Prasad, M. G., and Fisher, F. T. (2009). A coupled piezoelectric–electromagnetic energy harvesting technique for achieving increased power output through damping matching. *Smart Materials and Structures*, *18* (9), 950-979.

Chalasani, S., and Conrad, J. M. (2008). A survey of energy harvesting sources for embedded systems. *Conference Proceedings of IEEE South and East*, Charlotte, 442–447.

Chen, X., and Liu, Y. (2015). Finite Element Modelling and Stimulation with ANSYS Workbench, CRC Press, Taylor & Francis Group, Boca Raton, London, New York.

Chen, S., and Hu, J. (2011). Experimental study of a hybrid vibration energy harvesting mechanism. *Symposium Piezoelectricity, Acoustic Waves and Device Applications* (SPAWDA), Dec 9-11, Nanjing, China.

Ching, N.N., Wong, H.Y., Li, W.J., Leong, P.H. and Wen, Z., (2001). A laser micromachined vibrational to electrical power transducer for wireless sensing systems. *The 11th International Conference on Solid-Sate Sensors and Actuator*, June 10-14, Munich, Germany.

Cho, K. H., Park, H. Y., Heo, J. S., and Priya, S. (2014). Structure-performance relationships for cantilever-type piezoelectric energy harvesters. *Journal of Applied Physics*, *115* (20), 4108-4115.

Dahari, Z., Chye, W. C., Sidek, O., and Miskam, M. A. (2011). A Comparative Study of Electromagnetic Generator via Finite Element Element Analysis. *International Conference on Electrical Engineering and Informatics*, July 17-19, Bandung, Indonesia.

Dayal, R., Member, S., Dwari, S., Parsa, L., and Member, S. (2011). A New Design for Vibration-Based Electromagnetic Energy Harvesting Systems Using Coil Inductance of Microgenerator. *IEEE Transactions on Industry Applications*, *47* (2), 820–830.

Duffy, M. and Carroll, D., (2004). Electromagnetic generators for power harvesting. *35th Annual IEEE Power Electronics Specialists Conference*, Aachen, Germany.

Eggborn T. (2003). Analytical models to predict power harvesting with piezoelectric materials. Master Thesis, Virginia Polytechnic Institute and State University, USA.

El-Hami, M., Glynne-Jones, P., White, N.M., Hill, M., Beeby, S., James, E., Brown, A.D. and Ross, J.N., (2001). Design and fabrication of a new vibration-based electromechanical power generator. *Journal of Sensors Actuators and Physical, 92* (1), 335-342.

Emilio, M. D. P. (2017). The fundamentals of energy harvesting. *Journal of Microelectronic Circuit Design for Energy Harvesting Systems*, 11-20.

Erturk, A., and Inman, D. (2009). An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations. *Smart Materials and Structures*, *18* (2), 964-1726.

Fang H-B, Liu J-Q, Xu Z-Y, Dong L, Wang L, Chen D. (2006). Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting. *Journal of Microelectronics, 37* (11), 1280–1284.

Fundamental ambient energy transducers energy harvesting systems. (online). https://www.ecnmag.com/article/fundamentals-ambient-energy-transducers-energy-harvesting-systems/ (6 December 2016).

Glynne-Jones P, Tudor M.J, Beeby S.P, White N.M. (2004). An electromagnetic, vibration powered generator for intelligent sensor systems. *Journal of Sensor Actuators and Physics*, *110* (1–3), 344–353.

Guo, D. (2016). Piezoelectric Energy Harvester Array with Magnetic Tip Mass, *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, 1–6.

Hassan, M.F., Yusoff, A.R., Mansor, M.H. and Kar, M.T.C., (2013). Parametric study of an electromagnetic energy harvester. *Journal of Applied Mechanics and Materials, 47* (1), 113-118.

Hadas, Z., Kluge, M., Singule, V., and Ondrusek, C. (2007). Electromagnetic vibration power generator. *International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, SDEMPED,* Munich, Germany, 451-455.

Harne R. L. and Wang K. W. (2013). A review of the recent research on vibration energy harvesting via bistable systems. *Journal of Smart Material Structure*, *22,* 023001.

Ibrahim, M. (2014). Design, Modelling and Fabrication of a Hybrid Energy Harvester. Master Thesis, University of Waterloo, Canada.

Ikeda, T. (1996). Fundamentals of piezoelectricity. Oxford University Press, *Oxford Science Publications*.

Jacobson, M. Z. and M. A. Delucchi. (2011). Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials. *International Symposium on Micro-Mechanical Engineering (ISMME),* Japan, *3* (9), 1154-1169.

Jeon, Y.B., Sood R., Jeong J.h., Kim S.G. (2005). MEMS power generator with transverse mode thin film PZT. *Journal of Sensor Actuators and Physics*, *122* (1), 16–22.

Jenden, J., Lloyd Ellen., Stenhouse, K., Yyelland, B., Donev, J., (2018). Energy Education of Renewable and Sustainable. University of Calgary, Canada.

Jiang, S., Li, X., Guo, S., Hu, Y., Yang, J., and Jiang, Q. (2005). Performance of a piezoelectric bimorph for scavenging vibration energy. *Smart Materials and Structures*, *14* (4), 769-774.

Karami, M.A., (2012). Micro-scale and nonlinear vibrational energy harvesting PhD Thesis,Virginia Polytechnic Institute and State University, USA.

Karekezi, S., Kithyoma, W., and Initiative, E. (2003). Renewable energy development. *Workshop on African Energy Experts on Operationalizing the NEPAD Energy Initiative,* June 2-4, Novotel, Dakar, Senegal.

Khaligh, A., Zeng, P., and Zheng, C. (2010). Kinetic energy harvesting using piezoelectric and electromagnetic technologies-state of the art. IEEE *Transactions on Industrial Electronics*, *57* (3), 850-860.

Kim, H. S., Kim, J. H., and Kim, J. (2011). A review of piezoelectric energy harvesting based on vibration. *International Journal of Precision Engineering and Manufacturing*. *12* (6), 1129-1141.

Kim, M., Lee, S. K., Yang, Y. S., Jeong, J., Min, N. K., and Kwon, K. H. (2013). Design and fabrication of vibration-based energy harvester using microelectromechanical system piezoelectric cantilever for low power applications. *Journal of nanoscience and nanotechnology*, *13* (12), 7932-7937.

Kim S. (2002). Low power energy harvesting with piezoelectric generators, PhD Thesis University of Pittsburgh, USA.

Kim, S.-B., Park, H., Kim, S.-H., Wikle, H. C., Park, J.-H., and Kim, D.-J. (2013). Comparison of MEMS PZT cantilevers based on d31 and d33 modes for vibration energy harvesting. *Journal of Microelectromechanical Systems, 22* (1), 26–33.

Kulah, H., and Najafi, K. (2004). An electromagnetic micro power generator for low frequency environmental vibrations. *17th IEEE International Conference on Micro Electro Mechanical Systems*, Jan 25-29, Maastricht, Netherlands.

Krauter, S. (2007). Renewable: Problems, Solutions, and Policies. Renewable Energy: Potential and Benefits for Developing Countries. *Proceedings of a conference*, February 28, Brussels, Balgium.

Kwang, H. C. (2014). Sun Power. Kuala Lumpur: Report of Viz Urbana Sdn Bhd.

Lee, B. S., Lin, S. C., and Wu, W. J. (2010). Fabrication and evaluation of a MEMS piezoelectric bimorph generator for vibration energy harvesting. *Journal of Mechanics*, *26* (4), 493–499.

Lee, B., and Chung, G. (2015). Low -frequency driven energy harvester with multi-pole magnetic structure. *Journal of Mechanical Science and Technology*, *29* (2), 441–446.

Liu, H., Qian, Y., and Lee, C. (2013). A multi-frequency vibration-based MEMS electromagnetic energy harvesting device. *Sensors and Actuators, A: Physical, 204,* 37–43.

Liu, J. Q., Fang, H. B., Xu, Z. Y., Mao, X. H., Shen, X. C., Chen, D., and Cai, B. C. (2008). A MEMS-based piezoelectric power generator array for vibration energy harvesting. *Journal Microelectronics*, *39* (5), 802-806.

Li W.J, Wen Z., Wong P.K., Chan G.M.H., Leong P.H.W. (2000). A micromachined vibration-induced power generator for low power sensors of robotic systems. *8th International Symposium on Robotics with Applications,* Hawaii.

Lin, H. C., Wu, P. H., Lien, I. C., and Shu, Y. C. (2013). Analysis of an array of piezoelectric energy harvesters connected in series. *Smart Materials and Structures*, *22* (9), 964-1726.

Lumentut, M. F., and Howard, I. M. (2013). Analytical and experimental comparisons of electromechanical vibration response of a piezoelectric bimorph beam for power harvesting. *Mechanical Systems and Signal Processing*, *36* (1), 66–86.

Lu, W. L., and Hwang, Y. M. (2011). Modeling of electromagnetic power output in a vibration-induced micro-generator with a silicon-based helical micro-spring. *Journal of Microelectronics*, *42*, 452–461.

Marqui Junior, C. D., Erturk, A. and Inman, D. J (2009). An electromechanical finite element model for piezoelectric energy harvester plates, *Journal of Sound and Vibration*, *327* (1-2), 9-25.

Mitcheson, P., Yeatman, E., and Rao, G. (2008). Energy harvesting from human and machine motion for wireless electronic devices. *Proceedings of the IEEE,* London, UK*, 96* (9) 1457-1486.

Mizuno, M., Chetwynd, D.G. (2003). Investigation of a resonance microgenerator, *Journal of Micromechanics and Microengineering, 13* (2), 209-216.

Muralt P, Marzencki M, Belgacem B, Calame F, Basrour S. (2009) Vibration energy harvesting with PZT micro device. *Proceeding Chemicals*, *1* (1), 1191–1194.

Owusu, P. A., and Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Review Article of Civil and Environmental Engineering of Cogent Engineering, 3* (1), 1–14.

Ottman, G. K., Hofmann, H. F., Bhatt, A. C., and Lesieutre, G. A. (2002). Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. *Journal of IEEE Transactions on Power Electronics*, *17* (5), 669–676.

Paulo, J., and Gaspar, P.D. (2010). Review and future trend of energy harvesting methods for portable medical devices. *In Proceedings of the World Congress on Engineering* Vol II WCE 2010, June 30 - July 2, London, U.K.

Paradiso, J. A., and Starner, T. (2005). Energy scavenging for mobile and wireless electronics. *IEEE Pervasive Computing, 4* (1), 18–27.

Ṕerez-Rodŕıguez A, Serre C, Fondevilla N, Cereceda C, Morante JR, Esteve J., (2005). Design of electromagnetic inertial generators for energy scavenging applications. *In Proceeding Eurosensors XIX of Paper MC5*, Barcelona, Spain.

Pimentel, D., M. Herz, M. Glickstein, M. Zimmerman, R. Allen, K. Becker, J. Evans, B. Hussain, R. Sarsfeld, A. Grosfeld and T. Seidel. (2002). Renewable energy: current and potential issues. *BioScience*, *52* (12), 1111-1120.

Pop-Vadean, A., Pop, P. P., Latinovic, T., Barz, C., & Lung, C. (2017). Harvesting energy an sustainable power source, replace batteries for powering WSN and devices on the IoT. *IOP Conference Series: Materials Science and Engineering, 200* (1), 12-43.

Prušáková, L., Novák, P., Kulha, P., Očenášek, J., Savková, J., Pastorek, L., & Šutta, P. (2015). Modeling and fabrication of single cantilever piezoelectric microgenerator with optimized Zno active layer. *Thin Solid Films*, *591*, 305–310.

Rafique S (2011). Piezoelectric vibration energy harvesting and its application to vibration control. PhD Thesis, University of Manchester, United Kingdom.

Ramadass, Y.K. (2009). Energy processing circuits for low-power applications, Ph.D. dissertation, Massachusetts Institute of Technology, USA.

Razali, N.N.H.M. and Yusoff, A.R., (2018). Optimisation of Hybrid Energy Harvesting using Finite Element Method based on Vibration Excitation. *International Journal Progress in Industrial Ecology, 12* (3), 284-296.

Renewable energy resource such as solar, wind, water, and geothermal. (online). Retrieved from http://greenplanetethics.com/wordpress/renewable-and-non-renewable-energy-sources-explained/ (8 October 2016).

Robert, D., Wu, W. J., Chen, Y. Y., and Costa, F. (2008). A Hybrid Piezoelectric and Electromagnetic Energy Harvesting Device, *19th International Conference on Adaptive Structures and Technologies*, October 6-9, Ascona, Switzerland.

Roundy S, Wright P K and Rabaye J. (2003). A study of low-level vibrations as a power source for wireless sensor nodes. *Computer Communications*, *26* (11), 1131–1144.

Roundy S, Wright P K. (2004). A piezoelectric vibration-based generator for wireless electronics. *Journal of Smart Materials and Structures*, *13* (5), 1131–1142.

Roundy, S., (2005). On the effectiveness of vibration-based energy harvesting. *Journal of Intelligent Material Systems and Structures, 16* (10), 809-823.

Sang, Y., Huang, X., Liu, H., and Jin, P. (2012). A vibration-based hybrid energy harvester for wireless sensor systems. *IEEE Transactions on Magnetics*, *48* (11), 4495-4498.

Sardini, E., and Serpelloni, M. (2011). An efficient electromagnetic power harvesting device for low-frequency applications. *Sensors Actuators and Physical, 172* (2), 475-482.

Sari, I., Balkan, T., and Kulah, H. (2008). An electromagnetic micro power generator for wideband environmental vibrations, *Journal of Sensors and Actuators*, *146*, 405-413.

Sari, I., Balkan, T., and Kulah, H. (2009). An electromagnetic micro energy harvester based on an array of parylene cantilevers. *Journal of Micromechanics and Microengineering, 19,* 105-023.

Sari, I., Balkan, T., and Kulah, H. (2008). An electromagnetic micro power generator for wideband environmental vibrations. *Journal of Micromechanics and Microengineering*, *146*, 405-413.

Schiffer, H. W. (2016). World Energy Council. *World Energy Resources*, *2007*, 1-1028.

Shan, X., Xu, Z., Song, R., and Xie, T. (2013). A New Mathematical Model for a Piezoelectric-Electromagnetic Hybrid Energy Harvester. *Ferroelectrics*, *450* (1), 57–65.

Soliman, M.S., Abdel-Rahman, E.M., El-Saadany, E.F. and Mansour, R.R. (2009). A design procedure for wideband micropower generators. *Journal of Microelectromechanical Systems*, *18* (6), 1288-1299.

Soliman M.S.M, Abdel-Rahman E.M, El-Saadany E.F, Mansour R.R. (2010). Output power optimization for electromagnetic vibration energy harvesters. *4th International Conference on Micro and Nanosystemsl,* August 15–18, Quebec, Canada.

Songsukthawan, P., and Jettanasen, C. (2015). Simulation and FEM Analysis of Applied Force Effects for Energy Harvesting in Piezoelectric Bimorph Device. *The 3rd International Conference on Intelligent Systems and Image Processing 53*, 283–287.

Stephen, N.G. (2006). On Energy Harvesting from Ambient Vibration. *Journal of Sound and Vibration*, 29 (3), 409–425.

Stuart, D. (2015). Thermoelectric Power Generators or Seebeck Power Generation. (online). http://www.electrical4u.com/thermoelectric-power-generators-or-seebeck - power-generation/ (31 November 2015).

Tadesse, Y., Zhang, S., and Priya, S. (2009). Multimodal energy harvesting system: piezoelectric and electromagnetic. *Journal of Intelligent Material System and Structures, 20* (5), 625–632.

Timmons, D., Harris, J. M., & Roach, B. (2009). The Economics of Renewable Energy. *Renewable Energy, 15* (8), 1341–1356.

Thein, C. K., Ooi, B. L., Liu, J.-S., and Gilbert, J. M. (2015). Modelling and Optimisation of a Bimorph Piezoelectric Cantilever Beam in an Energy Harvesting Application. *Journal of Engineering Science and Technology, 2,* 212–227.

Torah R.N, Beeby S.P, Tudor M.J, O'Donnell T, Roy S. (2006). Development of a cantilever beam generator employing vibration energy harvesting. *6th international workshop on micro-nano technology power generation energy convers applications*, *1*, 4-7.

Townley, A. (2009). Vibrational energy harvesting using MEMS piezoelectric generators. Master thesis, Electrical Engineering, University of Pennsylvania.

Ulaby, F. T., Michielssen, E., and Ravaioli, U. (2010). Fundamentals of Applied Electromagnetics (6^{th} edition). Prentice Hall, New York, USA.

Upadrashta, D., and Yang, Y. (2015). Finite Element Modeling of Nonlinear Piezoelectric Energy Harvesters with Magnetic Interaction. *Smart Materials and Structures*, *24* (4), 42-45.

Wang, D.A., Chiu C.Y., Pham, H.T. (2012). Electromagnetic energy harvesting from vibrations induced. *Journal of Mechatronics, 22* (6),746–756.

Wang L and Yuan FG (2008). Vibration energy harvesting by magneto strictive material. *Journal of Smart Materials and Structures*, *17* (4), 45-59.

Wang, P., Dai, X., Fang, D., and Zhao, X. (2007). Design, fabrication and performance of a new vibration-based electromagnetic micro power generator. *Journal of Microelectronics*, *38*, 1175–1180.

Wei, W., Tongqing, Y., Xurui, C., Xi Y., Qifa, Z. (2011). Vibration energy harvesting using piezoelectric circular diaphragm array. *International Symposium on Piezo Response Force Microscopy and Nanoscale Phenomena in Polar Materials*. July 24-27, Vancouver, Canada.

Wei, C., and Jing, X. (2017). A comprehensive review on vibration energy harvesting: Modelling and realization. *Journal of Renewable and Sustainable Energy Reviews*, *74*, 1–18.

White, N.M., Glynne-Jones, P. and Beeby, S.P., (2001). A novel thick-film piezoelectric micro-generator. *Journal of Smart Materials and Structures*, *10* (4), 850-852.

Williams, C., and Yates, R. (1996). Analysis of a micro-electric generator for microsystems. *Sensors and Actuators A: Physical*, *52* (1-3), 8-11.

Williams, C., and Shearwood, C. (2001). Development of an electromagnetic micro-generator. *Circuits, Devices and system, 148* (6), 337 - 342

Wischke, M., Masur, M., Goldschmidtboeing, F., and Woias, P. (2010). Electromagnetic vibration harvester with piezoelectrically tunable resonance frequency. *Journal of Micromechanics and Microengineering*, *20* (3), 1-7.

Wu, X., Lee D.W. (2015) Magnetic coupling between folded cantilevers for high-efficiency broadband energy harvesting. *Journal of Sensor Actuators and Physics*, *23* (4), 17–22.

Xiong Xingyu and Oyadiji S. Olutunde. (2017). Design and experimental study of a multi-modal piezoelectric energy harvester. *Journal of Mechanical Science and Technology*, *31* (1), 5-15.

Yang, B., Lee, C., Loon, W., Siak, K., and Lim, P. (2010). Hybrid energy harvester based on piezoelectric and electromagnetic mechanisms. *Society of Photo-Optical Instrumentation Engineers*, *9* (2), 2-23.

Yang, J., Zhou, H., Hu, Y., and Jiang, Q. (2005). Performance of a piezoelectric harvester in thickness stretch mode of a plate. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, *52* (10), 1872-1876.

Yazid, M.A.F.M., Jamil, N., Razali, N.N.H.M. and Yusoff, A.R. (2017). Finite element analysis of hybrid energy harvesting of piezoelectric and electromagnetic. *In MATEC Web of Conferences of EDP Sciences*, *90*, 01039.

Yildiz, F. (2007). Potential Ambient Energy-Harvesting Sources and Techniques. *The Journal of Technology Studies*, 40–48.

Yu, H., Zhou, J., Yi, X., Wu, H. and Wang, W. (2015). A hybrid micro vibration energy harvester with power management circuit. *Microelectronic Engineering*, 131, 36-42.

Yu, H., Zhou, J., Deng, L., and Wen, Z. (2014). A vibration-based MEMS piezoelectric energy harvester and power conditioning circuit. *Sensors*, *14* (2), 3323-3341.

Yuan, J.B., Xie, T., Shan, X.B., Chen, W.S., (2009). Resonant frequencies of a piezoelectric drum transducer. *Journal of Zhejiang University-SCIENCE A*, *10* (9), 1313-1319.

Zhu, D., Roberts, S., Tudor, M. J., and Beeby, S. P. (2010). Sensors and Actuators A: Physical Design and experimental characterization of a tunable vibration-based electromagnetic micro-generator. *Sensors & Actuators: A. Physical*, *158* (2), 284-293.

Zhou, X., Gao, S., Liu, H., and Jin, L. (2018). Nonlinear Hybrid Piezoelectric and Electromagnetic Energy Harvesting Driven by Colored Excitation. *Journal of Energies*, *11* (3), 498-512.