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Harvesting of Kinetic Energy of the Raindrops

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***Abstract*—**This paper presents a methodology to harvest the kinetic energy of the raindrops using piezoelectric devices. In the study 1m×1m PVDF (Polyvinylidene fluoride) piezoelectric membrane, which is fixed by the four edges, is considered for the numerical simulation on deformation of the membrane due to the impact of the raindrops. Then according to the drop size of the rain, the simulation is performed classifying the rainfall types into three categories as light stratiform rain, moderate stratiform rain and heavy thundershower. The impact force of the raindrop is dependent on the terminal velocity of the raindrop, which is a function of raindrop diameter. The results were then analyzed to calculate the harvestable energy from the deformation of the piezoelectric membrane.

***Keywords*—**Raindrop, piezoelectricity, deformation, terminal velocity.

I. Introduction

THE raindrops falling from high altitudes have a significant kinetic energy, which is stored while them falling. One of the methods to harvest this energy is to store the rain water at a high elevation and converting that potential energy into kinetic energy and then into electrical power through hydro turbines, which is the concept of hydro power generation. However this method has certain limitations, because to install a hydro power plant it requires an appropriate geographical location with water storage at an elevation. Another method to harness this energy is to harvest it by means of piezoelectric devices which are capable of converting stress into electrical power. However for the piezoelectric materials to generate electricity, the material should undergo vibration. Therefore other than the strain energy resulting from stress, it is the vibration energy, which should be given concern regarding energy harvesting by piezoelectric materials.

The energy harnessed from raindrops which is a non-conventional energy source is greener and it is at micro level. But it is sufficient to power low energy density applications such as sensors and Micro-Electro Mechanical Systems (MEMS). Therefore this method has a high applicability in developing self-sustained, independent sensors and MEMS applications which do not need an external power source. Moreover it plays a vital role in micro level power generation, when solar power generation is not available.

The amount of rain, raindrop size and the terminal velocity are the major factors in determining the harvestable energy from the aforementioned methodology. According to a research study, in France the raindrop size vary from 1mm to 5mm in diameter [1].

In the research study we have performed a numerical analysis using MATLAB on the deformation of the piezoelectric membrane due to the raindrop impact. The analysis is undertaken for three types of rain, which can be described as light stratiform rain (LSR), moderate stratiform rain (MSR) and heavy thunderstorm (HT).

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II. Behaviour of a Raindrop

A. Terminal Velocity of a Raindrop

For the determination of the terminal velocity of the raindrop, it is considered that the raindrop is spherical.

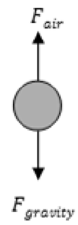

Fig. 1 Force acting on a spherical falling water drop

The drag force acting on the raindrop vertically upwards,

$$F_{air} = \frac{1}{2}\rho_a A C v^2 \quad (1)$$

The weight of the raindrop,

$$F_{gravity} = \frac{4}{3}\Pi r^3 \rho_w g \quad (2)$$

The raindrop reaches its terminal velocity, when the forces get balanced.

$$v = \sqrt{\frac{\Pi d^3 \rho_w g}{6\rho_a A C}} \quad (3)$$

According to the derived formulae the terminal velocity depends on raindrop diameter (d) and the drag coefficient (C). The formula for the terminal velocity is valid if the assumption of spherical shape of the raindrop is correct. But the shape of the raindrop is constantly changing due to the air resistance.

The shape changing nature of the raindrop due to the air resistance depends on the size of the drop. For drop sizes of 1mm and below, the shape is almost spherical, but it shape change gradually increases when the diameter of the raindrop increases. All tables and figures you insert in your document are only to help you gauge the size of your paper, for the convenience of the referees, and to make it easy for you to distribute preprints.

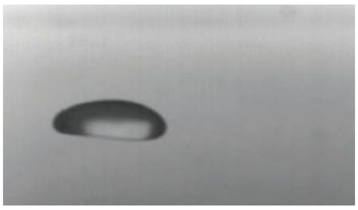

Fig. 2 Water droplet encountering air resistance

Fig. 3 Change of shape of raindrop with the diameter

B. Scenarios of Raindrop Impact

During a raindrop impact on a solid surface, three different types of behaviors can be observed; namely splashing, spreading and bouncing [2], [3] as illustrated in the Fig. 4. A raindrop impinging on a solid surface may adhere to bounce off the surface and break up after impact or it can spread quickly. The former case is called, "splashing". In order to predict the behavior of the impact of a raindrop on a solid surface and to understand the scenario of splashing, several studies have been carried out.

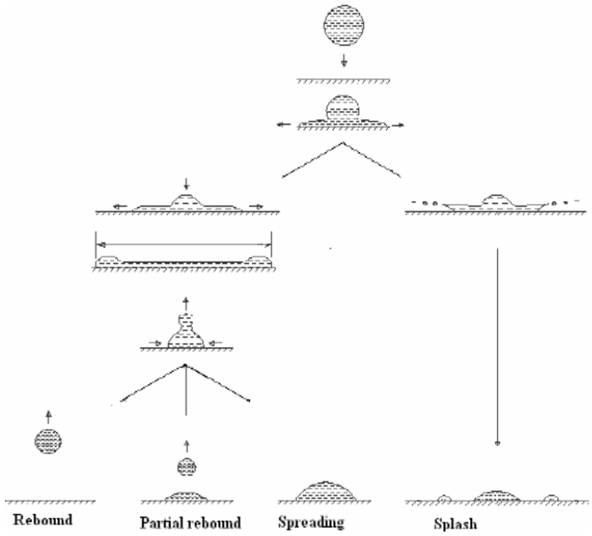

Fig. 4 Scenarios of water drop impact on a solid surface

A splash parameter has been established for the occurrence of splash, by Stow and Hadfield [4] in which they have shown that the splash parameter depends on the surface roughness. The correlation between the splashing/deposition limit is expressed as,

$$Re^{0.31} \times We^{0.69} = \xi \tag{4}$$

The splash deposition value (ξ) is dependent upon the surface roughness. Based on experiments, Mundo et al. [5] determined the limit between the splashing and deposition.

$$K = Oh \times Re^{1.25} > 57.7 \tag{5}$$

According to the formula, if K is greater than 57.7, the impact of the raindrop is in splashing regime. However this empirical formula does not capture the effect from surface roughness, which affects the contact angle between the liquid drop and the solid surface. Filling this gap, Thoroddsen and Sakakibara [6] carried out experimental studies showing that Mundo's criteria on splashing regime tends to be ineffective when the surface roughness is accounted for. Therefore according to their results, rougher the solid surface it will trigger splashing of raindrops.

C. Force Exerted on a Solid Surface by a Raindrop

In this paper we have focused on the raindrop splashing on a solid surface. According to the research study carried out by Guigon et al. [1], in their analysis they have used Mundo's criteria[5] and they have assumed that the impact of the splash mode is very close to the inelastic impact of a ball on a plate.

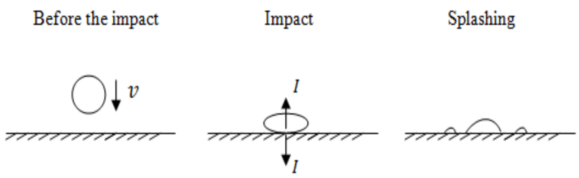

Fig. 5 Impact force on a surface by a raindrop

Therefore, the momentum transferred to the solid surface by the impact of the raindrop can be determined by applying Newton's experimental law and the Newton's second law.

Newton's experimental law states that during a collision of elastic objects, the ratio of relative velocities of the two objects determined in the direction of the common perpendicular constructed at the pint of impact after and before the impact is a constant and opposite in direction. This constant is termed as dynamic elastic coefficient and varies from 0 to 1.

$$0 \leq e \leq 1 \tag{6}$$

$e = 0;\ for\ perfectly\ inelastic\ impacts$
$e = 1;\ for\ perfectly\ elastic\ impacts$

Applying Newton's experimental law,

$$e = \frac{U}{v} \tag{7}$$

U is the velocity of the raindrop after impact (splashing) relative to the solid surface along the common perpendicular while v is the velocity of the raindrop before the impact relative to the solid surface along the common perpendicular. Since the collision is inelastic (e=0), U is equal to zero.

Applying Newton's second law on the raindrop,

$$I = mU - (-mv) = mv \tag{8}$$

According to Newton's third law, the impulse on the surface is equivalent to the impulse on the raindrop. The impact force on the solid surface is calculated by,

$$F = \frac{I}{\delta t} = \frac{mv}{\delta t} \tag{9}$$

In the formula, δt is an infinitesimal time value. But in our study we have considered a definite time value of 1s for the determination of impact force on the solid surface exerted by the raindrops.

III. Raindrop Energy Harvesting By Piezoelectric Materials

A. Selection of Piezoelectric Materials and Coupling Mode

Piezoelectricity describes the phenomenon of generating an electric charge in a material when subjected to a mechanical stress, which is considered as the direct stress and the converse effect is generating a strain in response to an applied electric field.

The piezoelectric materials should be selected according to the application in which piezoelectric materials are used to harness power. PZT (Lead ZirconateTitanate) is the widely used piezoelectric material. But its nature of extremely brittleness causes limitations for it to be used in harvesting raindrop energy, because the high frequency cyclic loading exerted on the piezoelectric membrane will cause fatigue failure. Therefore more flexible, lightweight and a piezoelectric material with low acoustic and mechanical impedance, PVDF (Polyvinylidene fluoride) is used [7].

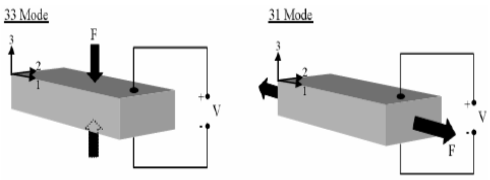

Fig. 6 Coupling modes of piezoelectric material

In order to increase the energy harvesting by the raindrops, it is important to use more efficient coupling method. The practical coupling methods which are being used are the 33coupling method and the 31 coupling method. In the 33 coupling the force is applied in the direction parallel to the poling direction while in the 31 coupling method the force is applied in the direction perpendicular to the poling direction.

TABLE I
Piezoelectric Properties of PVDF [8]

Property	Quantity	Units
Strain coefficient(d_{31})	20	10^{-12} m/v
Piezoelectric constant(g_{31})	0.21	Vm /N
Coupling coefficient(k_{31})	0.11	[-]
Dielectric constant	12	$\varepsilon/\varepsilon_0$

The application of energy harnessing of the raindrops involves a small force and the vibrational level is low. In such conditions 31 mode (cantilever configuration) proved most efficient in energy harvesting [9].

B. Raindrop Size and Terminal Velocity

According to the meteorological results, rain can be classified into three types as light stratiform rain (LSR), moderate stratiform rain (MSR) and heavy thunderstorms (HT) [10]. Table II provides the raindrop sizes, meteorological experimental terminal velocities and the theoretical terminal velocities.

TABLE II
Properties of Rain Types

Rain type	Drop size (mm)	Terminal velocity (Experimental) (m/s)
Light stratiform rain		
Small	0.5	2.06
Large	2.0	6.49
Moderate stratiform rain		
Small	1.0	4.03
Large	2.6	7.57
Heavy thundershower		
Small	1.2	4.64
Large	4.0	8.83
Largest	5.0	9.09

Another important data is the number of raindrops per unit area per unit time.

TABLE III
Number of Raindrops per Unit Time on Unit Area

Rain type	Number of rain drops (per 1s on 1m^2)
Light stratiform rain	280
Moderate stratiform rain	495
Heavy thundershower	818

C. Force on the Piezoelectric Membrane from Raindrops

The force on the piezoelectric membrane is caused by the impulse of the raindrop exerted on the surface during a time frame of one second. Table IV provides the force calculation of the raindrop impulse for different rain types.

TABLE IV
Force Calculation of Raindrop for Rain Types

Rain type	Drop size (mm)	Raindrop mass (kg)	Force calculation (N)
LSR			
Small	0.5	7.0 e-8	1.0 e-7
Large	2.0	4.19 e-6	2.72 e-5
MSR			
Small	1.0	5.2 e-7	2.1 e-6
Large	2.6	9.2 e-6	6.97 e-5
HT			
Small	1.2	9.0 e-7	4.2 e-6
Large	4.0	3.351 e-5	2.959 e-4
Largest	5.0	6.545 e-5	5.949 e-4

IV. Numerical Analysis

A. Simulation Model for Numerical Analysis

The simulation model selected for the numerical analysis is a PVDF piezoelectric membrane with a length of 1m and width of 1m. It is considered that the membrane is simply supported at the four edges of the plate. The material is assumed to isotropic. The deformation of the PVDF membrane from the impact force of the raindrop is determined from the governing equation for the transverse deflection.

TABLE V
Mechanical Properties of PVDF

Property	Quantity	Units
Young's modulus(E)	3	10^9 N/m^2
Poisson ratio(μ)	0.34	[-]
Material density (ρ)	1780	kg/m^3

B. Modeling of Transverse Deformation

The governing equation of transverse deformation of a simply supported plate is given by (10):

$$\nabla^4 w = \frac{q}{D} \qquad (10)$$

The determination of transverse deformation is accomplished by finite difference method (FDM) [12]. For this, $m \times n$ mesh is selected and the governing equation is discretized and region of interest is categorized according to the boundary conditions. According to the problem the regions of interest are classified for three sections; inner nodes, boundary nodes and special nodes.

Discretized equation for inner nodes,

$$20w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i-2,j} + w_{i+2,j} + w_{i,j-2} + w_{i,j+2} = \frac{h^4 q_{i,j}}{D} \qquad (11)$$

The boundary of the PVDF membrane consists of four edges, which are simply supported; the right, left, top and bottom boundary edges. Therefore the discretized equations are separately defined for the four boundary edges.

Discretized equation for nodes of the left boundary edge,

$$19w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i+2,j} + w_{i,j-2} + w_{i,j+2} = \frac{h^4 q_{i,j}}{D} \qquad (12)$$

Discretized equation for the nodes of the right boundary edge,

$$19w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i-2,j} + w_{i,j-2} + w_{i,j+2} = \frac{h^4 q_{i,j}}{D} \qquad (13)$$

Discretized equation for the nodes of the upper boundary edge,

$$19w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i-2,j} + w_{i+2,j} + w_{i,j-2} = \frac{h^4 q_{i,j}}{D} \qquad (14)$$

Discretized equation for the nodes of the lower boundary edge,

$$19w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i-2,j} + w_{i+2,j} + w_{i,j+2} = \frac{h^4 q_{i,j}}{D} \qquad (15)$$

There are four special nodes at the locations of (2,2), (2,n-1), (m-1,2) and (m-1,n-1) which should be separately considered and their discretized equations are considered for the analysis distinctly.

Discretized equation for the (2, 2) node,

$$18w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i+2,j} + w_{i,j+2} = \frac{h^4 q_{i,j}}{D} \qquad (16)$$

Discretized equation for (2, n-1) node,

$$18w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i+2,j} + w_{i,j-2} = \frac{h^4 q_{i,j}}{D} \qquad (17)$$

Discretized equation for (m-1, 2) node,

$$18w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i-2,j} + w_{i,j+2} = \frac{h^4 q_{i,j}}{D} \qquad (18)$$

Discretized equation for (m-1, n-1) node,

$$18w_{i,j} - 8w_{1-1,j} - 8w_{i+1,j} - 8w_{i,j-1} - 8w_{i,j+1} + 2w_{i-1,j-1} + 2w_{i+1,j-1} + 2w_{i-1,j+1} + 2w_{i+1,j+1} + w_{i-2,j} + w_{i,j-2} = \frac{h^4 q_{i,j}}{D} \qquad (19)$$

V. Results

A. Transverse Deformation from a Raindrop

In the study we have considered three types of rain mentioned as light stratiform rain, moderate stratiform and heavy thundershowers. In Table IV, the forces are calculated for the respective raindrops stated as small, large and largest.

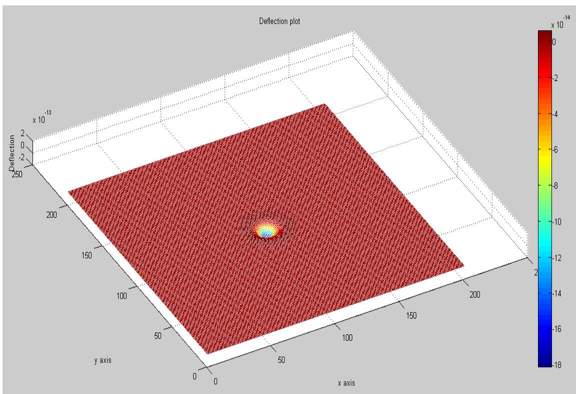

Fig. 7 Mesh plot of deformation of PVDF membrane by HT largest raindrop

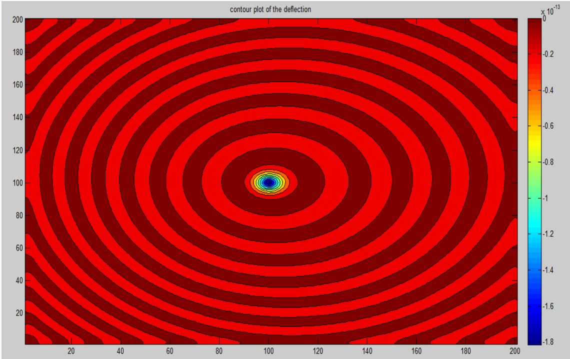

Fig. 8 Contour plot of deformation of PVDF membrane by HT largest raindrop

B. Deformation and Harvestable Energy

According to the simulation carried out for the respective raindrop types of the different rain types, the deformation and harvestable energy per rain drop are calculated. They are provided in Table IV. The harvestable electrical energy can be calculated by (20) [11]:

$$U = \frac{{k_{31}}^2 . EV}{2} d^2 \tag{20}$$

TABLE VI
DEFORMATION AND ENERGY HARVESTED PER RAINDROP BY PIEZOELECTRIC MEMBRANE

Rain type	Drop size (mm)	Deformation (m)	Harvestable energy (J)
LSR			
Small	0.5	4.039 e-19	7.7081 e-40
Large	2.0	1.099 e-16	5.7068 e-35
MSR			
Small	1.0	8.483 e-18	3.4001 e-37
Large	2.6	2.815 e-16	3.7441 e-34
HT			
Small	1.2	1.697 e-17	1.3607 e-36
Large	4.0	1.195 e-15	6.7474 e-33
Largest	5.0	2.403 e-15	2.7284 e-32

According to the experimental data provided in the table about the number of raindrops per unit area, the harvestable power from a 1m^2 area of PVDF membrane can be determined as follows.

TABLE VII
HARVESTABLE POWER FROM 1M^2 OF PVDF MEMBRANE

Rain type	Harvestable energy per raindrop (J)	No. of raindrops per 1m^2 per 1s	Total harvestable power(W)
LSR			
Small	7.7081 e-40	280	2.158 e-37
Large	5.7068 e-35	280	1.597 e-32
MSR			
Small	3.4001 e-37	495	1.683 e-34
Large	3.7441 e-34	495	1.853 e-31
HT			
Small	1.3607 e-36	818	1.113 e-33
Large	6.7474 e-33	818	5.519 e-30
Largest	2.7284 e-32	818	2.231 e-29

VI. CONCLUSION

The impact of the raindrop on the piezoelectric membrane is assumed to be a perfect inelastic impact considering raindrop splash in the numerical model. However the raindrop impact is cannot be simple narrowed down to splashing, neglecting the other scenarios of rebound, partial rebound, spreading and splashing. Therefore the research has a potential of carrying it out further to study about the dynamics of raindrop impact on a surface considering its scenario of the impact and the coefficient of collision.

Moreover in the study we have focused on the deformation of the PVDF piezoelectric membrane for the determination of harvestable energy from the raindrop. However for the generation of electrical energy by means of piezoelectric materials, the PVDF membrane should subjected to vibration. Although the behavior of vibration of the piezoelectric membrane caused by one raindrop can be analyzed numerically by simulation, the scenario of two-raindrop impact has high complexity. Therefore it is one of the research gaps in this research and it is further to be studied using numerical methods and expected to be validated using appropriate experimental method.

The kinetic energy of the raindrops substantially wasted in by means of noise energy and in the study the estimated harvestable kinetic energy is at a minute level where electric and electronic appliances require small scale such as MEMS applications etc. Therefore at the next phase of the research it is planned to study an appropriate method to improve the concept to enhance the harvestable energy.

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