Science and Technology Publishing (SCI & TECH)
ISSN: 2632-1017
Vol. 8 Issue 12, December - 2024

Comparative Evaluation Of Piezoelectric Energy Harvester Model For Wireless Sensors

M. A. Umoren[1], U. I. Itaketo[2] and K.M. Udofia[3]
[123]Department of Electrical/Electronics Computer Engineering,
University of Uyo, Akwa Ibom, Nigeria
Email addresses:
[1]mfon4gigis@yahoo.com,
[2]uwanaitaketo@uniuyo.edu.ng,
[3]kufremudofia@uniuyo.edu.ng

***Abstract*— In this study, comparative evaluation of piezoelectric energy harvester model for wireless sensors is presented. The MATLAB simulated analytical models used to characterize the Piezoelectric Energy Harvester (PEH) system were compared with the simulated results d using Autodesk inventor and ANSYS software. Also, the results obtained from the PEH presented in this study were compared with the results obtained in some selected related works conducted by other researchers. The results also showed that there is a percentage variation in the resonance frequencies of the MATAB analytical model and the ANSYS simulation; it varied within a span of 13.2 – 15.9% for the current, voltage and power output. The discrepancies were due to the differences between the geometrical model, analytical parameters and assumptions in both MATLAB and ANSYS. In addition, in order to produce the oscillating motion, in this study, a force of 10.5 N was used to excite the airfoil, resulting in an output of 12900 mW, which provided clear evidence of a substantial improvement in output power over previous research efforts.**

Keywords*— *Piezoelectric, Energy Harvester, Wireless Sensors, Lagrange Equation, Autodesk Inventor, ANSYS Software, Euler Bernoulli Theory

1. INTRODUCTION

As the global demand for smart systems based on Internet of Things (IoT) sensors expands, the need for suitable energy sources for the diverse sensor installations becomes a running challenge for researchers and practitioners [1,2]. Notably, IoT sensors are in most cases resource constrained wireless devices with limited battery power source [3,4]. In some cases, the battery-powered sensors are supported with renewable energy harvesters such as solar power, wind power or piezoelectric energy sources [5,6]. While solar and wind energy sources are widely studied because they can be used to generate energy for high energy consuming devices and systems, the piezoelectric energy source are also needed for the low energy consuming devices like sensor nodes [7,8].

Piezoelectric energy technology has a significant potential in the industrial sector, where they can capture electrical energy from vibrations in engines or machines that vibrate [9,10]. Industries like oil and gas, as well as manufacturing, can benefit from energy harvesting as a cost-efficient substitute for wired infrastructure in monitoring technology. The piezoelectric energy-based sensor technology has the capability to oversee or monitor the condition of bridges, oil pipelines and other infrastructure thereby enhancing safety in transportation and protection of oil installations [11,12]. For example, units could be set up on roads or railway systems, responding to the movement of vehicles. This generates energy that can be utilised for powering light emitting diode (LED) and monitoring of traffic conditions such as speeding and congestion. Energy harvester can help in the fight against climate change and environmental impairment by reducing battery usage on low power devices. Piezoelectric mechanism can be beneficial in the kitchen as an automatic gas lighter thereby eliminating the use of gas lighters. It can also be used to take generate energy from the vibration of the oil pipeline and such energy can then be used to power the oil pipeline monitoring sensor nodes. Such energy harvester can completely eliminate the need for battery in sensor nodes or it can be used to extend the battery lifetime.

The design of Vibration-based Energy Harvester (VbEH) system requires complex mathematical models and carefully selected geometric design of the system components' shapes, dimensions and interconnections. Remarkably, this paper presents an aspect of an ongoing study on piezoelectric energy harvester model. It leveraged on the analytical models presented earlier work in [2] and another study that *focused* on the Autodesk inventor and ANSYS software-based simulated work on the piezoelectric energy harvester model as presented in [13]. The focus in this paper is to present comparative evaluation of the results obtained from the analytical model in [14] and those produced from the simulation models conducted using the Autodesk inventor and ANSYS software, as presented in [13]. Notably, previous works in this area have centered mostly on using a static clamped base as a boundary condition for electromechanical coupling, but in the study presented in [13] and [14] an improved aero-structurally of the airfoil and the structural support was considered, therefore, improving the amount of energy that can be extracted from the wind (kinetic energy) which contributed to the amount to electrical output produced from the system. Hence, this paper seeks to compare the results obtained from the piezoelectric energy model presented in [13] and [14] with those from other authors that worked on similar piezoelectric energy harvesters. This paper also seeks to compare the results obtained from the analytical model of the piezoelectric energy harvester presented in [14] with the Autodesk inventor and ANSYS software simulated version presented in [13].

2. METHODOLOGY

In this study, mathematical models which were used to characterize the Vibration-based Energy Harvester (VbEH) system as presented in the previous two publications [13,14] were adopted to conduct comparative evaluation of the analytical models' results obtained using MATLAB simulation program (developed based on the analytical models) and the simulated results obtained using Autodesk inventor and ANSYS software. Also, the results obtained from the piezoelectric energy harvester (PEH) presented in this study are compared with the results obtained in some selected related works.

The VbEH system was powered from the energy of the wind, which induces a vibrational force on a cantilever beam through the help of an oscillating airfoil. Lagrange's equation was used for the modelling of the airfoil while Euler Bernoulli theory (for thin beams where the beam length to thickness ratios is 20 or more) was used for the modelling of cantilever beam. The Lagrange equations were used to determine the equations of motion for complicated discrete (finite degree of freedom) systems. This can include translational (plunge motion) and rotational (pitch motion) motion. The final modified equations are used in developing MATLAB code in order to find out the amount of power, voltage and current that can be produced from the system.

A replica of the analytical model was first developed in two dimensions (2D) in Autodesk inventor software by drawing the individual parts of the structure and then transforming them to three-dimensional (3D) objects. The individual parts were assembled to form a single unit. The 3D developed model was then imported into ANSYS software to determine the current, voltage and power that can be produced from the harvester. The mathematical models were simulated with MATLAB/Simulink and ANSYS software. The results obtained were compared with results published in related literatures.

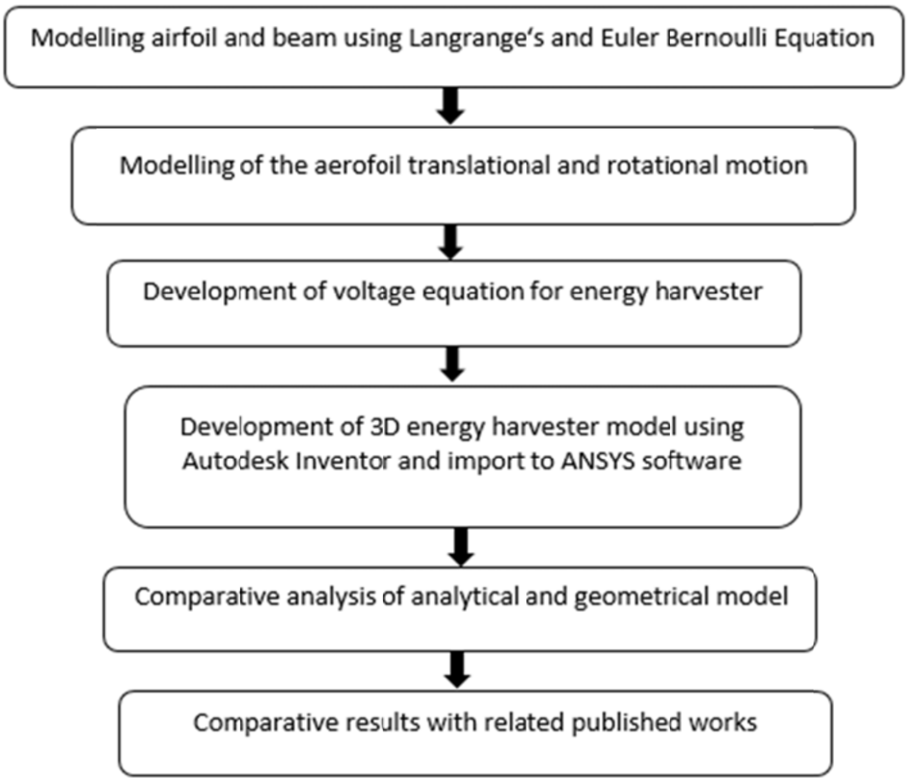

Figure 1 The flow diagram of the procedure used in this study

The flow diagram of the procedure used in this study is presented in Figure 1. The cross-sectional view of PEH setup, as utilised in the mathematical model development in [13] is presented in Figure 2. The sequence of steps used to create the 3D model of the vibration-based (piezoelectric) energy harvester in Autodesk inventor are captured in the flow diagram shown in Figure 3. The 3D Autodesk Inventor rendition of the vibration-based (piezoelectric) energy harvester as depicted in [13] is presented in Figure 4.

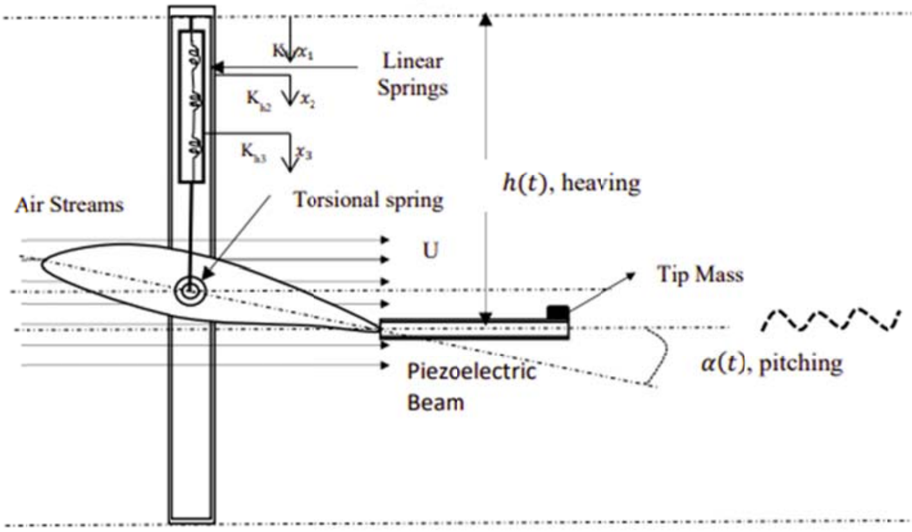

Figure 2 The cross sectional view of the vibration-based (piezoelectric) energy harvester setup, as utilised in the analytical model development in [13]

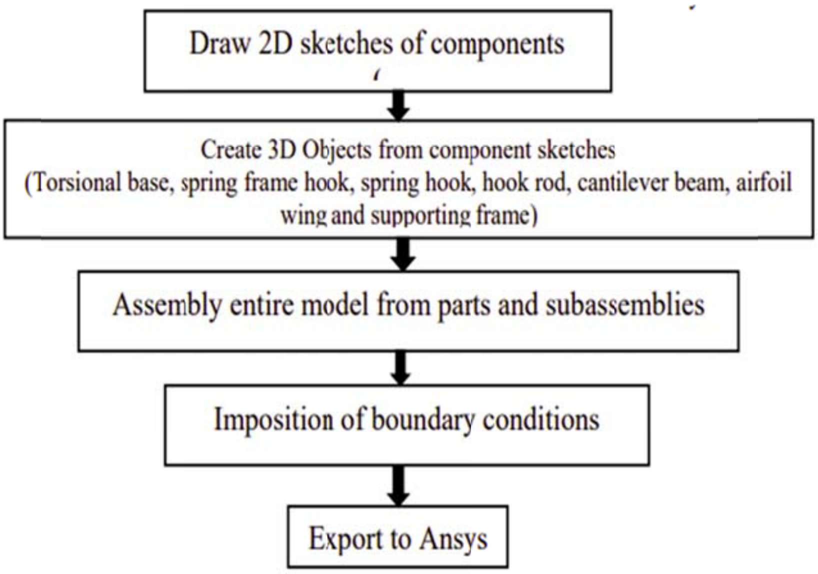

Figure 3 The flow diagram showing the sequence of steps used to create the 3D model of the vibration-based (piezoelectric) energy harvester in Autodesk inventor

Geometrically constructed virtual version of the system was made using Autodesk Inventor. This virtual version was then applied on ANSYS, to simulate, hence determine the amount of energy that can be produced during plunge and pitch motion. The steps taken to create the 3D model in Autodesk Inventor are demonstrated in Figure 3. A 2D diagram of the system was developed in Autodesk inverter and transformed to a 3D structure comprising different components amassed to form the structure illustrated in Figure 3.9. This structure comprises a rod, torsional spring, linear spring, beam, aerofoil wing and a supporting structure to hold all the components together.

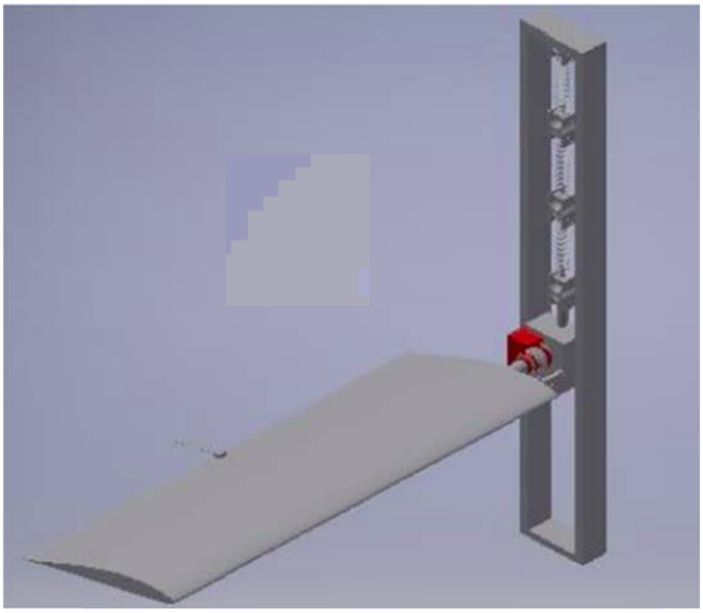

Figure 4 The 3D Autodesk Inventor rendition the vibration-based (piezoelectric) energy harvester [13]

The simulation, the 3D model of the PEH system was first imported into the ANSYS Fluent (which is a cutting-edge software tool for modelling of fluid flow and related thermodynamic systems). The ANSYS Fluent was used to model the air fluid environment (wind tunnel) for the PEH system. The computational fluid dynamics package which is a contained in ANSYS simulation software was used to conduct the electromechanical analysis of the PEH. In this case, the simulation software was used to simulate the wind induced vibrations which are required for energy harvesting through dedicated electromechanical coupling, that results in the plunge and pitch motion.

The wind-induced beam vibration causes continuous plunging and pitching motion and the motion excites the piezoelectric beam which makes the beam to undergo electromechanical stress and strain. This resultant dynamic deformation of the beam is then coupled to the modal analysis tools which generates the mode shapes as well as the fundamental resonance frequencies. The essence of the model analysis was to determine resultant voltage and the current and also the power generated by the PEH. Again, harmonic analysis was carried; this is used to generate the voltage frequency response of the piezoelectric beam. These results from the simulation software are compared with the one obtained from the analytical model implemented in MATLAB. The results are further compared with those obtained from some selected related works.

3. RESULTS AND DISCUSSION

In this research, the simulation results considered are (i) the steady state aerodynamic power output frequency characteristics, (ii) analytical and ANSYS model comparison for plunge motion of voltage, current and power output and (iii) comparison of the results obtained for the PEH presented in this study and the ones presented in related works.

3.1 The results of the steady state aerodynamic power output frequency characteristics

The power output at steady state, where the simulations were conducted using electrical load resistance in the range of 0.33 $T\Omega$ to 33 $P\Omega$ are presented in the graphs in Figure 5, Figure 6 and Figure 7. The results in Figure 6 show that the highest power output is recorded in the first mode at a frequency of 76.5 Hz with a load that has resistance of 33 TΩ. On the other hand, the next mode involving plunge movement attained a power output of 32.50 milli watt with a load that has resistance of 33 TΩ at frequency of 302.0 Hertz. In the third mode, the maximum power is reached at a resistive load of 3 TΩ at frequency of 676.0 Hertz. The key finding from the analytical model results is that the peak current, voltage and power were obtained at the load resistance value of 0.3 $T\Omega$, 3 $T\Omega$ and 33 $T\Omega$. Also, the second key finding is that the designed PEH presented in this study is capable of generating up to 12900 mW of power at the frequency of 676.5 Hertz.

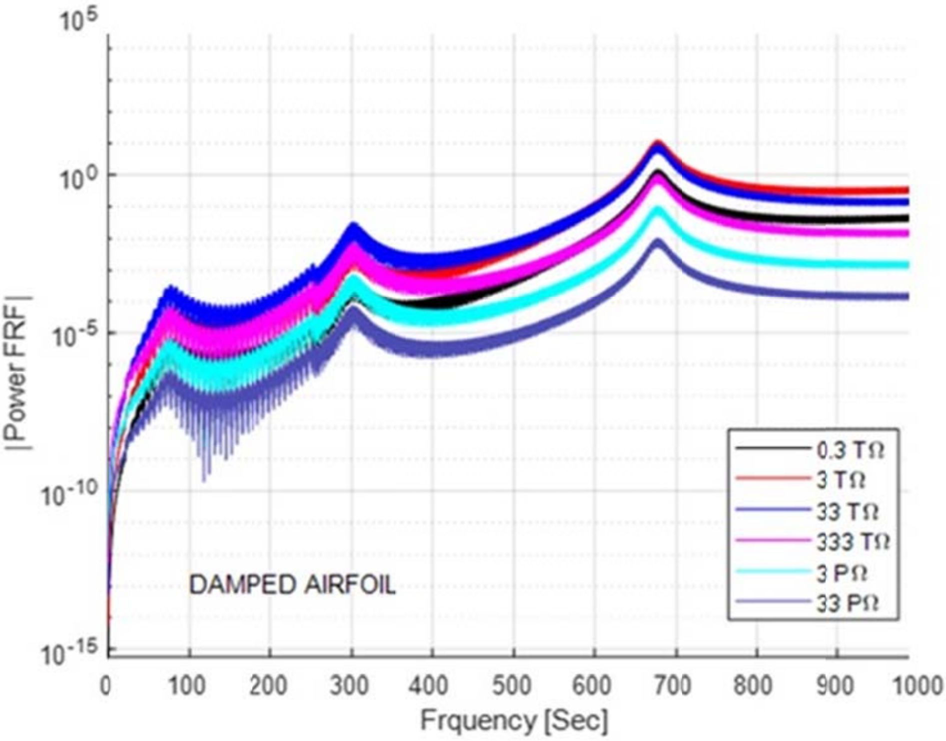

Figure 5: Power output for plunge motion of harvester for different load resistance

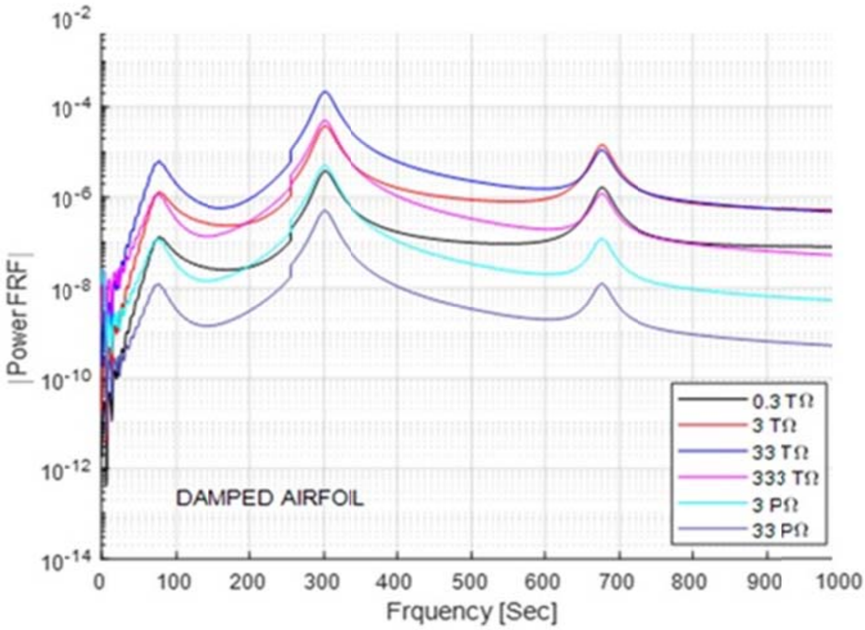

Figure 6: Power output for pitch motion of harvester for different load resistance

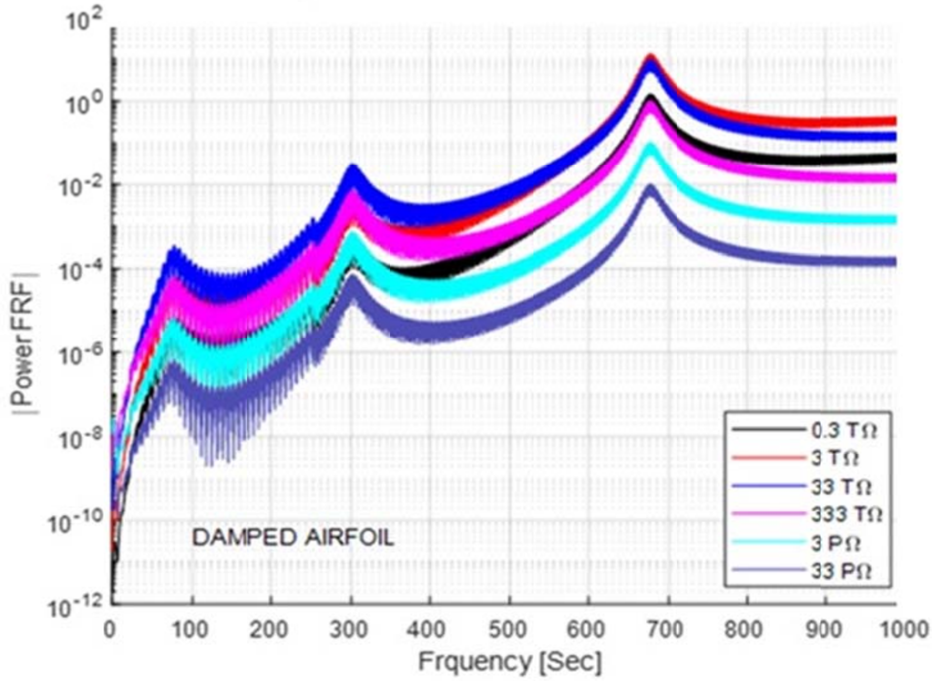

Figure 7: Power output for pitch-plunge motion for different load resistance

3.2 Comparison of MATLAB Model and ANSYS Simulation Model Results

A comparative analysis was perform using the MATLAB result obtained from the analytical model for the second mode of the plunge and pitch motion. The results were transferred from ANSYS to an Excel spreadsheet and then to MATLAB to facilitate the comparison. The ANSYS simulations were carried out at the maximum load resistances to compare the resonance frequencies with the model used in MATLAB, for the voltage, current and power output generated by the system. The result shown in Figure 8 and Figure 9 are for the plunge and pitch motion respectively.

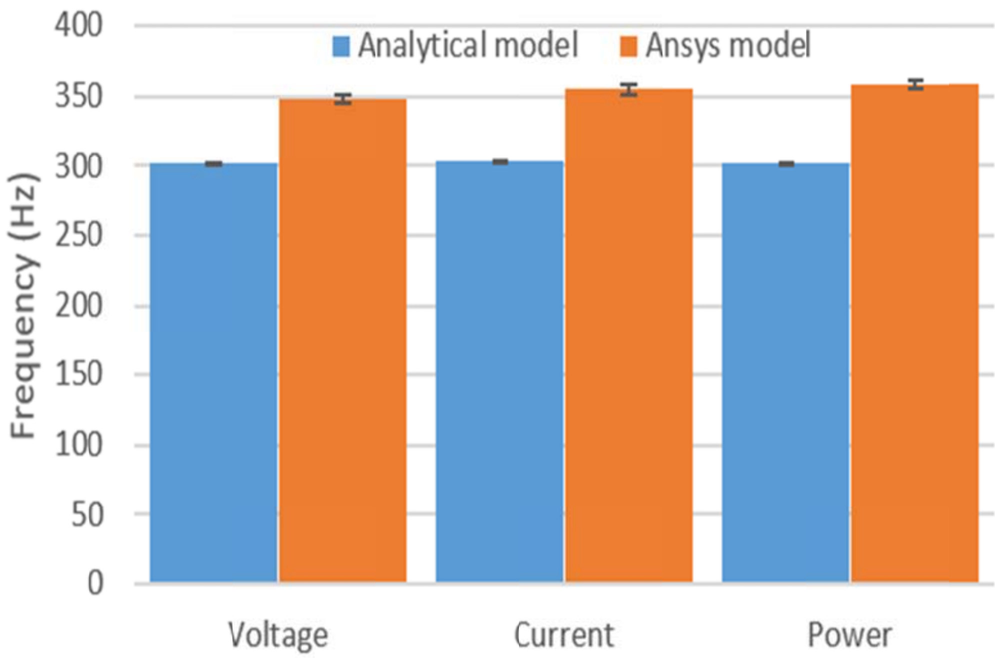

Figure 8: Analytical and ANSYS model comparison for plunge motion of voltage, current and power output

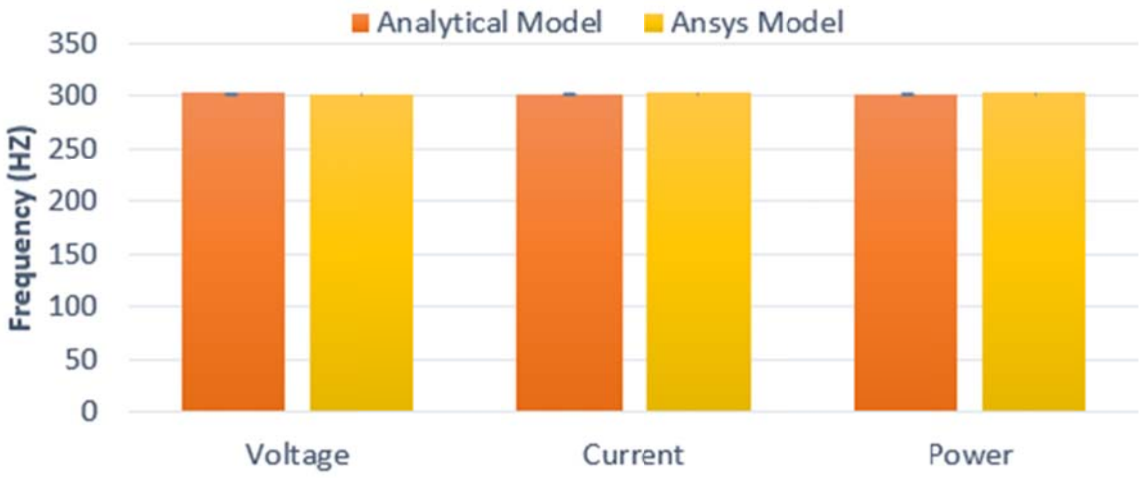

Figure 9: Analytical and ANSYS model comparison for pitch motion of voltage, current and power output

The results in Figure 8 show that there is a percentage variation in the resonance frequencies of the MATAB analytical model and the ANSYS simulation for the plunge or vertical motion and it varied within a span of 13.2 – 15.9% for the current, voltage and power output (as shown in Figure 8). On the other hand. the percentage discrepancy for the pitch motion was 0.003% for the current, voltage and power output (as shown in Figure 9). It can be noticed in Figure 9, that the analytical model ANSYS model generally follows the dynamics behaviour of the system thus indicating a proper coupling of the electrical domains.

The discrepancy between the MATLAB and ANSYS graphs is due to the difference between the geometrical model, analytical parameters and assumptions in both MATLAB and ANSYS software. While ANSYS software considers the physical configuration and geometry of the system MATLAB makes use of the mathematical equation assumptions. Some parameters like damping and theodorsen function (used to construct the circulatory aerodymamic forces resulting from harmonics oscillation of an airfoil) were use in the analytical analysis and was not considered in ANSYS. This can affect the stability of the system, energy conversion and the resonance frequency. The software settings and configurations are not the same for the two software and this can affect the accuracy of the results and percentage of the discrepancies.

3.3 Comparison of the results with those of previous related works

Numerous research efforts have been devoted to finding more efficient ways of producing more power from piezoelectric energy harvesters (PEHs). In this pursuit, different configurations have been studied to find out which geometrical configuration will result in more power output. Many researchers have traditionally followed a common procedure, focusing on harvesting energy from only one direction. The system developed in this research produces more power compared to the previous related works, as demonstrated in Table 1. In order to produce the oscillating motion, in this study, a force of 10.5 N was used to excite the airfoil, resulting in a maximum output of 12900 mW, which provided clear evidence of a substantial improvement in output power over previous research efforts.

Table 1: Comparison of the results with those of previous related works

Material Type	Power (mW)	Volume	Frequency (Hz)	Applied Force	Source
Lead Zirconate Titanate fiber	120	2.2cm^3	-	-	Mohammadi, 2003
Lead Zirconate Titanate ceramics	39	1cm^3	100	7.8 N	Kim *et al*, 2004
Lead Zirconate Titanate ceramics	52	1.5cm^3	100	70 N	Kim *et al*, 2005
Lead Zirconate Titanate ceramics	4.48		-	-	Liya et al., 2017
Lead Zirconate Titanate ceramics	0.205	27 mm^3	154	-	Aktakka 2012
Lead Zirconate Titanate nano fibers	4.9	-	-		Gu et al., 2013
Lead Zirconate Titanate thin film	3	-	-	-	Park et al., 2014
Lead Zirconate Titanate ceramic	30	-	-		Sodano et al., 2003
Lead Zirconate Titanate ceramic	28.8				Tang et al., 2012
Lea Zirconate Titanate ceramics	12900	1.95cm^3	676.5	10.5 N	This Study

Source: Park *et al*., (2014); Tang *et al*., (2012)

4. CONCLUSION

This work presents an aspect of an ongoing study on piezoelectric energy harvester model. It leveraged on the analytical models presented in earlier work in [2] and another study that focused on the Autodesk inventor and ANSYS software-based simulated work on the piezoelectric energy harvester model as presented in [1]. The focus in this paper is to present comparative evaluation of the results obtained from the analytical model and those produced from the simulation models conducted using the MATLAB and ANSYS software. The results were also compared with those from other authors that worked on similar piezoelectric energy harvesters.

The study showed that there were some little discrepancies between the results obtained from the analytical model implemented using MATLAB and simulated model implemented using ANSYS software. The discrepancies were due to the differences between the geometrical model, analytical parameters and assumptions in both MATLAB and ANSYS. Finally, the piezoelectric energy harvester model presented in this research produced more power compared to the previous related works.

REFERENCES

[1] Albreem, M. A., Sheikh, A. M., Alsharif, M. H., Jusoh, M., & Yasin, M. N. M. (2021). Green Internet of Things (GIoT): Applications, practices, awareness, and challenges. *IEEE Access*, *9*, 38833-38858.

[2] Mahbub, M. (2020). A smart farming concept based on smart embedded electronics, internet of things and wireless sensor network. *Internet of Things*, *9*, 100161.

[3] Pereira, F., Correia, R., Pinho, P., Lopes, S. I., & Carvalho, N. B. (2020). Challenges in resource-constrained IoT devices: Energy and communication as critical success factors for future IoT deployment. *Sensors*, *20*(22), 6420.

[4] Sarker, V. K., Gia, T. N., Tenhunen, H., & Westerlund, T. (2020, June). Lightweight security algorithms for resource-constrained IoT-based sensor nodes. In *ICC 2020-2020 IEEE International Conference on Communications (ICC)* (pp. 1-7). IEEE.

[5] Grossi, M. (2021). Energy harvesting strategies for wireless sensor networks and mobile devices: A review. *Electronics*, *10*(6), 661.

[6] Tsiropoulos, Z., Gravalos, I., Skoubris, E., Poulek, V., Petrík, T., & Libra, M. (2022). A Comparative Analysis between Battery-and Solar-Powered Wireless Sensors for Soil Water Monitoring. *Applied Sciences*, *12*(3), 1130.

[7] Dziadak, B., Kucharek, M., & Starzyński, J. (2022). Powering the WSN node for monitoring rail car parameters, using a piezoelectric energy harvester. *Energies*, *15*(5), 1641.

[8] Wang, L., Zhao, L., Luo, G., Zhao, Y., Yang, P., Jiang, Z., & Maeda, R. (2020). System level design of wireless sensor node powered by piezoelectric vibration energy harvesting. *Sensors and Actuators A: Physical*, *310*, 112039.

[9] Sezer, N., & Koç, M. (2021). A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. *Nano energy*, *80*, 105567.

[10] Kraśny, M. J., & Bowen, C. R. (2021). A system for characterisation of piezoelectric materials and associated electronics for vibration powered energy harvesting devices. *Measurement*, *168*, 108285.

[11] Yang, D., Zhang, X., Wang, T., Lu, G., & Peng, Y. (2023). Study on pipeline corrosion monitoring based on piezoelectric active time reversal method. *Smart Materials and Structures*, *32*(5), 054003.

[12] Kanoun, O., Khriji, S., Naifar, S., Bradai, S., Bouattour, G., Bouhamed, A., ... & Viehweger, C. (2021). Prospects of wireless energy-aware sensors for smart factories in the industry 4.0 era. *Electronics*, *10*(23), 2929.

[13] Umoren Mfonobong Anthony (2021) Analytical and Experimental Output Performance Comparison of Piezoelectric Energy Harvesters. *Science and Technology Publishing (SCI & TECH)* Vol. 5 Issue 3, March - 2021

[14] Umoren Mfonobong Anthony (2021) Analysis And Modelling Of Pitch And Plunge For Voltage And Power In Piezoelectric Harvesters. *International Multilingual Journal of Science and Technology (IMJST)* Vol. 6 Issue 4, April - 2021