DAMPING ENERGY HARVESTING SYSTEM

Inter IIT Tech Meet 9.0

Why harvest it?

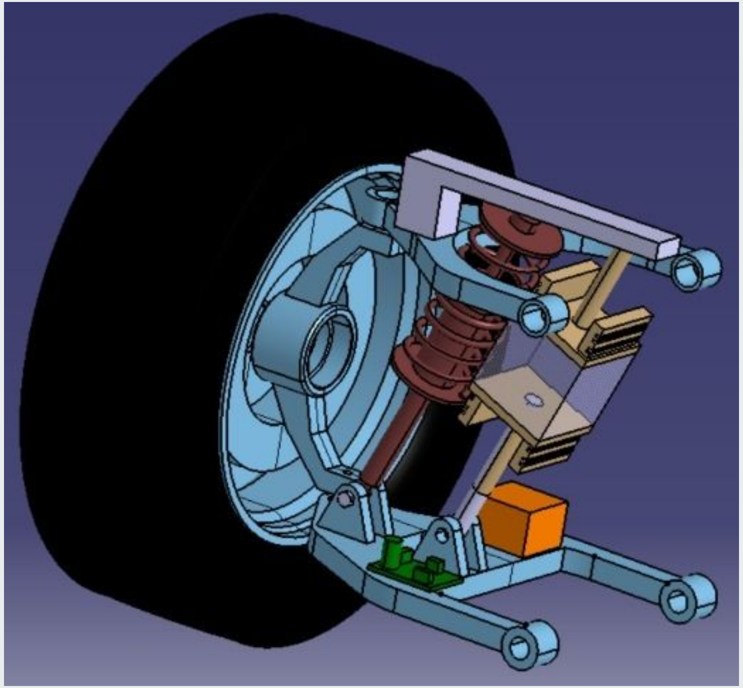
As the world is shifting towards renewable energies, low carbon foot prints, the inclination of automobile industry has already begun towards Electrification. However doing so gave rise to newer constraints like battery size, power savings, etc. Various mechanisms have been developed till date including regenerative braking, use of photovoltaic cells. Though these can be considered as discrete sources of regenerative energy, there is an entry on one mechanism, which can continuously provide regeneration. No wonder, it will revolutionize the market and automobile sector. This is DAMPING ENERGY HARVESTING SYSTEM!

How to harvest it?

Although Piezoelectric and Generator based regenerative mechanisms are quite common, we bring in few Maveric mechanisms, which will soon change the way of how harvesting is done.
They are:

1. **Capacitive Extraction Mechanism**
2. **Triboelectric Generator Mechanism**
3. **LVDT Based Mechanism**
4. **Thermo Electric Generator [TEG] Mechanism**
5. **Vortex Induced Vibration (VIV) Mechanism**

Capacitive Extraction Mechanism



Working Principle

Altering distance between capacitor plates causes changes in the capacitance thereby leading to a change in the stored electrical energy, which can be harnessed

Literature Survey

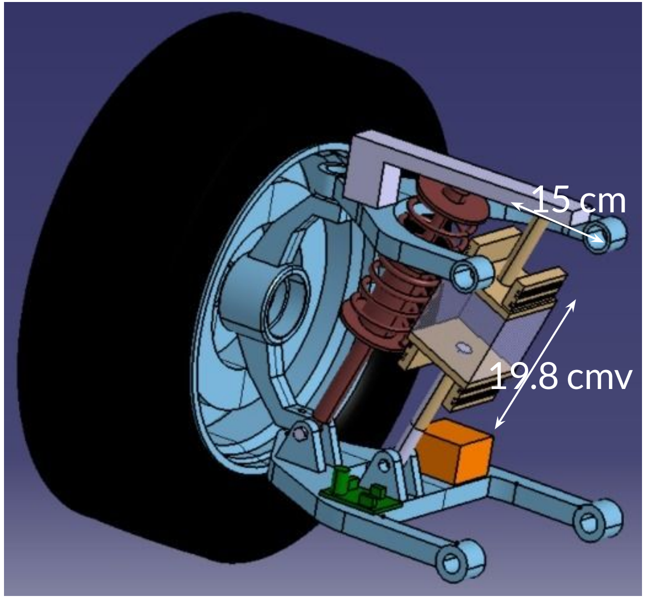
Title	Authors	Year	Summary
[1] Power MEMS—A capacitive vibration-to-electrical energy converter with built-in voltage	Ingo Kuehne, Alexander Frey, Djordje Marinkovic, Gerald Eckstein, Helmut Seidel	2006	Studied generation of electricity in an MEMS device using varying capacitances, which was altered for our use

Methodology

- The lower plate is held fixed whereas the upper plate moves with changes in the road surface
- Initially, the top and bottom parts maintain a small a separation distance with each other, the plates are given an external charge, hence we effectively have a capacitor between the two terminals
- When the suspension vibrates(top plate is made of zinc and bottom is a nickel plate) the capacitance alters hence a current flows, which can be rectified to convert it into DC
- The flowing current is used to power a load or is stored for future use.

System Layout

Material | Components	Weight	Quantity	Cost (in Rs)
GP10W-E3/73 - Diode Rectifier	0.01 kg	4	4x30.66 = 122.64
Nickel Sheet	1.33 kg	1	50
Zinc Sheet	1.07 kg	1	50
PCB	0.2 kg	1	1620



System Dimension : 150cm^2 x 8.21cm
System Weight : 3 kg, Cost: 1842.64 Rs

everything on this slide is referenced from [1]

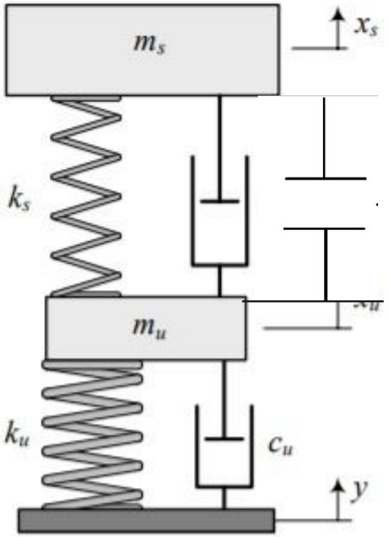
Governing Equations

$$i(t) = \frac{V_{out}}{R_L} = \frac{\phi_1 - \phi_2}{eR_L} - \frac{q(t)}{C(t) \times R_L}$$

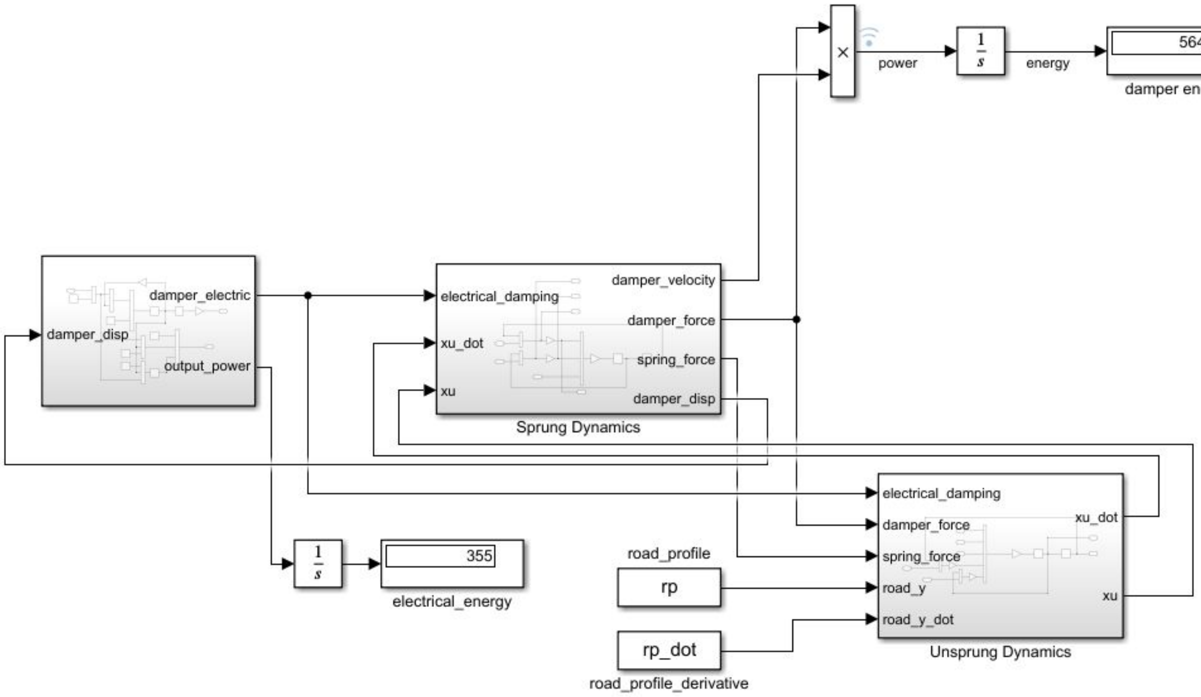
$$C(t) = \frac{A}{g - x(t)}$$

$$m_s a_s = -k_s(x_s - x_u) - c_s(v_s - v_u) + \frac{q^2}{2\epsilon A}$$

$$m_u a_u = k_s(x_s - x_u) + c_s(v_s - v_u) - k_u(x_u - y) - c_u(v_u - d/dt(y)) - \frac{q^2}{2\epsilon A}$$



Simulation (via SIMULINK)



Simulation Results

- Average electrical energy obtained in a span of 120s for 10 runs: 2.958W
- Average Efficiency: 37.85%

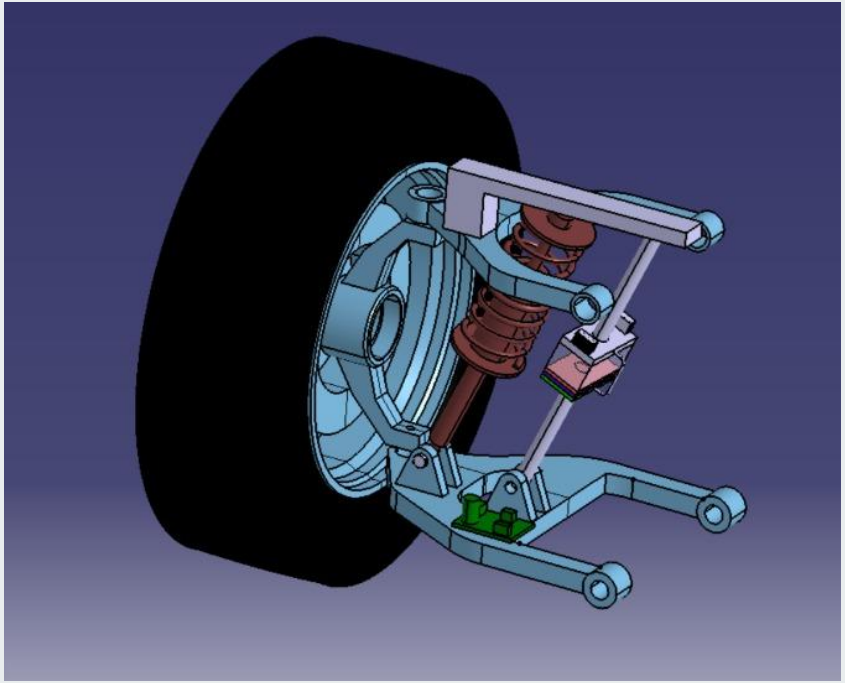
Claimed Points

Model is working : 200 points

Average power in 10 different road profiles = 355/120 = 2.958 W : 29.58 points

Total = 200 + 29.58 = 229.58 points

Triboelectric Generator Mechanism



Working Principle

The working principle of triboelectric energy harvesting is based on the coupling effect of contact charging and electrostatic induction.

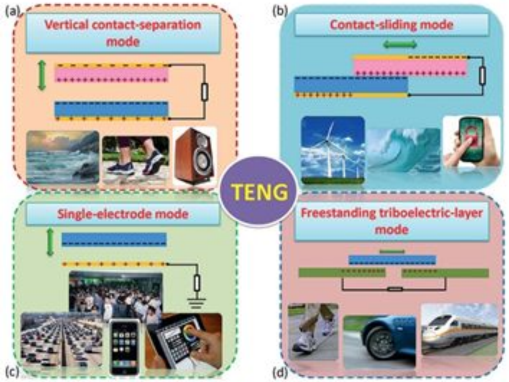
Literature Survey

Title	Authors	Year	Summary
Triboelectric nanogenerators as new energy technology and self-powered sensors – Principles, problems and perspectives [1]	Zhong Lin Wang	2014	Gave an introduction to triboelectric generators, its importance, and its applications. Discussed its principle modes and problems that can occur.
Nonlinear dynamics and triboelectric energy harvesting from a three degree of freedom vibro-impact oscillator [2]	Yiqiang Fu · Huajiang Ouyang · R. Benjamin Davis	2017	Modelled a three DOF triboelectric harvester and performed appropriate simulations
A Two Degree of Freedom Cantilever-Based Vibration Triboelectric Nanogenerator for Low Frequency and Broadband Operation [3]	Gang Tang, Fang Cheng, Xin Hu, Bo Huang, Bin Xu, Zhibiao Li, Xiaoxiao Yan, Dandan Yuan, Wenjing Wu and Qiongfeng Shi	2019	Modelled a 2 DOF cantilever based triboelectric harvester with two generators. Discussed a manufacturing method for triboelectric generator and has demonstrated a vibration testing assembly.

everything on this slide is referenced from [5],
learnings from [6]

Introduction

- There are several ways to harvest vibrational energy some of them are piezoelectric harvester, magnetoelectric harvesters and triboelectric harvesters. Compared to former two, triboelectric harvesters are comparatively new.[6]
- Triboelectric energy harvesting can be done in four principle modes namely[5]:
  1. Vertical contact separation mode
  2. Lateral Sliding mode
  3. Single electrode mode
  4. Freestanding triboelectric layer mode
- In general it is characteristic of triboelectric generators that it has high output voltage and low output current.[5]
- Now, we will be focusing our attention on Vertical contact separation mode

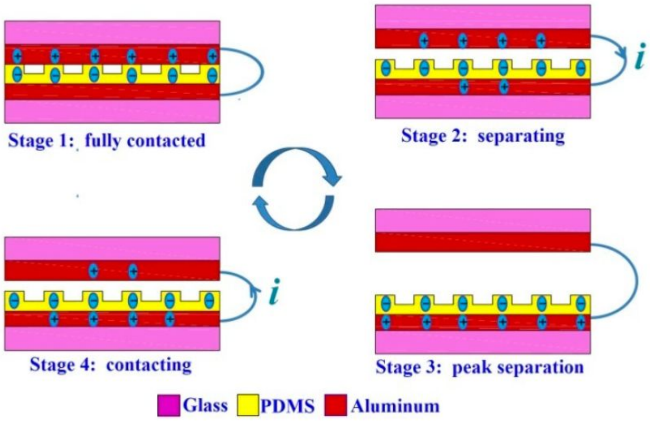


Modes of Triboelectric Energy Harvesting[1]

everything on this slide is referenced from [7]

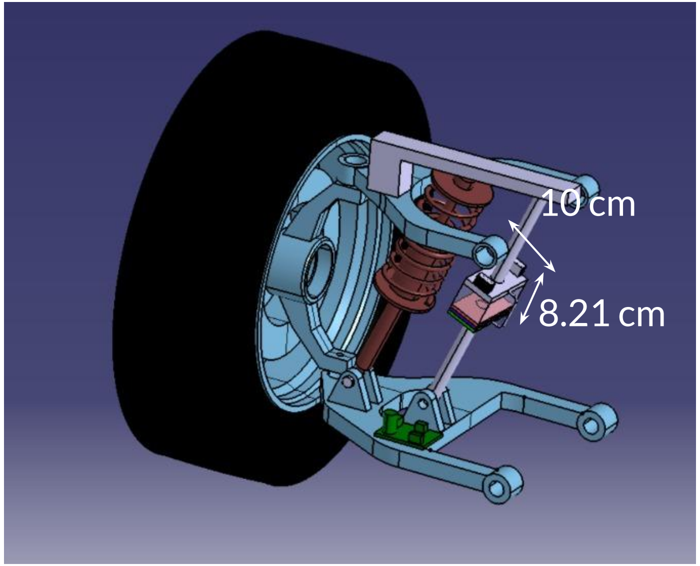
Methodology

- Initially, the top and bottom parts maintain a small a separation distance with each other and at this moment there is no charge on the plates.
- When the suspension vibrates, the top aluminum plate and bottom PDMS (Polydimethylsiloxane) plate with microstructures rub each other and charges are developed. Aluminium develops positive charge being more tribo-electrically positive as compared to PDMS which develops negative charge (Stage 1).
- Now as the plates move away from each other due to vibrations, the electrons from bottom aluminium plate move towards upper aluminium plate resulting on flow of current from top to bottom (Stage 2).
- This continues until the plates are at a position of peak displacement. At this point the current flowing is zero. Now when the plates start moving close the current starts flowing in opposite direction and this continues whenever the vibrations occur.
- The flowing current is used to power a load or is stored for future use.



System Layout

Material | Components	Weight	Quantity	Cost (in Rs)
GP10W-E3/73 - Diode Rectifier	1.2g	4	4x30.66 = 122.64
C44ASG(1)5100ZA0(3) - Capacitor	650g	1	3425
Aluminium	270g	$100cm^2$	16
PDMS sheet	1g	$50cm^2$	10
PCB Printing	100g	$48cm^2$	1620
SS | Springs	< 50 grams	2	50
SS | Vibration Rod	1 kg	1	200
Steel | Pipes	< 1 kg	2	200



Size: 10 cm x 5 cm x 8.21 cm | Weight: 3.1 kg | Cost: Rs 5640

everything on this slide is referenced from [7]

Governing Equations

The potential difference between the plates can be expressed as:

$$V = \frac{\sigma(d + z(t))}{\epsilon_0} - \frac{Q}{A\epsilon_0}\left(\frac{\delta}{\epsilon_P} + d + z(t)\right)$$

where Q is the charge flowing between electrodes, A is the contact area of the triboelectric layers,
ε_0 is the dielectric constant of air, ε_P is the relative dielectric constant of PDMS,
δ is the thickness of the patterned PDMS thin film,
d is the initial distance between top electrode and top surface of the PDMS film,
z(t) is the relative displacement of the top electrode with respect to PDMS layer,
and σ is the surface charge density of the patterned PDMS film.

everything on this slide is referenced from [7]

Governing Equations

The governing equations of this system are as follows:

$$m_1 y_1'' + \eta_1(y_1' - u_0') + k_1(y_1 - u_0) - \eta_2(y_2' - y_1') - k_2(y_2 - y_1) - F_{te} = 0 \quad (1)$$

$$m_2 y_2'' + \eta_2(y_2' - y_1') + k_2(y_2 - y_1) + F_{te} = 0 \quad (2)$$

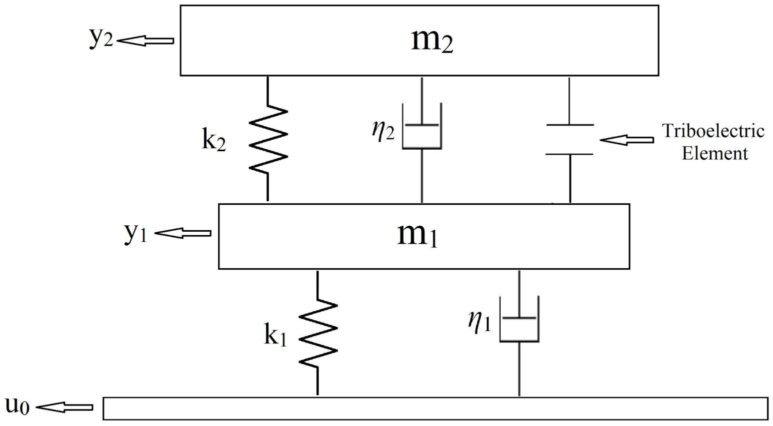
where $F_{te} = \frac{\epsilon_p \epsilon_0 A V^2}{2(u_2 - u_1)^2}$

Taking z_1 and z_2 as $z_1 = u_1 - u_0$ and $z_2 = u_2 - u_1$ where $z(t) = z_2 - z_1$

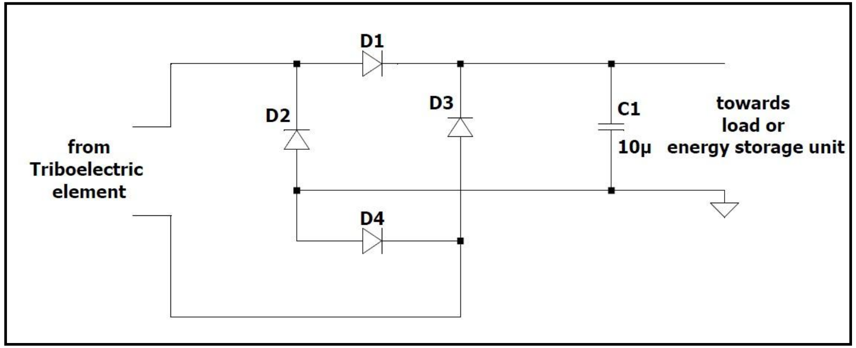
The equations become

$$m_1 z_1''(t) + \eta_1 z_1'(t) + k_1 z_1(t) + m_2 z_2''(t) - F_{te} = -(m_1 + m_2) u_0''$$

$$m_2 u_2'' + \eta_2 z_2'(t) + k_2 z_2(t) + F_{te} = \eta_2 z_2'(t) + k_2 z_1(t) - m_2 u_0''$$

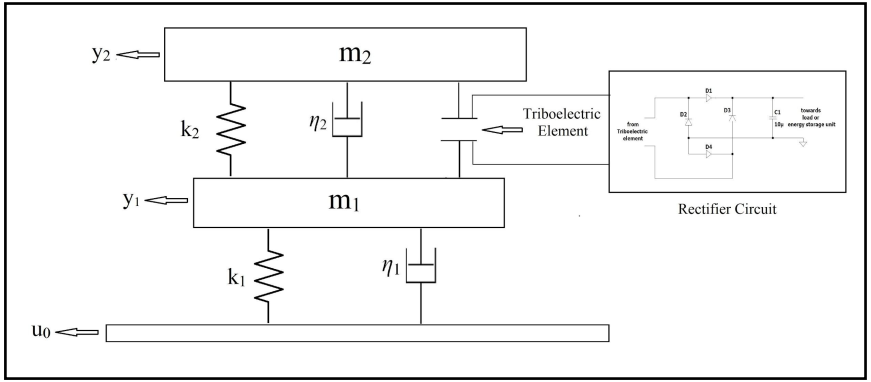


Electrical circuitry



Rectifier circuit along with a capacitor filter has been added to get a near DC output

System Connection



Simulation Results

Sr no.	Electrical Energy(in J)	Average Electrical Power (in W)	Damper Energy(in J)	Total Energy (in J)	Efficiency (%)
1	258.7	2.155	543.9	802.6	32.23274
2	256.6	2.138	543.8	800.4	32.05897
3	299	2.491	616.3	915.3	32.66689
4	245.7	2.047	543.3	789	31.14068
5	277.8	2.315	746	1023.8	27.13421
6	236.7	1.972	543.9	780.6	30.32283
7	233.3	1.944	544.7	778	29.98715
8	255.2	2.126	542.5	797.7	31.99198
9	279.4	2.328	616.3	895.7	31.19348
10	284	2.366	598	882	32.19955

Average Power generated is 2.188 W

Claimed Points

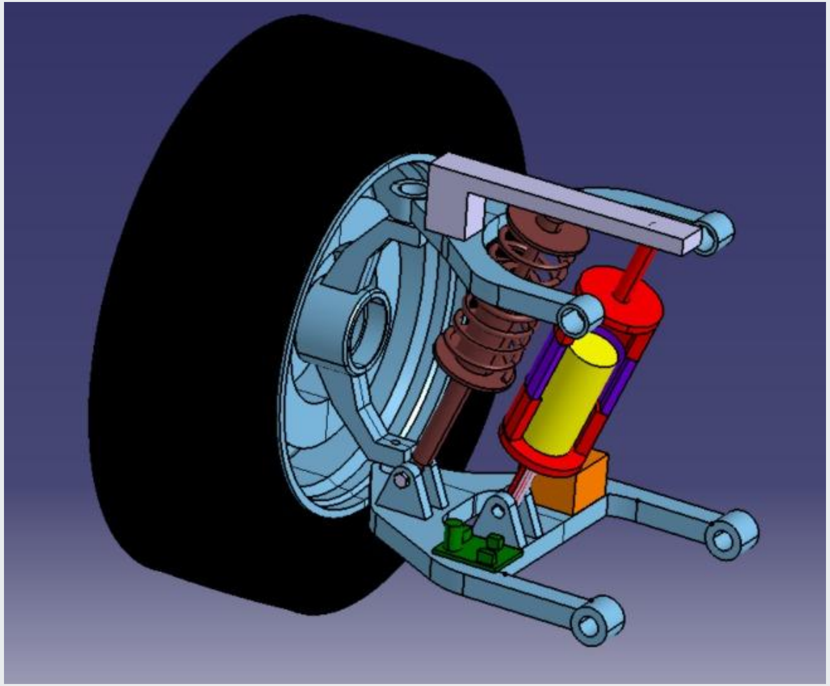
Model is working : 200 points

Average power in 10 different road profiles = 2.188 W : 21.88 points

Total = 200 + 21.88 = 221.88 points

LVDT Based Mechanism

Idea sourced from [2]



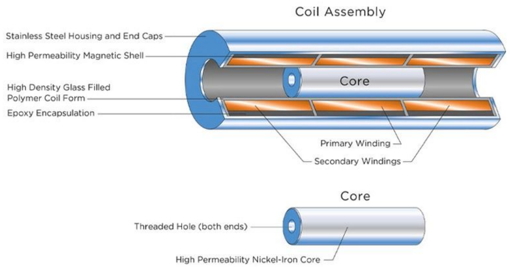
Working Principle

A linear variable differential transformer works on the same principle as the AC transformer but instead of supplying a load current or high voltage, it uses basic transformer principles of mutual inductance to measure linear movement.

everything on this slide is referenced from [4], learnings from [3]

Introduction

- It is a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal.
- The internal structure consists of a primary winding centered between a pair of identically wound secondary windings, symmetrically spaced about the primary. This coil assembly is usually the stationary element of the position sensor.
- The moving element of an LVDT is a separate tubular armature of magnetically permeable material called the core, which is free to move axially within the coil's hollow bore, and mechanically coupled to the damper.
- The primary winding is energized by an AC current.
- The electrical output signal is the differential AC voltage between the two secondary windings, which varies with the axial position of the core within the LVDT coil.



Literature Survey

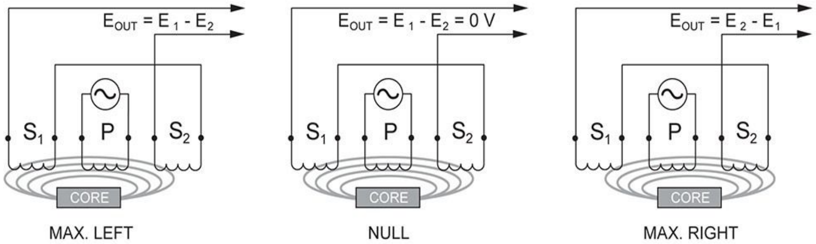
Title	Authors	Year	Summary
Energy regeneration from suspension dynamic modes and self powered actuation	Farbod Khoshnoud, Yuchi Zhang, etc.	2015	Studied energy harvesting from vehicle suspension systems.
Sensitivity Determination of Linear Variable Differential Transducer (LVDT) in Fluid Level Detection Techniques	U. K. Muhammad, S. Umar	2013	Studied use of LVDT to detect fluid levels. The sensitivity of the LVDT due to linear displacement and induced EMF was investigated.

everything on this slide is referenced from [4]

Working Principle and Methodology

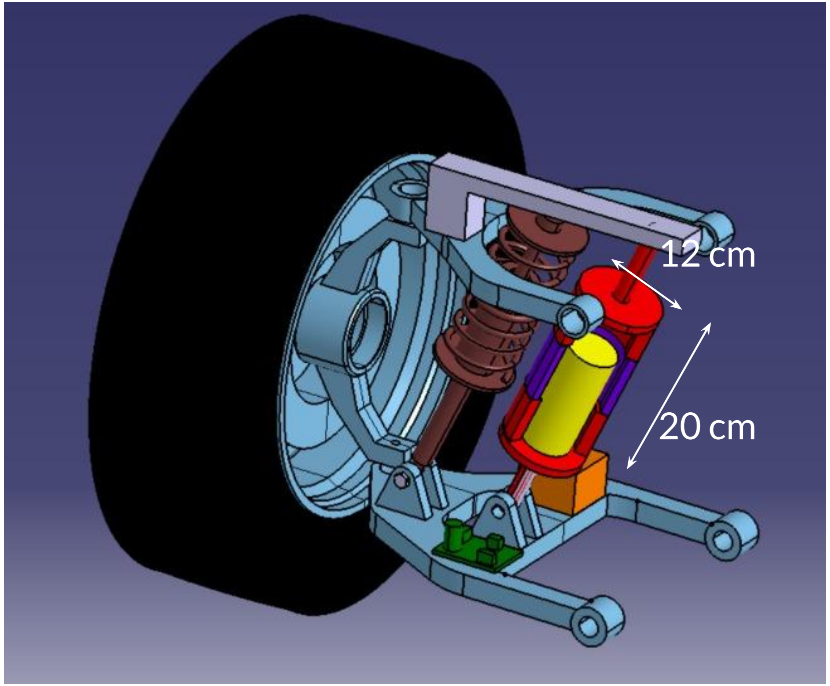
A linear variable differential transformer works on the same principle as the AC transformer but instead of supplying a load current or high voltage, it uses basic transformer principles of mutual inductance to measure linear movement.

- Initially the core is at the null position, with equal flux coupled to both secondary windings.
- When the suspension vibrates, the flux linked to both coils changes and accordingly a differential EMF is generated.
- The value of voltage at maximum core displacement from null depends upon the amplitude of the primary excitation voltage and the sensitivity factor of the particular LVDT.
- The output of an LVDT is very linear over its specified range of core motion, but the sensor can be used over an extended range with some reduction in output linearity.



System Layout

Material | Components	Weight	Quantity	Cost (in Rs)
GP10W-E3/73 - Diode Rectifier	< 50 grams	4	4x30.66 = 122.64
C44ASG(1)5100ZA0(3) - Capacitor	1 g	1	3425
LVDT Sensor	~2 kg	1	2874.00
PCB Printing	< 50 grams	$48cm^2$	1620



Size: 20 cm x 12 cm | Weight: 2.2 kg | Cost: 8041 Rs

Governing Equations

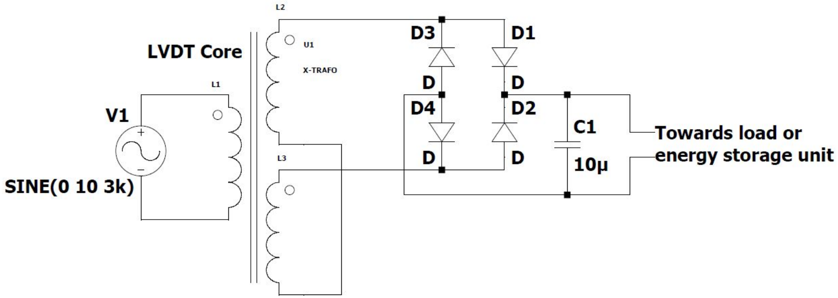
The output voltage can be expressed as: $V_{out} = V_1 - V_2 = MD$,

where V1 and V2 are voltages induced in the two secondary coils, M is the sensitivity(in V/m) of the transducer, and D is the displacement of the core from its mean position.

Sensitivity of the transducer is defined as the ratio of output to input and therefore, it is given by the following equation as:

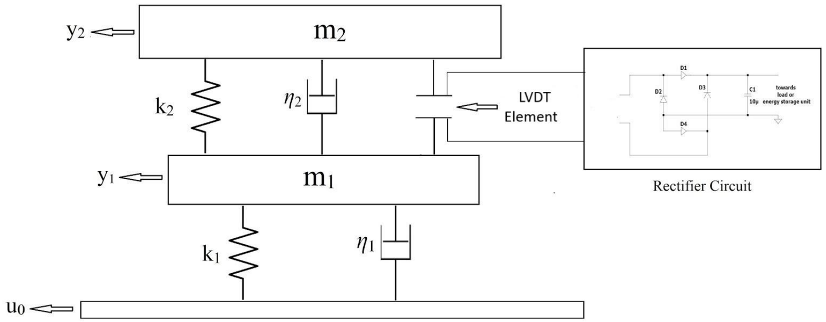
$Sensitivity\ (M) = \frac{N * V_{ex}}{D_{max}}$, where N is the turns ratio, V_{ex} is the excitation voltage applied to the primary coil, and D_{max} is the maximum displacement of the core in its linear region.

Electrical Circuitry

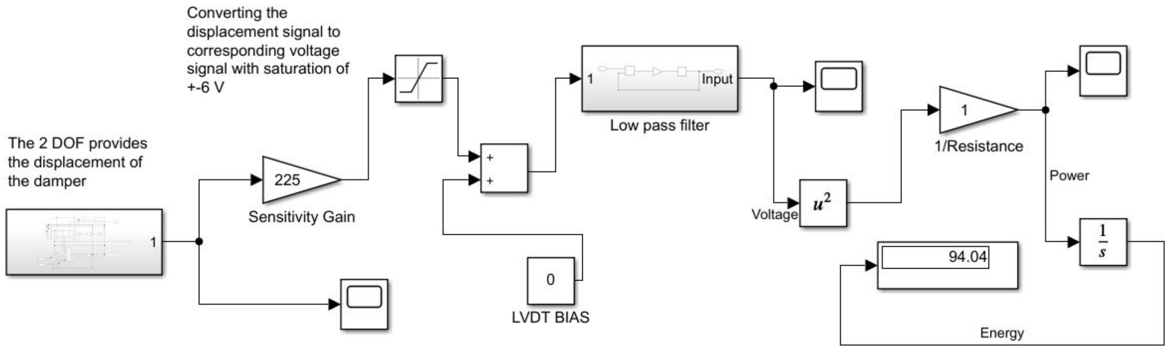


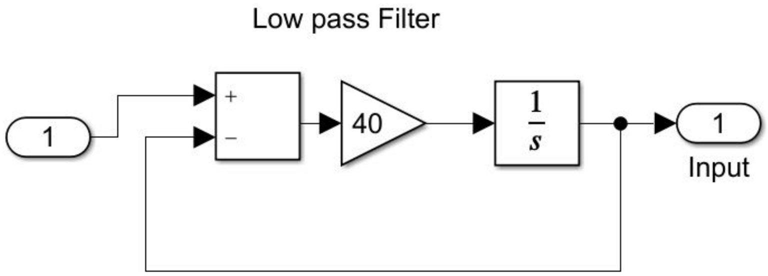
Rectifier circuit along with a capacitor filter has been added to get a near DC output

System Connection



Simulation (via SIMULINK)





Simulation Results

Sr no.	Mechanical Energy(in J)	Average Mechanical Power (in W)	Damper Energy(in J)m	Total Energy (in J)	Efficiency (%)
1	96.84	0.81	550.1	646.94	14.9883
2	101.9	0.85	562.7	664.6	15.3325
3	97.11	0.81	550.6	647.77	14.9914
4	111	0.93	658.2	769.2	16.8641
5	99.32	0.83	561.4	660.72	15.0320
6	106.9	0.89	586	692.9	15.4279
7	115	0.96	638	753	15.2723
8	96.91	0.81	558.3	655.121	14.7927
9	100.3	0.84	582	682.3	14.7003
10	94.04	0.78	542.9	636.94	14.7643

Average Power generated is 0.85 W

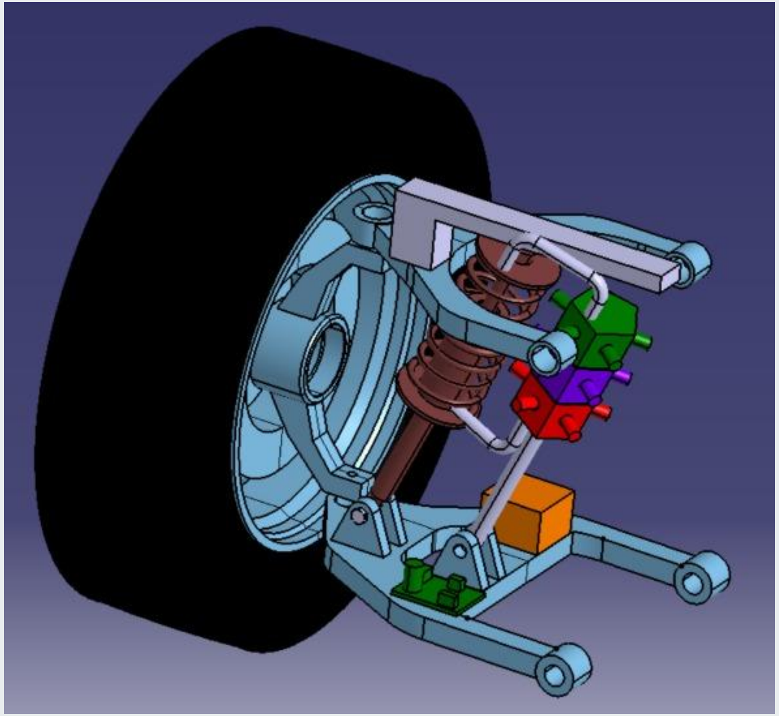
Claimed Points

Model is working : 200 points

Average power in 10 different road profiles = 0.85 W : 8.5points

Total = 200 + 8.5 = 208.5 points

Thermo Electric Generator [TEG] Mechanism



Working Principle

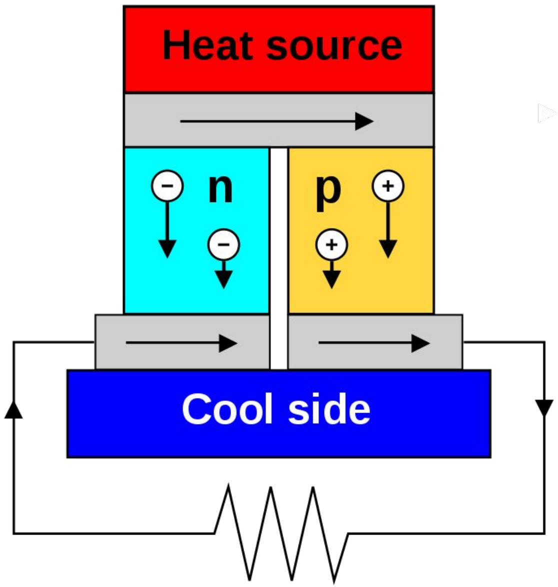
The kinetic energy of the piston in the shock absorber, gets dissipated as heat, which raises the temperature of the damper fluid. This heat energy of the fluid can be used to generate electricity using thermo electric mdules

Literature Survey

Title	Authors	Year	Summary
Experimental Analysis and Heat Transfer Study of Damping Fluid in Shock Absorber Operation[8]	Jignesh Rana, Swastik Gajjar, Ankit Patel	2014	Research work, on fluid’s temperature with respect to the no. of cycles of the damper, gives a fair estimate of the temperature we can take for simulation.

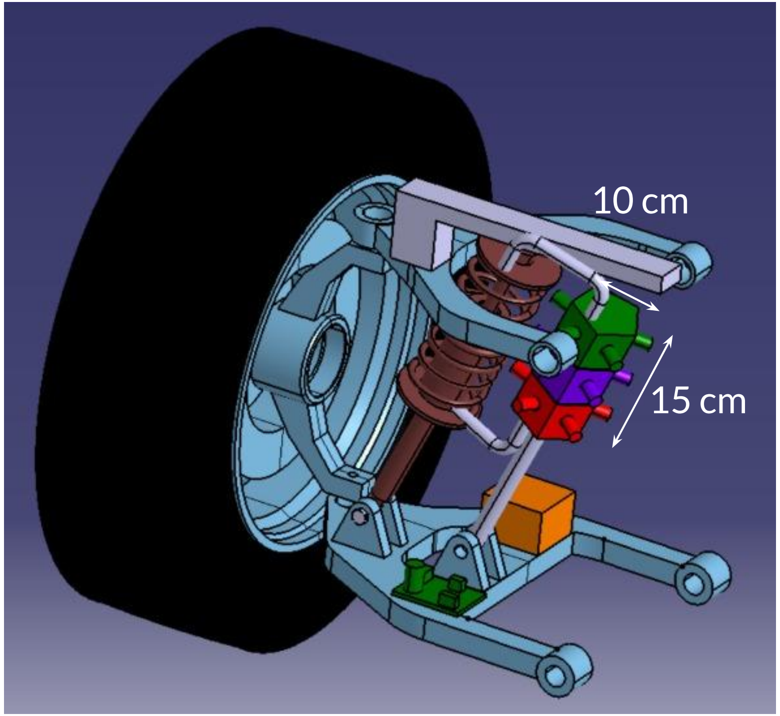
Methodology

- We need to make sure that the TEG modules come in contact with the fluid temperature. For this we have a separate tank connected to the damper. One end of the tanker connects to the region above the damper piston and and the other end to the region below. In this way the continuity in the damper fluid is maintained. Also this setup demands a completely new shock absorber for the car.
- The walls of the tanker are made from copper and the outside walls are where the TEG modules placed with their one surface in contact with the outer copper wall. Copper is chosen so that the walls can have the same temperature of the damping fluid, due to copper's high thermal conductivity.



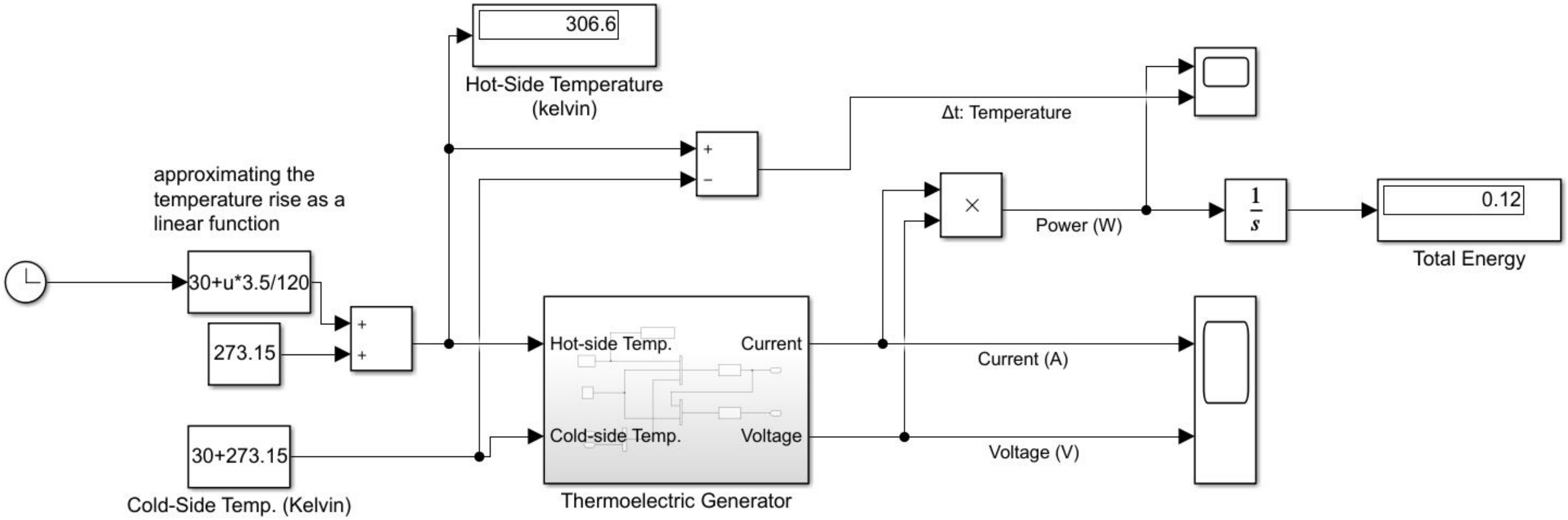
System Layout

Material | Components	Weight	Quantity	Cost (in Rs)
Std. | Thermo-electric Sensors	1kg (Total)	15	2550 (total)
GS | Oil Reservoir	4 kg (Filled)	1	500
Steel | Integrated pipes	< 1 kg	2	200
Std. | Rectifier diodes and Capacitor	< 1 kg	4 +1	50



Size: 10 cm x 15 cm | Weight: 7 kg | Cost: 3300 Rs

Simulation (via SIMULINK)



Simulation Results

- The simulations for the given setup are performed by using a reference simulink model[11]. The parameters used for simulation are changed to suit our temperature change, by referring to the specifications[12] of the TEG module of size 5.6 cm by 5.6 cm.
- From the given road profile we can assume that there are approximately 4 cycles of undulations in a second in the road, that results in 4 cycles of damper's motion, so in 120 seconds we get approximately 500 cycles, and from the reference literature on the fluid's temperature we can assume that there is approximately 3.5 degrees rise in temperature[8], and then linearizing the model with time, we run the simulation in simulink to get the following results:
- **TOTAL ENERGY = 0.12 J, AVERAGE POWER = 0.001 W,**
- And since we are going to fit in approximately 15 TEG modules in the set up (three rows of five each), total estimated power is **0.015 W.**

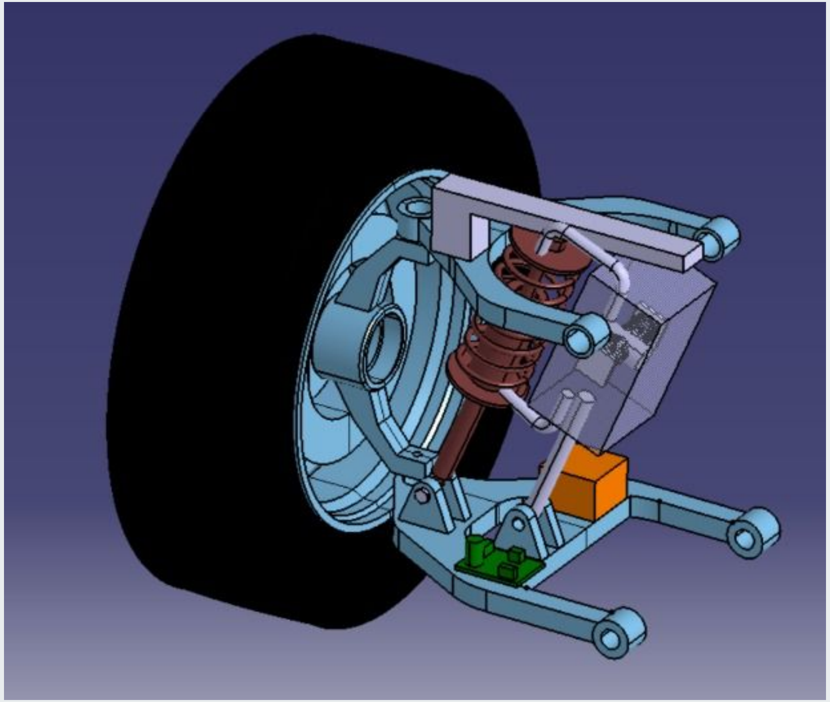
Claimed Points

Model is working : 200 points

Average power in 10 different road profiles = 0.015 W : 0.15 points

Total = 200 + 0.15 = 200.15 points

Vortex Induced Vibration (VIV) Mechanism



Working Principle

The flow energy associated with vortex shedding when flow over a cylinder, can be utilized for conversion of vibrational energy to other useful form. The vibrations which will be induced by the vortex (VIV) can be looked upon as conversion to mechanical energy.

Literature Survey

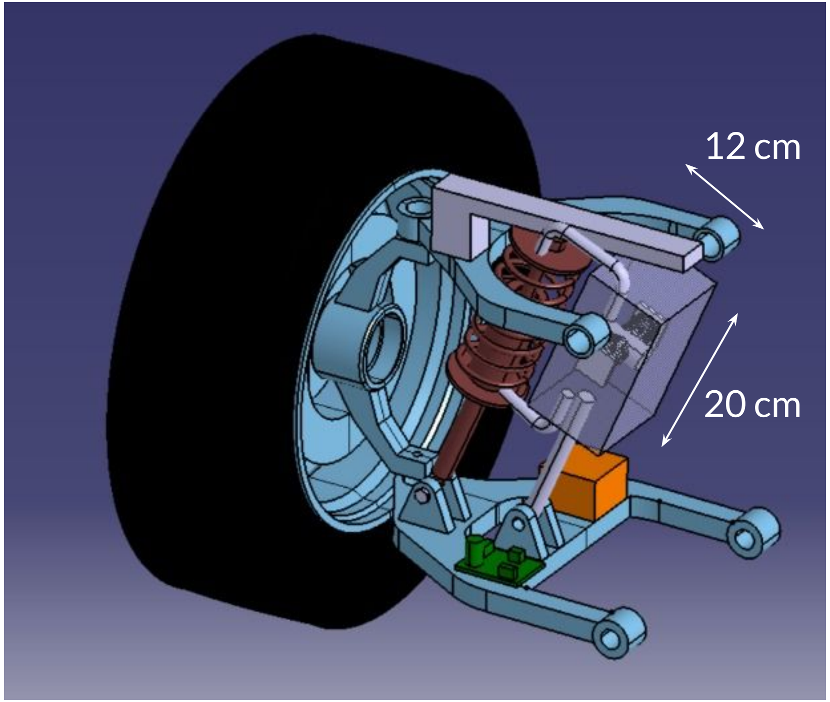
Title	Authors	Year	Summary
Passive vibration control of cylindrical offshore components using pipe-inpipe (PIP) concept: An analytical study	Hamid Matin Nikoo, Kaiming Bi	2017	Studied the Vortex Induced Vibration effect of Ocean waves in mechanical poer generation
Design Feasibility of a Vortex Induced Vibration Based Hydro-Kinetic Energy Harvesting System	Arindam Banerjee, J.W. Kimball	2011	Used the VIV (Vortex Induced Vibration) technique to develop a VIV generatorfor energy harvesting from Kinetic energy sources

Methodology

- The setup consists of integrated spring damper with a vibration rod suspended oil reservoir.
- With actuation of the suspension from road profile, the vibration will be captured by the fluid motion within the internal circuit A flow will be setup, whose velocity will keep changing with road profile.
- This flow is made to pass over a cylinder, causing the vortex shedding formation due to boundary layer phenomena.
- The net lift from the flow sets the oscillations of vibration rod. This mechanical energy can be later converted to electrical energy using load cells/capacitor modules.

System Layout: VIV

Material | Components	Weight	Quantity	Cost (in Rs)
SS | Springs	< 50 grams	2	50
SS | Vibration Rod	1 kg	1	200
GS | Oil Reservoir	5 kg (Filled)	1	500
Steel | Pipes	< 1 kg	2	200
Std. | Rectifier diodes, Capacitor	< 50 grams	4+1	100



Size: 20 cm x 12 cm | Weight: 7.1 kg | Cost: 1050 Rs

Governing Equations

$$m\ddot{y} + 2m\omega_n\zeta_s\dot{y} + m\omega_n^2 y = F_{fluid}(t) = F_L - F_R$$

$$\ddot{y} + 2\omega_n\zeta_s\dot{y} + \omega_n^2 y = \beta\omega_s^2 C_{fluid}(t)$$

$$\beta = \rho D^2/8\pi^2 S_t^2 m$$

$$C_{fluid}(t) = C_F \sin(\omega t + \varphi)$$

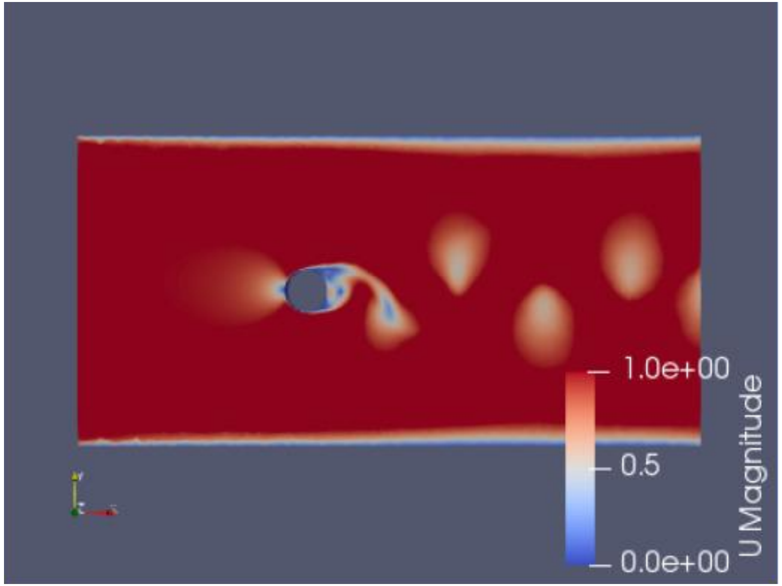
$$\ddot{y} + 2\omega_n\zeta_s\dot{y} + \omega_n^2 y = \beta\omega_s^2 C_F \sin(\omega t + \varphi)$$

Where m is the mass of the oscillating system, ωn is the natural frequency of the structure and ζs is the structural damping ratio. Cfluid (t) is the time-varying fluid coefficient on the oscillating structure defined by Cfluid (t) = CL−CR.

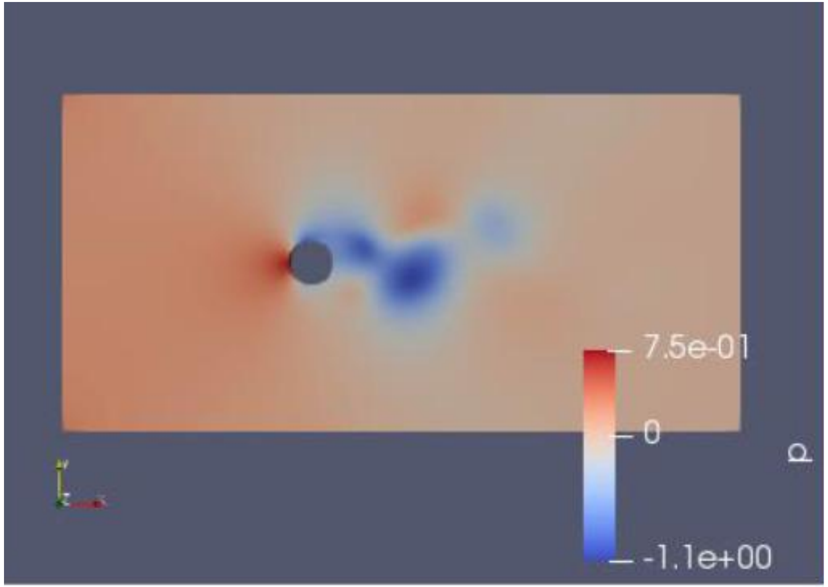
The differential equations were solved using Simulink. All required constants were referred from the papers cited [9.].

Simulation (via OpenFOAM for Vortex Generation)

Velocity Plot (for VIV mechanism)

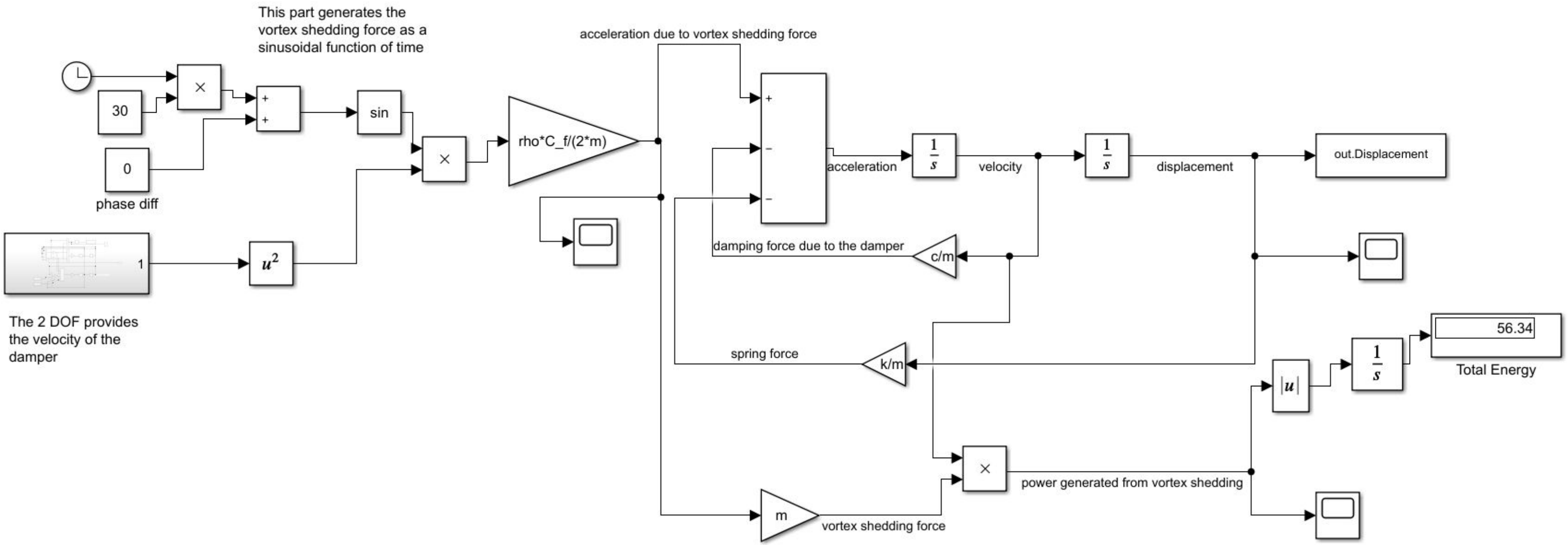


Pressure Plot (for VIV mechanism)



Average lift coefficient using Transient Flow solver PIMPLEFOAM is 1.57

Simulation (via SIMULINK)



Simulation Results

Sr no.	Mechanical Energy(in J)	Average Mechanical Power (in W)	Damper Energy(in J)m	Total Energy (in J)	Efficiency (%)
1	57.97	0.48	533.9	591.87	9.7943
2	65.82	0.55	531.8	597.62	11.0136
3	72.41	0.61	534	606.41	11.9408
4	68.44	0.57	514.7	583.14	11.7365
5	52.8	0.44	534.4	587.2	8.9918
6	56.34	0.47	533.7	590.04	10.5565
7	60.19	0.50	530.2	590.39	10.1950
8	57.68	0.48	529.1	586.78	9.8299
9	62.53	0.52	533.5	596.03	10.4911
10	71.31	0.59	519.6	590.91	12.0678

Average Power generated is 0.52 W

Claimed Points

Model is working : 200 points

Average power in 10 different road profiles = 0.52 W : 5.2 points

Total = 200 + 5.2 = 200.52 points

SUMMARY (ALL MECHANISMS)

Mechanism Name	Dimension	System Weight	Power Output (W)	Overall Efficiency (%)	System Cost
Capacitive Extraction Mechanism	150cm^2 x 8.21cm	3 kg	2.958 W	37.85	1842.64 Rs
Triboelectric Generator Mechanism	10 cm x 5 cm x 8.21 cm	3.1 kg	2.188 W	32.05	5640 Rs
LVDT Based Mechanism	20cm x 12 cm Dia	2.2 kg	0.85 W	15.21	8041 Rs
Thermo Electric Generator [TEG] Mechanism	15 cm x 10 cm Dia envelope	7 kg	0.015 W	0.3	3300 Rs
Vortex Induced Vibration (VIV) Mechanism	20 cm x 12 cm Dia envelope	7.1 kg	0.52 W	10.19	1050 Rs

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