iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8 Issue: V Month of publication: May 2020

DOI: http://doi.org/10.22214/ijraset.2020.5318

Simulation of Kármán Vortex Street of Bluff Bodies for Piezoelectric Energy Harvesters

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Abstract: This study investigates the creation of Kármán vortices generated from bluff bodies. Computational analyses were carried out to understand the effects of various parameters on the frequency of the vortices. From the concept of resonance and exploiting the deviation in Strouhal's law, we propose to achieve efficient power output from piezoelectricity. After an in-depth survey, flexible piezoelectric materials were considered to be most feasible in the given case for harvesting energy. This paper presents a novel approach to substantiate and consolidate the results of resonance between the shedding frequency from the bluff body and the natural frequency of the piezoelectric material through a one-way coupled fluid-solid interaction analysis. Given the prevalence and protean nature of piezoelectric materials, it is deemed to be the future for energy harvesting and as a source of power for a variety of electronic sensors.

Keywords: ***Kármán Vortex Street, Piezoelectricity, Energy Harvesters, Fluid-Solid Interaction, Vortex-Induced Vibrations.***

I. INTRODUCTION

Renewable energy sources, such as wind, solar, geothermal, and gravitational are receiving increased attention due to the continuing depletion of natural resources used for coal or gas-fired electrical power generation together with the associated environmental emissions. An alternative approach to electrical power generation is to convert the available flow energy of a free-flowing fluid into electrical energy, wind turbines being a prominent example. One of the lesser-known examples being the use of flexible piezoelectric structures [1]. Piezoelectric materials have been in use for many years; however, with increasing concern about global warming, piezoelectricity has gained significant importance in research and development for extracting energy from the environment [2]. In this paper, we have comparatively studied the amplitude responses of both PVDF (Polyvinylidene fluoride) and PZT (Lead zirconate titanate) structures to fluid flow with an objective of using piezoelectric materials as an efficient power source for electronic devices. This study presents the creation of a Kármán vortex for a vibrating piezoelectric energy harvester device using a bluff body. The effects of two parameters, which are the diameter of the bluff body and mean inflow velocity, were investigated on the Kármán vortex profile and the amplitude of the vibrating piezoelectric material, respectively. Various simulations were conducted to determine the effect of the creation of the Kármán vortex by the bluff body i.e., the cylinder.

This study also reviews the current state of research on piezoelectric energy harvesting devices for low frequency (0–100 Hz) applications and the methods that have been developed to improve the power outputs of the piezoelectric energy harvesters [3]. Various aspects that contribute to the improved efficiency of a piezoelectric energy harvester are discussed, including types of piezoelectric materials used, techniques employed to match the natural frequency of the piezoelectric material to the shedding frequency of the bluff body i.e., the cylinder. This paper is divided into six sections. Sect. 2 presents the literature survey. Sect. 3 discusses the methodology followed. Eigenfrequency analysis and the simulation of Kármán Vortex Street are presented in Sect. 4. Fluid-Solid Interaction (FSI) simulations and resonance matching are discussed in Sect. 5 followed by the conclusion.

II. LITERATURE SURVEY

In this section, modelling and simulation of bluff bodies are discussed along with the analysis of various kinds of piezoelectric energy harvesters (PEHs). This review performs numerical simulations by attaching a PZT patch to the transverse degree of freedom (DOF) by taking into account Reynolds numbers (R_e) ranging from 96–118. R_e are selected on the basis that they can accumulate pre-synchronization, synchronization, and post-synchronization regimes [4]. A simulation study of the vortex creation was performed to investigate the effects of cylinder diameter on the vortex profile. An experimental study was conducted to determine the effects of the cylinder position on the amplitude of the PEH [5]. In order to design efficient piezo-aeroelastic energy harvesters that can generate energy at the operating freestream velocity, researchers investigated the effects of varying the cylinder's tip mass, length of the piezoelectric sheet, electrical load resistance on the synchronization region, the performance of the harvester, its power density, and its aero-electromechanical efficiency.

It was demonstrated that there is a compromise between these parameters to design an enhanced piezoelectric energy harvester from VIVs [6]. In this study, the flow has been investigated experimentally by using thin flexible cantilevered beams consisted of a PVDF layer deposited on a mylar substrate. Several orientations of the beam in reference to the flow have been explored but the most promising appeared to be the case of the beam parallel to the upstream flow in a face-on configuration [7]. It is also observed that when the wind speed is in the lock-in or synchronization region, it was demonstrated that using a single piezoelectric energy harvester under a combination of vibratory base excitations and vortex-induced vibrations significantly improves the level of the harvested power compared to using two separate harvesters [8]. From a numerical study it was found, that for a Reynolds number, $R_e > 300$, a turbulent von Kármán vortex street appears in the pipeline wake, giving rise to multi-mode oscillations [9]. The average power is seen to increase with R_e. Two reasons could account for this increase in power with R_e increase in Strouhal number and increase in the vibration amplitude with R_e [1]. Piezoelectric vibration energy harvesters are reported to have a higher energy density for practical applications [10]. Efficiency and power density of a piezoelectric vibrational energy harvesting device are strongly frequency dependent because the piezoelectric generates maximum power at its resonance frequency [3].
It is evident from the literature that meticulous research was carried out in understanding the various energy harvesting mechanisms and numerous piezoelectric energy harvesting materials were investigated among which PZT and PVDF were mainly discussed. The prominent mechanisms for harvesting energy through PEHs were vortex-induced vibration and fluid-structure interaction based PEH.

III. METHODOLOGY

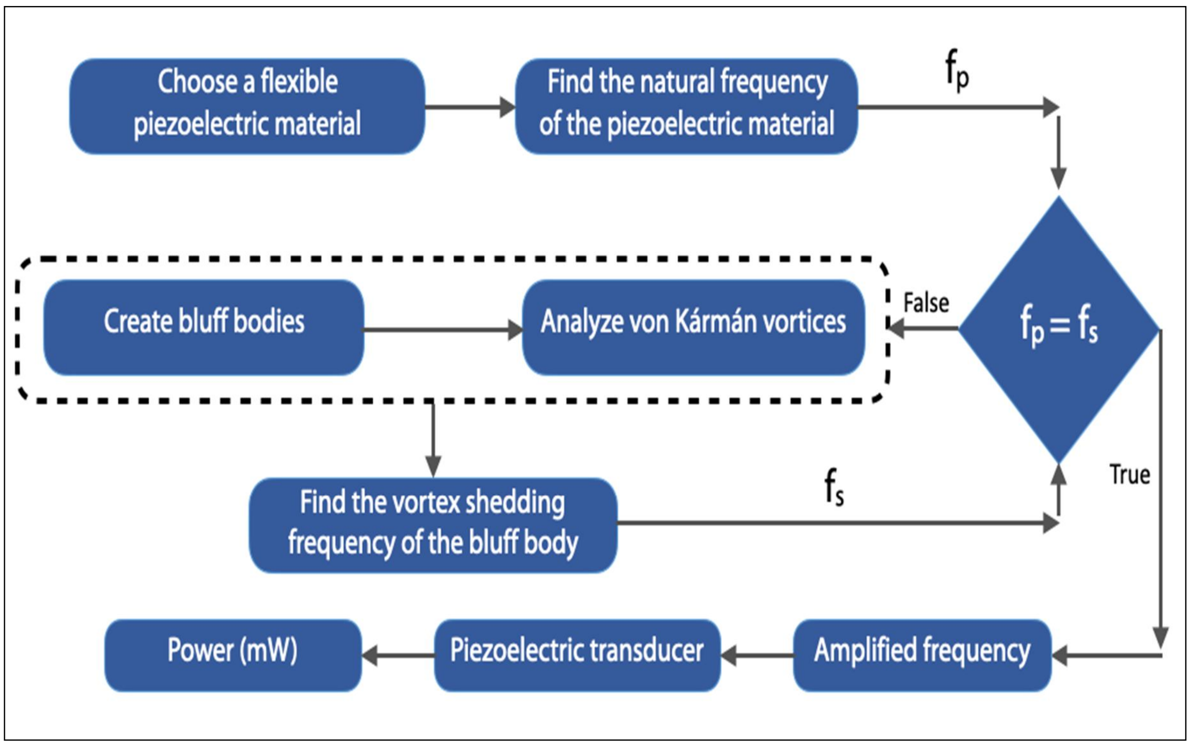


Fig 1: Methodology Flowchart

Initially, a thorough literature review is conducted on various piezoelectric transducers and the various parameters that affect the efficacy of energy. Apart from that, choosing the type of cantilever mechanism and the coupling mode of the piezoelectric transducer is imperative to this study. From research, *-31* coupling mode was chosen since even for a small force and low vibrational environment, this configuration of cantilever proved to be more efficient over *-33* coupling mode. It was also found that the resonant frequency of a system operating in the *-31* mode is much lower, making the system more likely to be driven at resonance in a natural environment, thus providing more power [11]. This is followed by creating bluff bodies of various dimensions and performing a laminar flow analysis to verify the generation of Kármán vortices. Consequently, the shedding frequency of the vortices is calculated to see if it matches the natural frequency of the piezoelectric material and upon matching the iterative process is ceased. The resonance frequency amplifies the output power since it leads to the higher amplitude of mechanical vibrations on the piezoelectric material.

IV. SOLID MECHANICS & LAMINAR FLOW

For the design of the piezoelectric energy harvester, an iterative process was carried out to determine the most suitable dimensional specifications in accordance with the desired eigenfrequency. A solid mechanics study on COMSOL Multiphysics was carried out while fixing one end of the piezoelectric transducer and keeping the other end free. This study was conducted to ascertain that a periodic excitation causes resonance with the piezoelectric material.

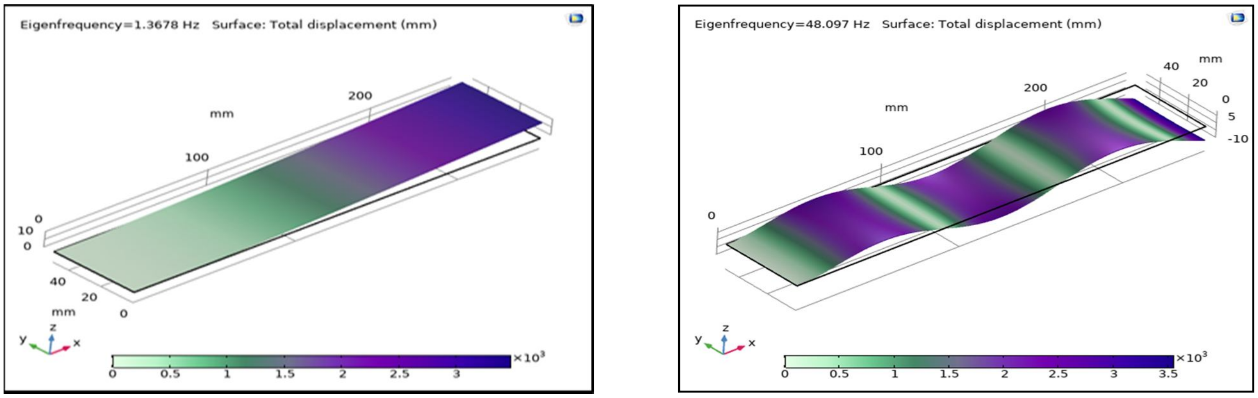


Fig 2: Eigenfrequency Analysis of PVDF

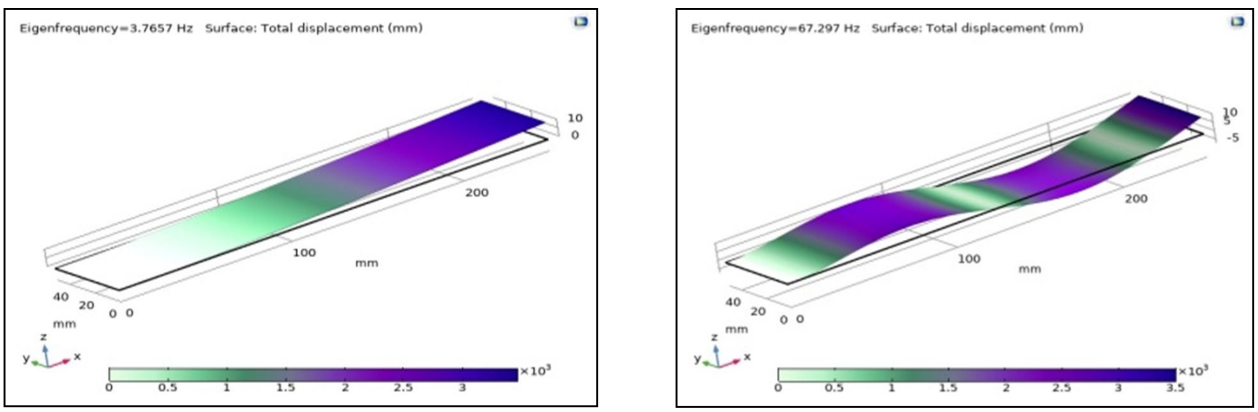


Fig 3: Eigenfrequency Analysis of PZT-5A

The eigenfrequency is directly proportional to the stiffness of the material and inversely proportional to the inertia of the material. To maximize the output power, the material with lower eigenfrequencies was selected. The stiffness of the material played a major role in the material selection as lower stiffness led to higher energy output and makes the material more flexible. This helps in sustaining the undulating forces due to the vortices generated leeward of the cylinder. This also augmented the fatigue cycle count of the material, thus making it highly desirable. The eigenfrequencies are tabulated for the corresponding piezoelectric materials and various eigenmode shapes.

Table I: Eigenfrequencies of PVDF and PZT-5A

Material	PVDF	PZT-5A
Mode	Eigenfrequency (Hz)	Eigenfrequency (Hz)
1	1.36	3.76
2	8.71	23.96
3	13.68	37.66
4	24.44	67.29
5	41.89	115.33
6	48.09	132.41

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue V May 2020- Available at www.ijraset.com

PVDF was the piezoelectric transducer that was incorporated as the energy harvester in this study mainly because of its flexibility, insusceptibility to fatigue, and a very high power density of 2mW/cm^3 [3]. The dimensions and the specifications of the chosen piezoelectric transducer are optimized such that a lower value of natural frequency is attained which is desirable since the potential output power is inversely proportional to the frequency [11]. Following this, the vortex shedding frequency is calculated using the below equation and the Strouhal number (S_t) is assumed to be constant for a broad range of Reynolds number and is approximated as 0.2 for cylindrical bluff bodies [5].

$$f_s = \frac{S_t \times U}{D} \tag{1}$$

The velocity (U) range is limited to 1m/s to 3m/s since the device is mostly used in ambient conditions. A set of shedding frequency and concurrent diameters (D) of the cylindrical bluff body is obtained [5].

The second part of this study will begin with the simulation of Kármán vortex street of the cylindrical bluff body. Initially, a 2D laminar flow analysis was conducted on different diameters obtained from vortex shedding frequency, of cylindrical bluff bodies on COMSOL Multiphysics, the following parameters were taken into consideration: Shape and size of the bluff body, Reynolds number, Strouhal number, Scruton number, and the mean inflow velocity.

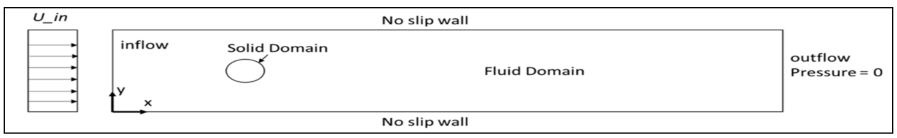


Fig 4: Domain and Boundary Conditions for vortex analysis [5].

The mean inflow velocity and the diameter of the bluff body were monitored to limit the Reynolds number from exceeding the range of 100 to 300. The following range of Reynolds number is considered as this is the transition range to turbulence in vortex generated by the bluff body and this is unsteady flow. A parametric sweep function was used in the initial parameterization since a parametric sweep allows for a parameter to be swept through a range of values and can be performed when running a transient analysis. The parabolic velocity profile is obtained from the expression below:

$$U_0 = U_{mean} \times 6s \times (1-s) \times step1(t\left[\frac{1}{s}\right]) \tag{2}$$

All functions in the COMSOL interface need unit less variable calls, "t" the time has a unit of seconds, and we normalize it by writing t[1/s]. "s" is an internal variable defined in 2D and running normally from 0 to 1 along each edge. The term s×(1-s) represents a parabola starting and finishing at "0" for s=0 and s=1, this is typically the velocity flow profile of a "no-slip" condition. Upon integrating s×(1-s) between the interval [0, 1] we obtain equation (2) which gives the average velocity at step=1. The figure below depicts the same [12].

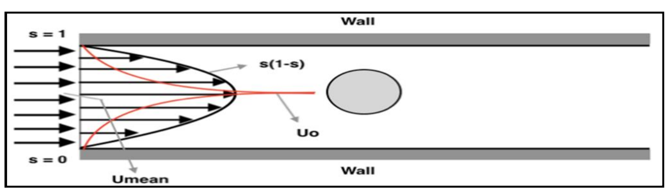


Fig 5: Fully Developed Parabolic Velocity Profile

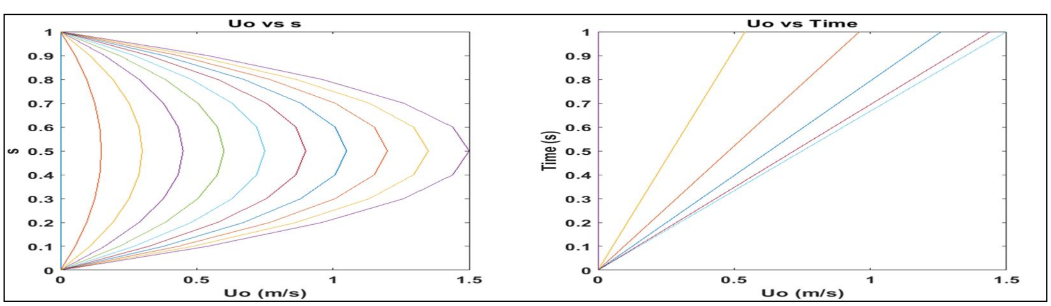


Fig 6: A plot of U_0 as a function of internal variable "s" and time respectively

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue V May 2020- Available at www.ijraset.com

The parameters were initialized to the following values:

Table II: Initialized Values

Mean Inflow Velocity (m/s)	1
Time Duration (s)	7
Diameter of Cylinder (m)	0.1
Density (kg/m^3)	1
Dynamic Viscosity (Pa.s)	1×10^{-3}

The time-dependent study was conducted until the flow was fully developed laminar flow. The laminar flow analysis was conducted at Reynolds number of 200, 90 being the limiting value of the Reynolds number to form von Kármán vortices.

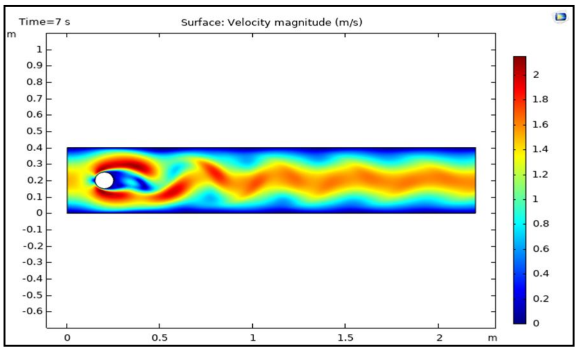


Fig 7: Velocity field

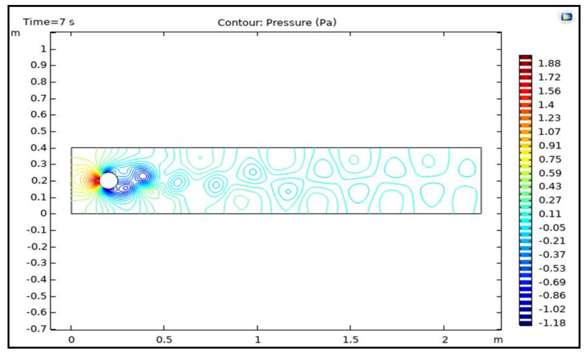
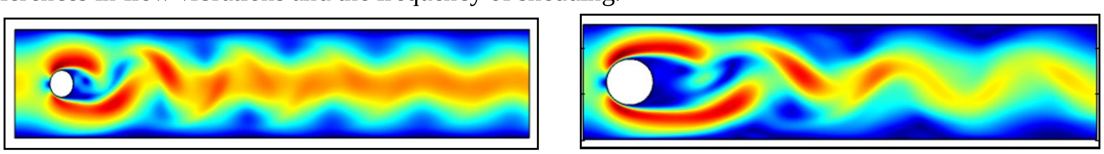


Fig 8: Pressure field

Laminar flow analysis for different diameters and velocities was carried out while maintaining the same Reynolds number to observe the differences in flow vibrations and the frequency of shedding.



(a) (b)

Fig 9: Fluid Velocity Plots of (a) Diameter = 0.1m and (b) Diameter = 0.2m respectively

The results show the Kármán vortex street that can be observed behind the cylinder. If the frequency of shedding matches the natural frequency, resonance transpires and the resultant frequency is amplified which makes the entire system of the bluff body and the piezoelectric energy harvester to be incoherence. This is the main objective which was to be achieved. If the frequencies do not match, the cycle is repeated with fine-tuning of the various parameters. The potential output power is estimated to be close to 50mW [4].

V. FLUID-SOLID INTERACTION

A fluid-structure interaction (FSI) is a multiphysics analysis which describes the coupling between the laws that describe fluid dynamics and structural mechanics, which here is the coupling between the flow behind the cylinder and the deforming piezoelectric material. This phenomenon is characterized by interactions which can be stable or oscillatory between a deformable or moving structure and a surrounding fluid flow. The piezoelectric material is modelled as a deformable moving mesh. It was observed that the resonance phenomenon did not occur at one single frequency but rather it happened in a range of frequencies and this lock-in was a deviation from Strouhal's law. This proved to be advantageous since now, for a range of eigenfrequencies of PVDF and the frequency of vortex shedding, resonance was observed and this increases the total power output. In this case, the cylinder and the piezoelectric material are modelled and analyzed together. A coupled analysis was carried out to verify the results obtained earlier from the computation of laminar flow analysis and solid mechanics study. The FSI analysis was mainly performed to observe the change in eigenfrequency of the piezoelectric material when placed in the downstream region of the bluff body and also due to fluid loading on PVDF. This is a one way coupled fluid-solid interaction, where the deformation of the piezoelectric material can be seen along with the pressure field around it due to fluid forces. The figures below show the bluff body and the piezoelectric material which is being placed in the leeward side of the cylinder and shows the velocity field around PVDF.

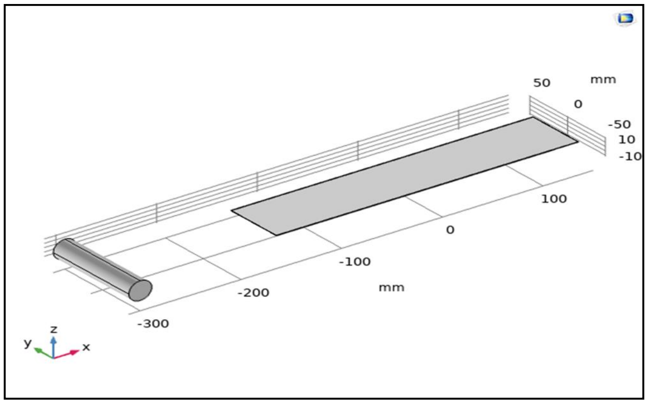


Fig 10: 3D Model of Cylinder and PVDF

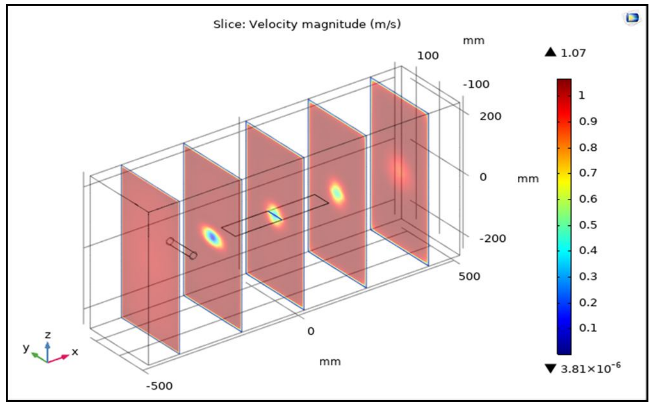


Fig 11: Velocity Field of Fluid

Table III: Eigenfrequencies at different modes

Mode	Eigenfrequency (Hz)
1	8.74
2	54.79
3	69.49
4	154.78
5	215.74
6	306.69

It was observed that from the solid mechanics study and fluid-solid interaction study that the frequency of the individual at mode 2 (Table I) and the system at mode 1 matches.

VI. CONCLUSION

The results of the analyses conducted in this study, inclusive of simulation of Kármán vortex street, proves that PVDF offers better performance when compared to PZT-5A. As the research has demonstrated that the shedding frequency generated by the bluff body through Kármán vortices is nearly equal to the eigenfrequency of the piezoelectric flag. This brings the transducer efficiency to its experimentally maximum value. The novel one-way coupled FSI analysis is proposed to validate the resonance of the system as a whole. This type of energy harvester is suggested to have a wide spectral of applications. This paper inherently provides an alternative methodology to improve the efficiency of energy harvesters by moulding the system in accordance with the energy harvester, as opposed to the conventional need for changing the chemical and physical composition of the harvester.

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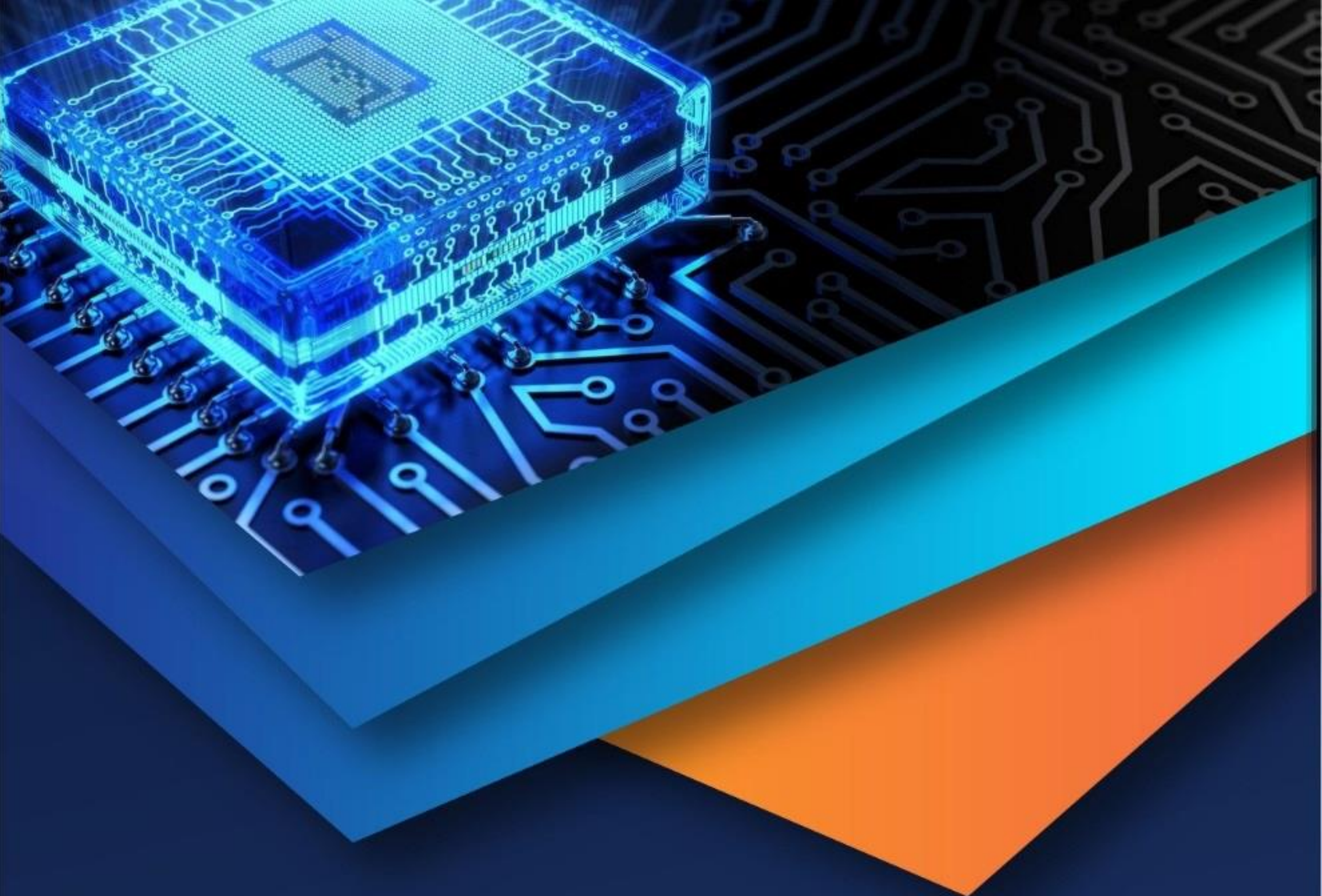

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