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Validation Of Analytical Model Of Piezoelectric Energy Harvesters With Fea Model Using Ansys

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Abstract— **This paper presents the process and results of validating piezoelectric energy harvesters with FEA model using ANSYS. The piezo-aeroelastic energy harvester was designed with an airfoil wing shaped base structure capable of inducing dynamic flutter at a low airflow speed of $3.25\,\mathrm{m/s}$ which is suitable for both low and high wind speed environment. The focus is placed on software modeling and validations of the problem of generating electricity at the flutter boundary of a piezoaeroelastic airfoil. Notably, distributed-parameter models of a piezoelectric energy harvester using an oscillating or dynamic airfoil wing as a base structure and attached to a bimorph piezoelectric cantilevered beam is developed. The develop energy harvester was able to produce a maximum power output of $15340\,mW$, delivered to a resistive load of $10\,\mathrm{m\Omega}$ in the parallel connection case at bimorph beam resonance frequency of $854.80\,\mathrm{Hz}$.**

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Keywords: ***Piezoelectric, Piezoceramics, Cantilevers, Aeroelastic Vibrations, Harmonic Response***

I. INTRODUCTION

Energy harvesting is a rapidly growing area of endeavor. Vibration-based energy harvesting using piezoelectric transduction has been investigated by several researchers over the past decade. Typically, cantilevers with piezoceramics are used as piezoelectric energy harvesters and the source of excitation is assumed to be base vibrational motion [1, 2]. Piezoelectric energy harvesting from aeroelastic vibrations has been studied by a few authors and limited archived work exists. Some researchers have investigated energy harvesting from the flapping of piezoelectric films and cantilever arrays located behind bluff bodies [3]. The use of a curved airfoil section with macrofiber composite piezoceramics for energy harvesting was reported by [4]. Later at other conferences, energy harvesting from aeroelastic vibrations using an airfoil section attached to a cantilever theoretically and experimentally have been discussed [5]. Finite element models for piezoelectric energy harvesting using cantilevered plates under airflow excitation has also been developed [6,7]. This paper presents an experimentally validated piezoaeroelastic model with a focus on the generated electrical power and its effect on the aeroelastic response [8,9,10]

II. ANSYS MECHANICAL

In ANSYS mechanical, the fluid domain was suppressed and all the necessary joints and the three transverse springs were setup before meshing was carried out to obtain 148,966 elements and 155,427 nodes just as shown in Figure 1.

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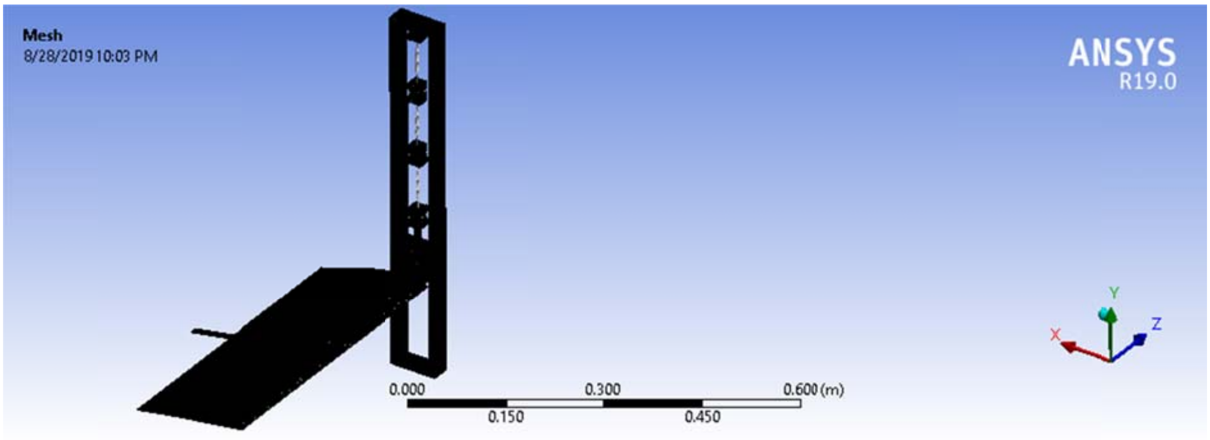


Figure 1: Meshing of the base structure and beam for transient analysis

The main procedure for achieving the aero-structural coupling is to import the fluid static pressure in the fluid domain to the mechanical or structural domain as surface pressure forces and moments. These fluid pressure forces are transferred to the structure and this induced stress, strain and deformation in the structure [11,12]. This is one-way coupling between aerodynamic and structural interaction, meaning that no forces are sent back to fluid domain for air particles disturbance as shown in Figure 2. Twenty load steps were used in the fluid analysis and all the sub steps were imported into ANSYS mechanical but because of the huge computational resources required to run all the load steps, only the last step was used This was simulated for 0.05s to obtain the maximum stress, strain and deflection of the structure and the piezoelectric cantilever beam.

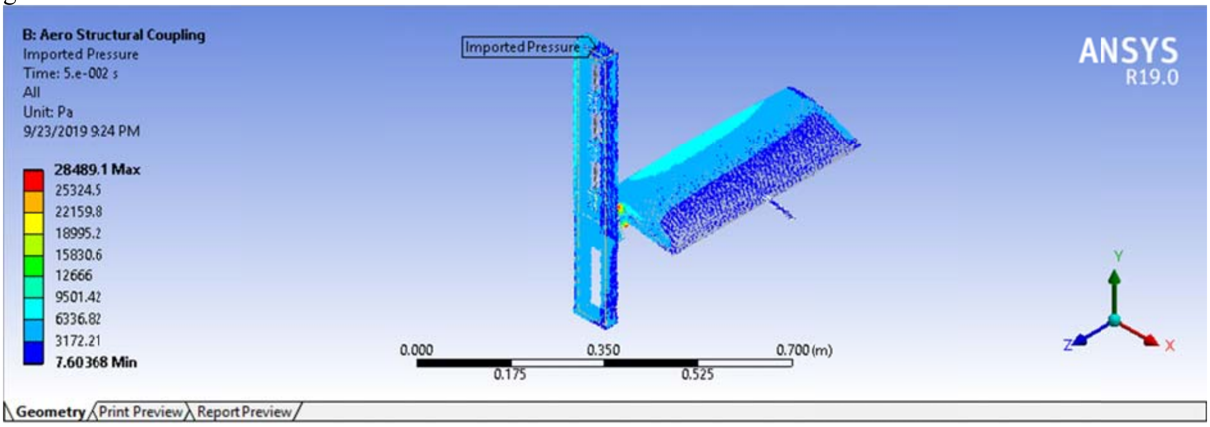


Figure 2: Imported static pressure as surface pressure forces and moments

III. Analysis, Mode Shapes and Natural Frequencies of System

A modal analysis determines the vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component. It can also serve as a starting point for another, more detailed, dynamic analysis, such as a transient dynamic analysis, a harmonic analysis, or a spectrum analysis. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. If there is damping in the structure or machine component, the system becomes a damped modal analysis.

For a rotating structure or machine component, the gyroscopic effects resulting from rotational velocities are introduced into the modal system. These effects change the system's damping. The damping can also be changed when a bearing is present, which is a common support used for rotating structure or machine component. The evolution of the natural frequencies with the rotational velocity can be studied with the aid of Campbell Diagram Chart Results.

In applying this to the present work, it is worth mentioning here that the Micro-Electromechanical (MEM) systems extension is used at this level to incorporate electromechanical coupling between the structural or mechanical system and the electrical part of the piezoceramics layers. The coupling is duly represented by the diagram in Figure 3.

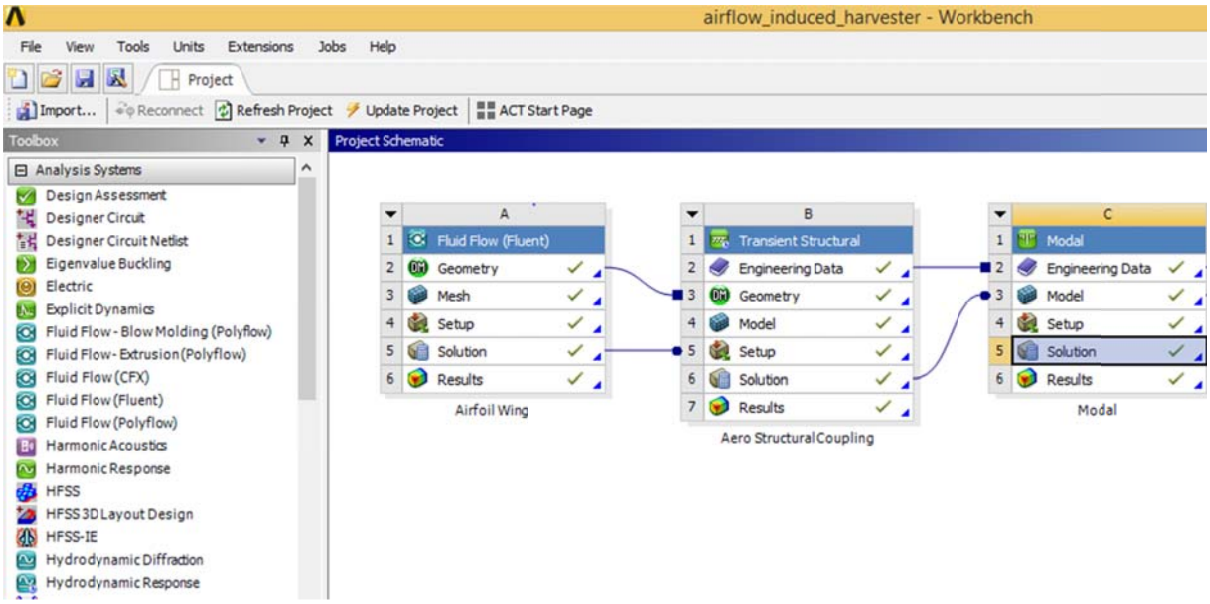


Figure 3. Electromechanical coupling structural deformation and electrical domain

A piezoelectric body is created and assigned to the two piezoceramics layers with the substructure. In order to inject piezo polarization in the system, the coordinate systems of the piezoceramics layers are reversed such that the y-axes of both top and bottom layers are equally opposed to one another to depict the transverse polarization of the 33 mode as shown in Figure 4. The piezo polarization is injected to the top and bottom of the cantilever beam as the system electrodes.

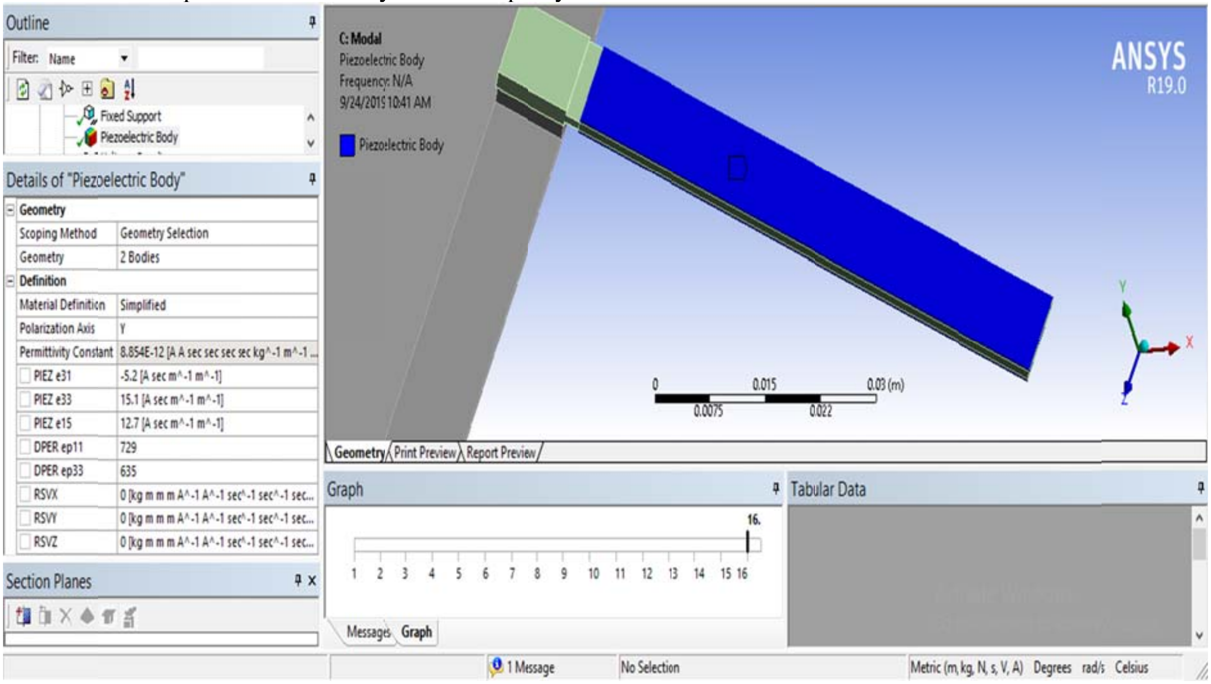


Figure 4: Piezoelectric body and direction of polarization

The next step is to set the boundary condition and loads on the system by first specifying a voltage object and assign it to the top layer of the piezoceramics. Besides, a voltage coupling object representing the electromechanical coupling is inserted, and this is assigned to the bottom piezoceramics layer and aluminium substructure. In the analysis settings, select modal analysis and request 15 modes of vibration to create the mode shapes and obtain the natural frequencies of all the specified modes. Insert a fixed support at the base of the steel structure. From different research studies, it has been proven that piezoelectric energy harvester operates under low frequency range for it to obtain the highest power generation possible, and as a result, the solver was restrain to calculate the natural frequencies within a specified range of 0-5000 Hz.

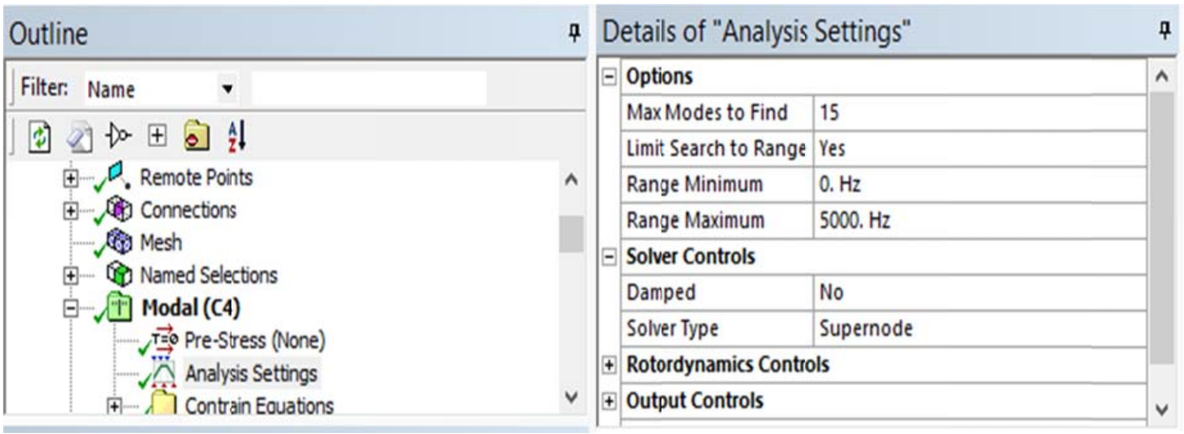


Figure 5: Analysis settings for the modal analysis

In Figure 5, the supernode solver was requested and the supernode eigensolver works by taking the matrix structure of the stiffness and mass matrix from the original FEA model and internally breaking it into pieces (supernodes). These supernodes are then used to reduce the original FEA matrix to a much smaller system of equations. The solver then computes all of the modes and mode shapes within the requested frequency range on this smaller system of equations. Then, the supernodes are used again to transform (or expand) the smaller mode shapes back to the larger problem size from the original FEA model. The power of this eigensolver is best experienced when solving for a high number of modes, usually more than 200 modes. Another benefit is that this eigensolver typically performs much less I/O than the Block Lanczos eigensolver and, therefore, is especially useful on typical desktop machines that often have limited disk space and/or slow I/O transfer speeds. The results inserted are the system deformation, piezoelectric energy harvester deformation, voltage generated by the harvester and all the 15 associated mode shapes of the system. Note that one can request for as many modes as possible so long there is enough computational resources available.

IV. HARMONIC RESPONSE OF PIEZOELECTRIC ENERGY HARVESTER

Harmonic analyses are used to determine the steady-state response of a linear structure to loads that vary harmonically with time, thus enabling the verification of the system's ability to successfully overcome resonance, fatigue, and other harmful effects of forced vibrations. In a structural system, any sustained cyclic load by the wind on the airfoil will produce a sustained cyclic or harmonic response. This analysis technique calculates only the steady-state, forced vibrations of a structure. The transient vibrations, which occur at the beginning of the excitation, are not accounted for in a harmonic analysis. In this analysis all loads as well as the structure's response vary sinusoidally at the same frequency. A typical harmonic analysis will calculate the response of the structure to cyclic loads over a frequency range as shown in Figure 6. In order to achieve this, the modal analysis was coupled to the harmonic response analysis as shown below.

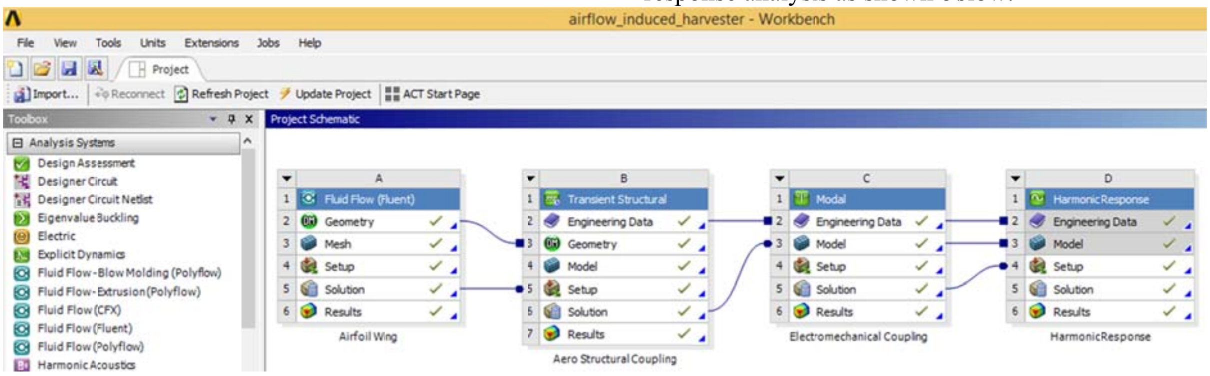
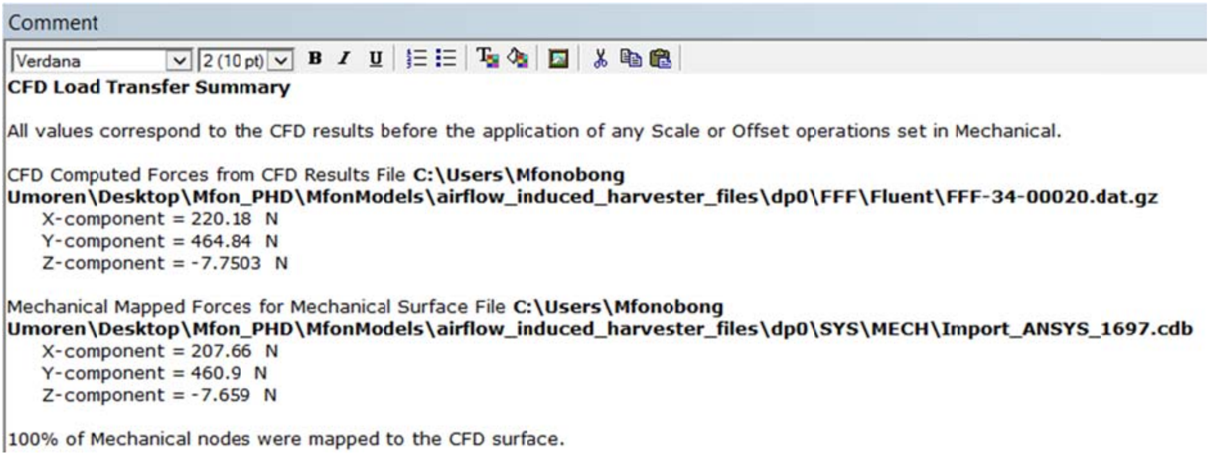


Figure 6: Harmonic response of pre-stressed structure of piezoelectric energy harvester

The next step is to set the boundary conditions and loads on the system. From the figure it can be seen that actual forces transferred to the structure is lower than that from the fluid domain. So the mechanical mapped forces are inserted into the harmonic response analysis as loads generated by the wind speed over the piezoelectric energy harvester surface.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CFD Load Transfer Summary

All values correspond to the CFD results before the application of any Scale or Offset operations set in Mechanical.

CFD Computed Forces from CFD Results File **C:\Users\Mfonobong Umoren\Desktop\Mfon_PHD\MfonModels\airflow_induced_harvester_files\dp0\FFF\Fluent\FFF-34-00020.dat.gz**

X-component = 220.18 N
Y-component = 464.84 N
Z-component = -7.7503 N

Mechanical Mapped Forces for Mechanical Surface File **C:\Users\Mfonobong Umoren\Desktop\Mfon_PHD\MfonModels\airflow_induced_harvester_files\dp0\SYS\MECH\Import_ANSYS_1697.cdb**

X-component = 207.66 N
Y-component = 460.9 N
Z-component = -7.659 N

100% of Mechanical nodes were mapped to the CFD surface.

Figure 7: CDF load transfer and mechanical mapped forces

V. VALIDATION OF PIEZOELECTRIC ENERGY HARVESTER MODEL WITH FEA MODEL USING ANSYS

First a fluid analysis was carried out with computational fluid dynamics (CFD) package of the ANSYS simulation software to determine the static pressure necessary for generation of the required lift and pitching moments responsible for the plunge and pitch motion modelled in the analytical section. The generated fluid forces and moment by the airfoil was transferred to the structural part of the piezoelectric bimorph beam attached at the trailing edge. This lead into proffering a suitable method for coupling the fluid physics to the structural domain in order to induced the vibrations required for harvesting energy through a dedicated electromechanical coupling technique. A direct coupling was used for the aero-structural coupling to transform the generated static pressure forces into actual mechanical surface forces and moments acting on all the finite elements constituted in the mesh envelope developed within the ANSYS transient structure package. These now sets the system into a continuous heaving and pitching motion which excited the piezo beam to undergo mechanical stress and strain. It is this dynamic deformation that are being coupled to the modal analysis tools to obtain the mode shapes, fundamental resonance frequencies.

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VI. PIEZOELECTRIC ENERGY HARVESTER SYSTEM LEVEL ANALYSIS IN SIMPLORER

The analysis is brought to ANSYS Simplorer is to enable the determination of the current and power generated by harvester. The electrical circuit is developed in ANSYS simplorer by first importing the electromechnical system from the Reduced Order Model (ROM) into sml (Simplorer Modeling Language) file, which enables the inputs and outputs of the models to be designed as a physical domain pins capable of functioning within the Simplorer environment. These pins are graphical connectors linking the electric circuit.

The voltages generated in the modal analysis section were exported into a text file which was later imported as a time dependent data for the voltage source generated by the piezoceramics layers electrodes. The circuit constructed in Simplorer, contains two piezoelectric beam layers representing the bimorph configuration of the piezoceramics electrodes, is shown in Figure 8.

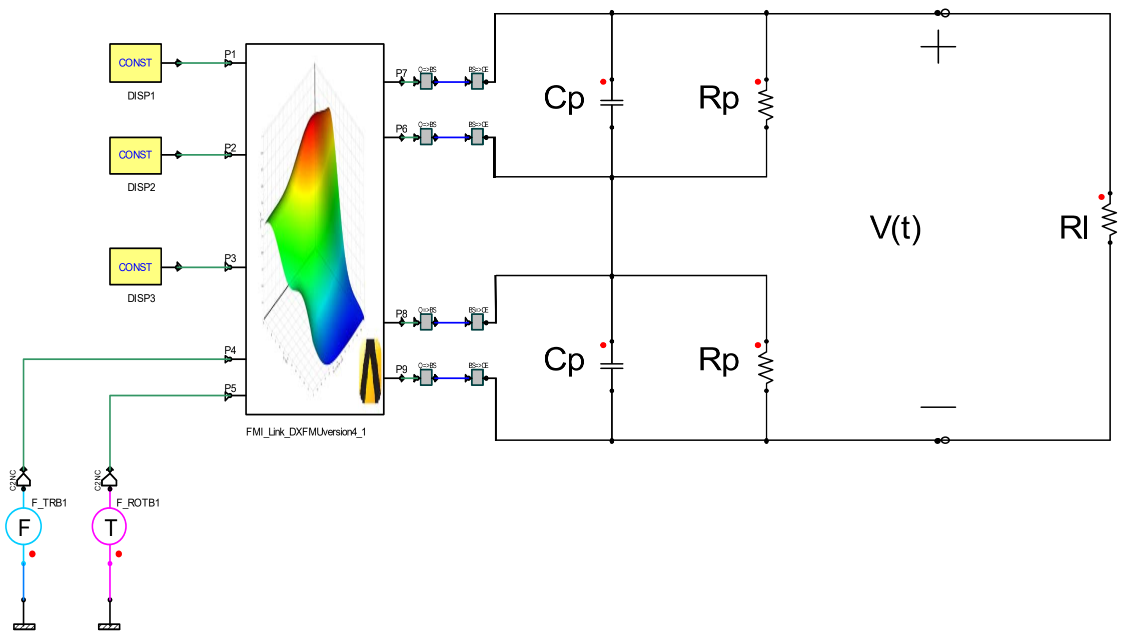

Figure 8: Coupled electrical circuit for piezoelectric energy harvester in ANSYS Simplorer

VII. DISCUSSION OF RESULTS

In carrying this assessment, four categories would be dealt with their suitability for providing power wireless sensor. These include undamped airfoil excited under quasi-steady aerodynamic condition with series connection of piezoceramic layers, damped airfoil excited under unsteady state aerodynamic condition with series connection of piezoceramic layers, undamped airfoil excited under quasi-steady state aerodynamic condition with parallel connection of piezoceramic layers, and damped airfoil excited under unsteady state aerodynamic condition with parallel connection piezoceramic layers.

The maximum power outputs of the series connection and parallel connection cases are not identical due to the different aerodynamic condition of excitation of the base structure, but they correspond to different values of optimum load resistance. A maximum power output of $468.30\ mW$ is delivered to a resistive load of $10\ m\Omega$ in the series connection case with damped airfoil base and unsteady state base excitation, whereas a maximum power output of $15340\ mW$ is delivered to a resistive load of $10\ m\Omega$ in the parallel connection case (see Table 1). The series connection case generates this power with a current amplitude of 383.40 mA and a voltage amplitude of 363.30 mV. In the parallel connection case, a different power output is obtained with a current amplitude of 1592 mA and a voltage amplitude of 720.40 mV. From the analysis, parallel connection should be preferred for wireless sensor with large voltage supply requirement whereas series connection should be used for sensors with large current supply demands.

Table 1: Summary of piezo-aeroelastic energy harvester's design specification for wireless sensors application

Mode (r)	Voltage $[mV]$	Current $[mA]$	Deflection $[mm]$	Power $[mW]$	Connection	Airfoil Design	Condition
3,1	136.20	3.83	0.0754	246.00	Series	Undamped	Quasi-steady
3	363.30	383.40	0.0822	468.30	Series	Damped	Unsteady
3	270.10	5.78	0.0414	5751.00	Parallel	Undamped	Quasi-steady
3	720.40	1592.00	0.1105	15340.00	Parallel	Damped	Unsteady

VIII. Application of Piezo-aeroelastic Energy Harvester to Wireless Sensor Network.

In this section, a samples of hand-picked wireless sensors were chosen and tabulated in Table 2, specifying their manufacturers, power consumption, supply voltage and current requirement. The application of this piezo-aeroelastic energy harvester is not limited to the wireless sensors listed in the table below, one can explore other manufacturers and products and see how effective the design in this research can be.

Table 2: Wireless sensors specifications (https://www.microstrain.com/wireless/g-link)

Manufacturer/ Model	Type	Power $[mW]$	Voltage $[V]$	Current $[mA]$
Monnit	Temperature	15	3.0	0.38
Monnit	Distance	1800	3.8	1.0
Honeywell/ 7939WG	Contact	150	3.0	300
Lord Microstrain/ LXRS	Acceleration	39	3.7	220

IX. CONCLUSION

The piezo-aeroelastic energy harvester designed with damped airfoil, parallel piezoceramic layers connection and system excitation at unsteady state aerodynamic, is capable of generating $15340\,mW$ of power at bimorph beam resonance frequency of 854.80 Hz . The distributed-parameter electromechanical formulation is based on the Euler- Bernoulli beam theory and it is valid for thin piezo-aeroelastic energy harvester for the typical vibration modes of interest. The research had demonstrated that the piezo-aeroelastic energy harvester developed is well suited for deployment in very low wind speed areas. The system is also characterized with low short-circuit and open-circuit load resistances of $1\,\mu\Omega$ and $10\,m\Omega$ at the same short-circuit and open-circuit resonance frequencies of 95.44 Hz for mode one and 854.80 Hz for mode three respectively. It is also shown that unlike other conventional energy harvester, the piezo-aeroelastic energy harvester in this research is capable of supplying power to most wireless sensors node and MEMS devices. It would be an amazing breakthrough, once the models and design is validated experimentally.

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