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Design Optimization of Micro Electromagnetic Generator Used for Energy Harvesting from Breathing

KEYWORDS: Energy Harvesting, Microelectromechanical generator, Human exhalation, Magnets

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ABSTRACT *Energy harvesting from human exhalation using microelectromechanical generator is presented in this paper. Human exhalation is having low force and pressure and hence need careful consideration of the generator from designing point of view. The main objective is to study particular configuration of a MEMS generator used for energy harvesting and optimizing the design parameters of the same to try and obtain maximum power for a given load resistance. The configuration under observation is a micro electromechanical generator that converts energy generated from ambient vibrations produced by exhalation to useful electrical energy. This generator is a moving magnet type of generator with the wire wound coil stationary in its plane. It consists of four oppositely polarized magnets, to get a maximum flux generated and a copper coil which is wire wound. This paper consists of designing the dimensions of moving magnets desirably for maximum energy to be generated and also by optimizing the coil parameters such as the no. of turns of coil and coil resistance and simulating the results, for a given load resistance.*

I INTRODUCTION:

BIOMEDICAL ENERGY HARVESTING:

Energy harvesting is the process by which energy is extracted from external sources, captured, stored and used in many devices, implantable and non-implantable. Mostly many human devices like pace-makers,etc. are always battery powered. These batteries have a specific battery life and it becomes very difficult and troublesome for both the user and the doctor. For such and other purposes energy harvesting through renewable and inexhaustible sources is taken into consideration. There are a lot of ambient energies that are just give out by the human body which can be used to generate considerable power and run such devices. Human energies like the beating of heart, walking, breathing, etc. can be captured and can be used to generate usable power.

LITERATURE SURVEY:

There are different generators that can be used for the purpose of energy harvesting from vibration energy like electrostatic, electromagnetic and hybrid or energy harvesting using piezoelectric materials. In paper [1] authors have also included and studied different ways of energy harvesting form human passive motion. Out of these, there has been a lot of work being done mostly on different configurations and prototypes of electromagnetic generators, one of which employing a moving coil structure is studied in detail by authors in paper [2].They had developed a for optimization in order to extract maximum power output and can be used for energy harvesting. Instead of harvesting mechanical vibration paper [3] talks about designing of two types of electromagnetic power generators exploiting direct conversion of airflow. One of them was windbelt energy scavenger and the other was Helmholtz resonator type energy scavenger. The Helmholtz-resonator-based energy scavenger achieved a peak-to-peak output voltage of 4 mV at 1.4 kHz, from an input pressure of 0.2 kPa. [4]On the same path a similar model presented in "*An electromagnetic, vibration-powered generator for intelligent sensor systems*" by P. Glynne-Jones, M.J. Tudor, and N. M. W. S.P. Beeby is being studied in detail for optimization and use in energy harvesting.

II BREATHING MECHANISM AND FORCE GENERATED BY EXHALATION

In breathing, air moves into the lungs from the nose or mouth during inhalation, and then moves out of the lungs during exhalation. Moving of air into the lungs through the mouth and from the lungs back to the atmosphere, without any obstruction is very important for proper functioning of body. Therefore, an instrument called spirometer is used by doctors in order to detect any problem in breathing. It is also used to monitor the amounts of air and air flow into the lungs while inspiration and forced inspiration and those for expiration and forced exhalation. The results of this device can also be used to calculate the force generated in the breathing process, exhalation particularly. A spirogram is used to show the measurements of a spirometer and is hence useful for doctors and physicians in order to diagnose any difficulty or obstruction in normal breathing.

VALUES OF MEASUREMENTS DEDUCED FROM A SPIROGRAM:

	FLOW RATE(l)		PRESSURE(Kpa)		FORCE(N)	
			MIN	MAX	MIN	MAX
NORMAL	FEV1	2.22	0.26	2.109	0.014	0.118
	FIV1	3.01	0.36	2.85	0.020	0.159
MILD OBSTRUCTION	FEV1	1.49	0.178	1.415	0.009	0.079
	FIV1	1.39	0.166	1.32	0.009	0.073
MODERATE OBSTRUCTION	FEV1	1.77	0.214	1.68	0.011	0.094
	FIV1	3.1	0.372	2.94	0.020	0.164

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SEVERE OB-STRUC-TION	FEV1	0.89	0.106	0.845	0.005	0.047
	FIV1	2.10	0.42	1.99	0.023	0.111

The values of the pressure in Kpa and the force generated by forced exhalation and inhalation can be calculated from the measurements of volume exhaled and inhaled per unit time.

$$Flow = \frac{pressure}{resistance}$$

$$Force = pressure\ X\ area$$

Here, the resistance in the air blow pipe (because of the resistance produced by air in the path) is taken to be 0.12-0.31 kPa L^{-1} which is mentioned in [9] and values are calculated accordingly. The force of the breathing is calculated (pressure * area ( )) as per force exerted on the generator through the blow pipe used for exhalation, which is assumed to have 12cm diameter according to ATS standard [10]. This force is calculated by using the maximum and minimum pressure exerted while exhalation and the area of impact of the generator. As the generator for our application is assumed to be cubical, the area of impact is square of dimension of cube(d) which is having same area as circular pipe.

III METHODS OF ENERGY HARVESTING FROM LOW FORCE VIBRATIONS

Ambient vibrations from breathing are very low frequency vibrations. Such vibrations can be used to generate electrical power by using different types of micro-electromechanical generators. They can be classified into three according to the different principles they incorporate. They are:

MICRO ROTATIONAL GENERATORS:

Magnetic generator usually contains multipolar magnet and planar coil, Mechanical energy from the environment drives the rotor spindle and the spindle leads to the spin of rotor magnet. When rotor rotates relative to the stator coil, there will be induced electromotive force in coil.

According to Faraday's law of electromagnetic induction: the relative motion of magnet and coil generates induced electromotive force in coil, induced voltage can be deduced from the following equation

$U(t) = -d\phi(t) = -S\ dB(t)$

where U(t) is the induced voltage, ϕ is the change of the magnetic flux through the area around the coil, t represents time, B strands for magnetic flux density and S is the coil surrounding area.

Research has been going on with improving power outputs from these rotary generators. From the equation above it can be seen that there can be two ways to improve the output of the generator

1) Increase the magnetic flux density through the coil;

2) Enlarge the area around the coil.

VIBRATIONAL GENERATORS

The vibration type generators capture energy from vibration and convert it to useful electrical energy. Vibrational magnetic generator usually contains magnet and coil. According to Faraday's law of electromagnetic induction, distance changes between magnet and coil (vibration) leads to magnetic flux through the coil varying and generates induced electromotive force in coil. Vibrational generators are generally designed as a mass-spring-damping system which the mechanical parts move associated with transducers under the influence of the external vibration [38]. Thus, the maximum output power is commonly achieved at their resonances. Researches on magnetic generator have been always focusing on improving output power. For vibrational generator, there are three methods to improve power density or to increase output voltage:

1) Resonance with high external vibration;

2) Increase magnetic flux density of the air gap between the magnet and the coil;

3) Enlarge area around the coil.

IV MODEL USED IN OUR APPLICATION

This design has been chosen to create a magnetic field through a greater proportion of the length of each coil winding when compared to double or single magnet designs (fig1). To improve the degree of coupling, it is important to choose a type of magnet that will produce a strong flux density. Neodymium Iron Boron (Nd Fe B) magnets have the most powerful magnetic properties per cubic centimetre (cm^3) known at this time, and can operate at up to 120°C.

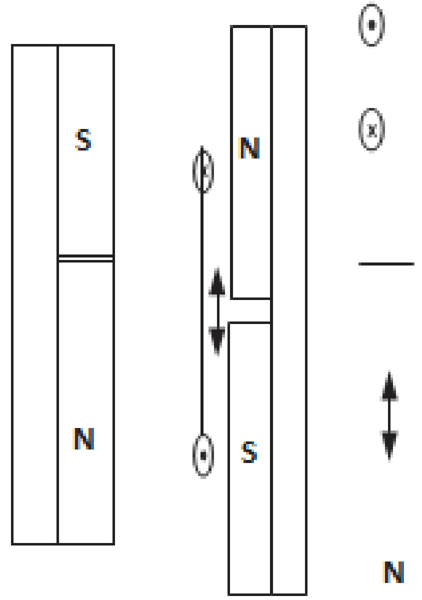

Fig 1. Model used for design

DESCRIPRTION AND CHARACTERISTICS OF MODEL

The coil has parameters like no. of turns and the coil resistance that can be optimized. A printed coil can be formed by screen printing layers of conductive materials and insulators onto a substrate using standard thick film technology. Printed coil as well as wire wound coils can be the choice for this application. But the disadvantage of printed coil is that the small thickness of each layer will result in a high series resistance for the coil. If windings of a larger thickness are required, so a wound coil will be more suitable and economic to manufacture.

The magnetic field, *B*, is calculated using the formula

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$$B = \frac{Vcoil}{NlA\omega}$$

where l is the length of coil in the field, and A is the amplitude of the displacement, x.

For scaling of the generator parameters, B is considered to be constant.

V SCALING OF VIBRATION GENERATOR

In order to study the scaling effects there are two factors to be considered. The first is the mechanical energy in the system, which provides an upper limit on the power which can be generated. The second factor to be considered is the efficiency with which the mechanical energy can be transformed to electrical energy.

In a vibrational power generator shown in fig.2, the available mechanical energy is related to the maximum movement of a mass. The available mechanical energy will decrease with the dimensions as both the mass of the moving object and the distance moved is decreased. The electrical energy is extracted from the system using electromagnetic damping factor. The electromagnetic damping factor depends on flux linkage gradient, the number of coil turns, coil impedance and load impedance. Hence, the efficiency of extraction of the electrical energy will also decrease with size because there would be a decrease in the flux linkage gradient as well as size of coils and no. of turns.

This model consists of a coil between magnets. The upper and lower magnets consist of two pairs of oppositely polarised magnets. This opposite polarity creates a flux gradient for the coil in the direction of movement i.e. is in the x-direction.

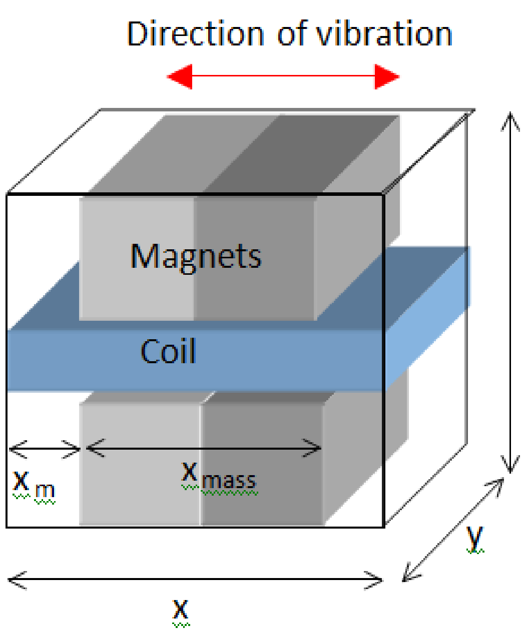

Figure 2: Schematic representation of the electromagnetic generator.

In this structure it is assumed that the coil remains fixed while the magnets move in response to the vibration. Since the magnets generally have greater mass, m, than the coil, movement of the magnets is more beneficial than movement of the coil. By placing the coil is the gap between the magnets this structure has the advantage of creating a relatively large magnetic field in the area of the coil. The use of the two pairs of oppositely polarized magnets ensures that the coil is placed in an area of high magnetic field gradient.

For the purpose of this study we have assume a cubic volume, i.e. x = y = z = d where d is the dimension of the device. Note that only the magnet and coil dimensions are included in the volume. The available mechanical energy will depend on the level of vibrations and acceleration to which the device is subjected. However the maximum displacement will be constrained by the volume of any self-contained device, i.e. the peak displacement, x_m , is given by the difference between the external dimension, d, and dimension of the mass, x_{mass}. It is of interest to find the optimum ratio of peak displacement, x_m, to mass dimension, x_{mass}, which maximises the mechanical energy. Assuming a sinusoidal vibration, and expressing the peak displacement of the mass as $x_m = (x - x_{mass})/2$, the kinetic energy of the mass can be expressed in terms of the mass dimensions and its displacement;

$$KE = \frac{1}{2} mV^2 = \frac{\rho y z x mass \omega 2 (x - x mass)2}{8}$$

where V is the velocity of the mass, m, ρ is the density of the mass material, x_{mass}, y and z are the dimension of the mass and ω is the angular frequency. By taking the derivative of this with respect to x_{mass} and equating to zero it can be found that the kinetic energy is maximized when x_m = x/3. Thus a single magnet x-dimension is taken to be 1/6 of the overall dimension. The magnets are assumed to extend for the full y-dimension. The z dimension of the magnet is taken as 0.4 times the overall dimension. This leaves the gap between the magnets as one fifth of the overall dimension. The coil thickness is assumed to occupy half of the gap.

The parasitic damping represents loss mechanisms such as air damping, squeeze film effects, thermoelastic damping, and friction in the clamping. The electromagnetic damping represents the mechanism by which the electrical power is extracted from the system, i.e. the current flowing in the coil.

SCALING WITH RESPECT TO K.E. OPTIMIZATION

Magnets:

• 4 magnets(2 pairs of oppositely polarized magnets)

• Neodymium Iron Boron (NdFeB) magnets

• the peak displacement- xm , is given by the difference between the external dimension, d, and dimension of the mass- xmass .

• dimension of mass= dimension of magnets together

• xm = x/3.

• Thus a single magnet x-dimension is taken to be 1/6 of the overall dimension. (height)

• The magnets are assumed to extend for the full y-dimension.(length)

• The z- dimension of the magnet is taken as 0.4 times the

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overall dimension.(thickness)

- We assume the case to be cubical. Therefore, x=y=z=d.
- xm=d/3;
- y=d;
- z=0.4d; of one magnet

SCALING OF DIMENSIONS:
Kinetic energy of the magnets as moving mass

$$K.E. = \frac{mV^2}{2}$$

$$K.E. = \frac{\rho xmassyz\omega^2(x - xmass)}{8}$$

Where

ρ= density of magnets

xmass= dimension of magnets

y= width of magnets

z= thickness of magnets

ω= natural frequency of magnets

Considering,

ω= 1000 Hz

x=y=z=d

SAMPLE CALCULATION FOR K.E.

$$mass = \rho V$$

$$V = xyz = \frac{d}{3} * d * \frac{2d}{5}$$

$$V = \omega x$$

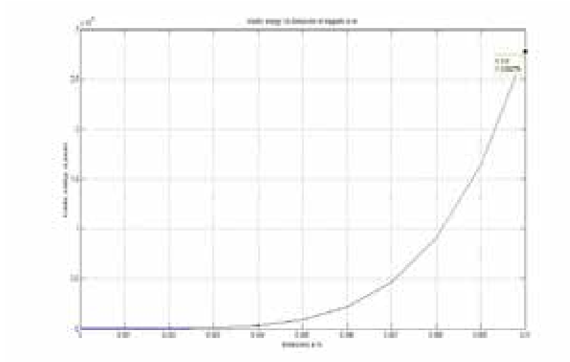
$$= \omega * \frac{d}{3}$$

Therefore,

$$K.E. = \frac{\frac{\rho 2d^3\omega^2 d^2}{15*9}}{8}$$

Here, the mass of the magnets together can be expressed in terms of dimension by expressing the mass in terms of density and volume of the magnets. Likewise, the velocity of the mass is also taken in terms of the natural frequency and the amplitude of movement of the magnet. A direct relation between kinetic energy and dimension is thus obtained in order to study characterstics.

VARIATION OF KINETIC ENERGY WITH DIMENSION:



COMMENTS:
Here, the trend of the graph is that kinetic energy is increasing with dimension. But for higher kinetic energy, it is not possible to increase the dimension too much as there is a size constraint to be met. Therefore, the maximum energy is obtained at d=10mm and 0.00277 J in magnitude.

SCALING OF NO.OF TURNS OF COIL

$$Presonance = \frac{DeFo^2}{2(Dp + De)^2}$$

From the above equation ,we can deuce that in order to get maximum power output, the electromagnetic damping has to be equated with the parasitic damping. This condition can only be met with a Q factor as high as 2,000-30,000. This Q factor and condition to equate Dp and De can be satisfied in a wire wound coil structure. For printed coils, the Q factor is as low as 300 and hence Dp>>De. Therefore, in such cases, the load resistance has to be made equal to the coil resistance for maximum power.

$$\varepsilon p = \frac{1}{2Qoc}$$

Dp=2mωεp

The above equations can be used to get the value of Dp, then substitute this Dp in De. This value of De is obtained by setting appropriate values of N and load resistane in the relation of De. This procedure is the one used for setting the no. of turns of coil according to the load resistance.

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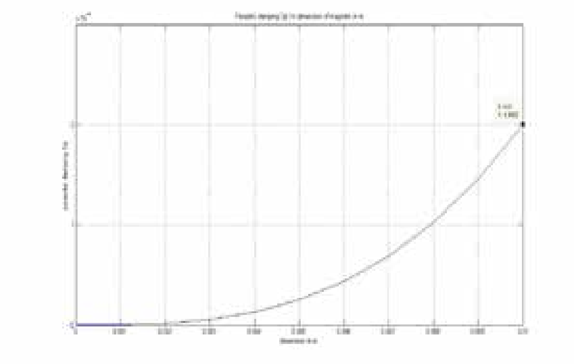
DAMPING FACTOR VS DIMENSION



COMMENT:
From the graph, we can see, that the parasitic damping for the dimension 10mm is 0.0002, which can be substituted as electromagnetic damping for maximum power output.

Damping factor and load resistance:

$$De = N^2 X \frac{d\emptyset^2}{dx} X \frac{1}{(Rc + Rload + jLc\omega)}$$

De =damping factor

d∅/dx = flux gradient= 12X 10^-3

Rc=coil resistance

Rload= load resistance

Lc= coil inductance

For Rc,

$$Rc = \frac{\rho cuNLmt}{Awire}$$

$$Rc = \frac{\rho cuN^2\pi(ro + ri)}{Kcu(ro - ri)t}$$

$$Rc = \frac{\rho cuNX2\pi R}{\pi(D)^2/4} = 0.46N$$

ρcu = density of copper=1.68X10^-8

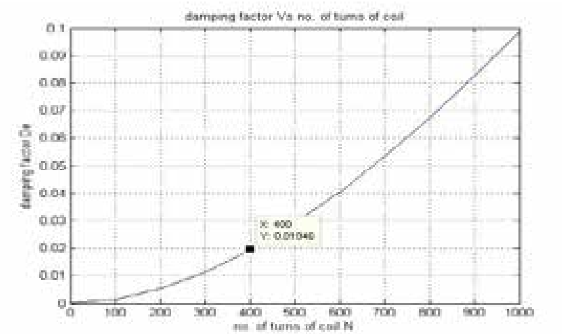
Radius of coil (R)= d/20

Kcu = fill factor of copper=0.5

Diameter of the wire (D)= 12 micro meters

Here, the coil resistance is expressed in terms of the no. of turns in the coil

Damping factor Vs no. Of turns of coils



COMMENTS:

From the graph, it can be inferred that there is a relation between De and N. It can hence be concluded that for value of 0.0002 of De the no. of coils to be used would be 400.

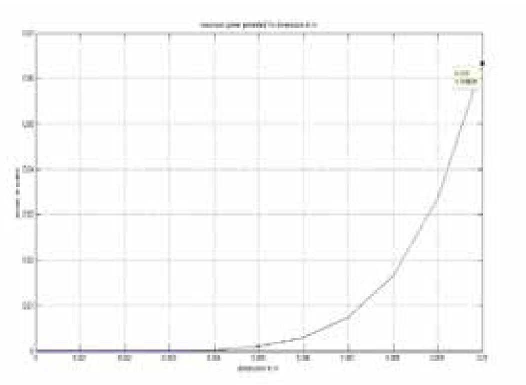
POWER GENERATED:

$$Pmax = \frac{(ma)^2}{8De}$$

m= mass of magnets

a= acceleration of movement

De=damping factor



COMMENTS:
This graph gives the change in maximum power with the changing dimensions of the magnets. For given expression for maximum power, De=Dp, which is obtained above by calculations from Q factor of the system. By substituting values of De and by expressing mass in terms of density and volume of the magnets, we get the direct relation of power generated and the dimensions of the magnet which can further be plotted and characteristic values for different dimensions can be obtained. Hence, from the graph, we can see that for the dimension 10 mm , power output is highest i.e. 0.063 W i.e. 63mW

CONCLUSION:
A micro-electro mechanical vibration type generator has been studied. The parameters of this moving magnet type generator are also checked for optimization, to design and scale parameters for the purpose of energy harvesting. After series of simulations using MATLAB, the exact relations

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and behaviour characteristics of these parameters have been observed. These simulations have led to scaling and designing of vibration based microgenerator which has following parameters:

MAGNET:

- length of magnet (x) : 10/6mm
- breadth of magnet(y) : 10mm
- thickness of magnet(z) : 20/5mm= 4mm

COIL:

- no. of turns of coil (N) : 400
- diameter of wire : 12 micro meters
- coil resistance (Rc) : 0.46X N= 184 ohms

Therefore, a generator with the above specifications, able to harvest a energy of upto 0.063W for 1kHz vibration frequency and input pressure of 0.2 kPa has been designed and scaled.

Future scope:

Work is in progress to build up the prototype.

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