Kurdistan Journal of Applied Research (KJAR) | Print-ISSN: 2411-7684 – Electronic-ISSN: 2411-7706 | kjar.spu.edu.iq
Volume 2 | Issue 3 | August 2017 | DOI: 10.24017/science.2017.3.6

# Mechanical Behavior of A MEMS Based Capacitive Energy Harvester

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**Abstract**: ***Energy harvesting is defined as a technology that converts the available excess energy in the environment into usable energy for low power consuming electronics. Past researches on vibration energy harvesting has focused mainly on the use of magnets or piezoelectric materials as the basis of energy transduction. This paper presents a new design for extracting energy using an electrostatic capacitive energy harvester which can be considered as a combination of charge constrained and voltage constrain cycles. In previous analyses, the constant charge and constant voltage operation were studied separately, but in this work both of these operations have been studied in a combination with each other. In this paper, the variable capacitor is formed by an out of plane gap closing structure. In order to investigate the mechanical behaviour of the capacitive energy harvester, a rectangular micro plate is considered with geometrical and material properties. Due to the nonlinearity and low displacement amplitude that result from electrostatic force, energy can be generated. In order to study the primer factors for increasing generated energy, geometrical parameters of the system have been changed. Time history of the shuttle mass and micro-plate undergone vibration are illustrated. It must be noted that after several cycle vibration of the plate, it reaches to stability and regular cycles.***

**Keywords:** Energy harvesting; Capacitive; electrostatic; constant charge; Constant voltage.

## 1. INTRODUCTION

Nowadays the growing interest in the field of energy harvesting systems originates from great developments in related technologies like micro-electromechanical-system (MEMS) technology, wireless sensor network (WSN) technology, very large scale integration (VLSI) design technology, and complementary metal oxide semiconductor (CMOS) fabrication technology [10].

MEMs have shown an excessive approval in engineering and industry because of the several advantages they provide, such as order of magnitude, smaller size, better performance than other solutions, possibilities for batch fabrication and cost effective integration with electronic systems, virtually zero DC power consumption and potentially large reduction in power consumption [4].

Because of the prominence of energy harvesting in MEMS sensors, many studies have been presented on this topic in recent years. As a matter of fact, the first concept of a vibration based energy harvester was introduced by [10], and was based on an electromagnetic approach [11].

Michelson et al., have surveyed and organized main features of published energy harvesters [8]. The thinkable transduction mechanisms that can be applied for motion micro energy harvesting are basically categorized as piezoelectric, electromagnetic, and electrostatic. Among these, the electrostatic principle is the one that relies on the most advanced MEMS processes. These devices typically use the same construction elements as applied for MEMS accelerometers, i.e. an on hold proof mass in some Beams, and variable capacitors built on one electrode set attached to the moving mass and one set of fixed counter electrodes attached elsewhere in the structure. Each transduction mechanism has different features such as damping effects, easy usage, scalability, and effectiveness. The suitability of each mechanism for any specific application dramatically depends on the practical constraints applied [1].

In this paper, a capacitive (electrostatic) transducer is considered. In spite of having the lowest energy harvesting capability, electrostatic energy harvesters have outstanding features and areas of application. The electrostatic devices are primarily made up of silicon by the means of semiconductor fabrication technology such that it facilitates CMOS integration. In another point of view, electrostatic energy harvesters could be a way for figuring out self-powered integrated circuits as an on-chip power source [5]. However, because of the air damping effect, the two plates of electrodes cannot come to contact so as to reach the maximum capacitance state in the electrostatic energy harvesters. It has also the key role which leads to low energy harvesting capability of electrostatic approach.

The principle of electrostatic generators is that the moving part of the transducer moves against an electrical field, thus energy can be generated.

Meninger et al. in MIT introduced an electrostatic generator that employs a variable micro machined capacitor [6]. As it was pointed previously the basis of electrostatic energy conversion is the variable capacitor. The variable capacitance structure, which will be made by MEMS technology, is driven through mechanical vibrations and oscillates between a maximum capacitance $C_{max}$ and a minimum capacitance of $C_{min}$. If the charge on the capacitor is constant, the voltage will increase as the capacitance decreases. If the voltage across the capacitor be constant, charge will transfer from the capacitor to a storage device like a battery as the capacitance decreases. Nevertheless, mechanical kinetic energy is converted to electrical energy. This paper will work with both of charge constrained and voltage constrained converters because two separate voltage sources are placed. A good description of charge constrained conversion superiority on voltage constrained conversion is given by [6]. These first electrostatic devices are passive structures requiring an energy cycle to convert mechanical energy into electricity. Many energy cycles enable such a conversion, but the most commonly used ones are charge-constrained and voltage constrained cycles. They both start when the converter's capacitance is maximal. At this point, a charge is injected into the capacitor thanks to an external source, to polarize it [3].

In the present work, a comprehensive analysis of moving electrode electrostatic energy harvesters, including a combination of both constant charge and constant voltage operations is performed. As a matter of fact, it's an attempt to synthesize two efficient methods to get a much more efficient one.Elena blokhina et al. offered a formal analysis and description of the steady-state behaviour of an electrostatic vibration energy harvester operating in constant charge mode and used different types of electromechanical transducers [2].
The majority of the electrostatic converters' shapes are derived from accelerometers. Capacitor shapes for electrostatic converters are categorized into four groups, in-plane gap closing, in-plane overlap, out-of-plane gap closing, and in-plane converter with variable surface.
Non-resonant based electrostatic MEMS of out-of-plane gap closing mechanism have been proposed by [7].

## 2. MODEL DESCRIPTION AND MATHEMATICAL MODELING

The standard mechanical model of a vibration-driven energy harvester is the same as of a mass-spring-damper system a schematic of the mechanical system is shown in Figure 1.

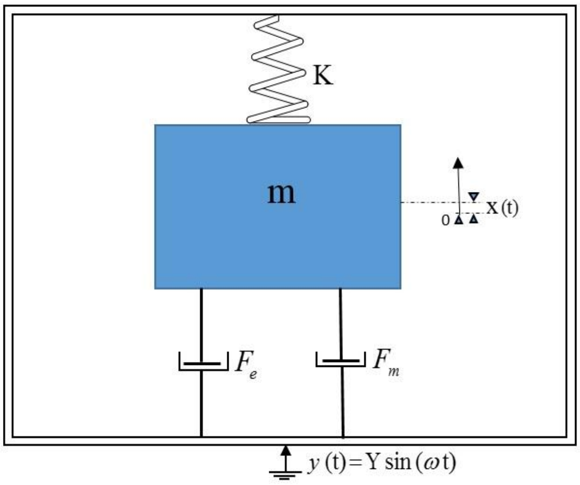


**Figure 1**Mechanical schematic of MEMs structure

A deeper look in this subject reveals that the actual travel of the variable capacitance structure, and therefor the value of $C_{max}$ and $C_{min}$ is determined by both the mechanical dynamics of the system and the design of the MEMS structure. The mass is damped by two forces, the mechanical damping ($F_m$) and electrically induced damping ($F_e$) that stand for the energy removed from the mechanical subsystem and stored in the electrical subsystem [9].

The equation of motion for the mechanical system illustrated in figure 3 is shown in Eq. (1). So the description equation becomes:

$$m\ddot{x} + F_e\,(x) + F_m(\dot{x}) + kx = -m\ddot{y} \qquad (1),$$

Where m is the mass of the oscillating MEMS structure, k is the stiffness of spring attached to the structure, $x$ is the relative motion of the mass compared to the frame, and $y$ is the input vibration signal. The capacitance of the MEMS variable capacitor at a given time is determined by the relative motion of the mass ($x$) and specifics of the design. For a sinusoidal excitation, $y(t) = Ysin(\omega t)$ where $y$ and $\omega = 2\pi f$ are the amplitude and angular frequency of the frame.
On the other hand, $F_e$ for charge constrained cycle at out-of-plane gap closing converter express by:

$$F_e = \frac{Q^2}{2\epsilon_0 S} \qquad (2),$$

Where $Q$ is the charge on the capacitor, which must be constant, $\epsilon_0$ is the dielectric constant of free space, and $S$ is the area of the capacitor plates. $F_e$For voltage constrained cycle is expressed by:

$$F_e = \frac{\epsilon_0 S V^2}{2(g_0 - x)^2} \qquad (3),$$

Where ($g_0$) is the initial gap between plates, and $V$ is the voltage between plates.
A circuit for electrostatic generator using charge constrained and voltage constrain is shown in Figure 2.

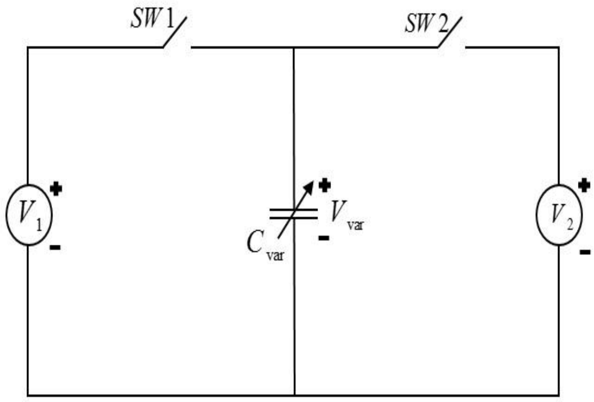


**Figure 2**Simple circuit representation for electrostatic converter

In this paper, the variable capacitor $C_{VAR}$ is formed by an out of plane gap closing structure. The out-of-plane gap closing structure uses two plates that one of them is fixed and the other one is movable as shown in Figure 3 [9].

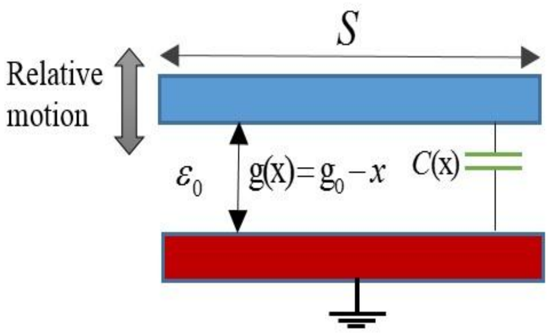


**Figure 3**Out-of- Plane Gap Closing Structure

The capacitance of the converter is expressed in equation (4).

$$C(x) = \frac{\epsilon_0 S}{g_0 - x} \qquad (4).$$

For describing the transduction of vibration energy to electric energy in this new design, Figure 3 is used. In the first step $C_{var} \neq C_{max}$ is assumed. As vibration pulls the capacitor plates apart and when the movable plate is at a certain distance $d$ from the fixed plate switch $SW1$ is closed, (Figure 3). At this point, $V_{var} = V_1$ and when $C_{var}$increases to reach $C_{max}$, since $V_2$ is constant and the distance between the plates is decreased, according to the equation (5) $C_{var}$is charged, let $Q_{var}$ be the charge on the variable capacitor.

$$V = \frac{Qd}{\varepsilon_0 A} \qquad (5).$$

As $C_{var}$ reaches to $C_{max}$ ($C_{var} = C_{max}$), $SW1$ will be open. When the distance of between plates is increased, $C_{var}$ decreases, which causes $V_{var}$ to rise in given constant $Q_{var}$. Capacitance is changed (decreases) and the voltage between plates will increase until $V_{var}$ reaches to$V_2$. At this viewpoint, the distance of between plates is at a certain value of $d_m$.

According to Eq. (4) the relation between $V_2$, $d_m$ and $Q_{var}$ is:

$$V_2 = \frac{Q_{var} d_m}{\varepsilon_0 A} \qquad (6).$$

In this process, the charge $Q_{var}$on the capacitor remains constant and the terminal voltage on the capacitor ($V_{var}$) is increased to make $V_2 = V_{var}$ .
At the moment $SW2$ is closed and the voltage of the capacitor remains constant ($V_2$). The distance of between plates increases, since the voltage is constant, the charge on $C_{var}$ is transferred to the battery ($V_2$) and the vibration energy is converted to the electrical energy. This process of discharging goes on until the capacitance is changed to $C_{min}$. At the same time $SW2$ is opened.
A little charge might remain inside the capacitor $Q_{rec}$ (remaining charge in the capacitor, which is not stored in the battery). With decreasing distance between plates, rest of the charge in the capacitor $Q_{rec}$ is constant. Thus, this process is a charge constant .When the mass reaches to a certain distance $d$ from the fixed plate**,** one cycle conversion is completed.

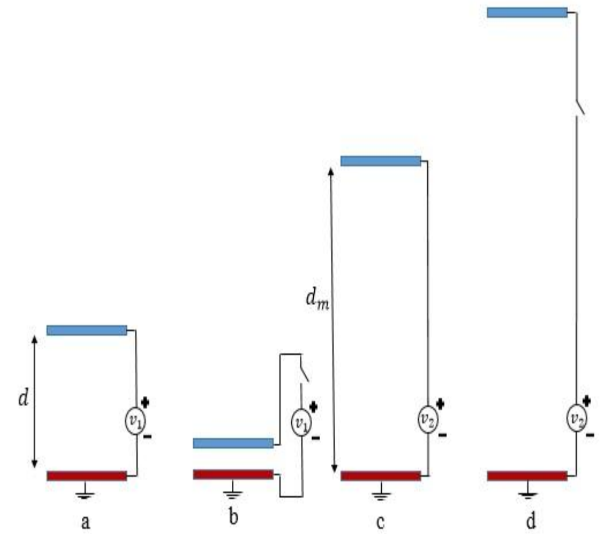


**Figure 4** A Schematic of the Transduction of Vibration Energy to Electric energy

if the value of variable capacitor alternate between $C_{min}$ and $C_{max}$, we define a complete energy harvesting cycle as one variation of $C_{var}$ from $C_{max}$ to $C_{min}$ and back to $C_{max}$. Let $Q_n$, where $n$ is an integer index starting from 0, representing the charge store on the battery where this charge be the sum of $Q_{n-1}$and $Q_{rec}$.Thus, the total charge, $Q_{CTORE}$ on the battery is described by following equation:

$$Q_{CTORE,\ n-1} = C_{max}V_1 + C_{min}V_{2,n-1}(5) \qquad (7).$$

The amount of energy per cycle that is removed from the mechanical system and stored in the electrical system (the applied battery) is given by equation 8 as follow:

$$E = 0.5C_{max}V_1^2 - 0.5C_{min}V_2^2 \qquad (8).$$

The energy transduction process just described is shown graphically as a $Q - V$ plane in Figure 5. In this diagram, in Point ($V_1, C_{var}V_1$ the capacitor plates are just starting to pull apart for the n[th] energy conversion cycle.
Point 1 corresponding to the time when both $SW1$ and $SW2$ are off. At Point 2, $SW2$ turns on, allowing charge to transfer from $C_{var}$ to the battery; as a result $Q_{var}$ falls from Point 2 to Point 3, during this part of the cycle $V_{var} = V_2$. At Point 3, it is seen that vibration has pulled the capacitor plates to their maximum separation, decreasing $C_{var}$ to $C_{min}$. In next stage $C_{var}$ increases and $V_{var}$ falls, turning off $SW2$. Correspondingly, $Q_{rec}$ remains constant until Point 4, then $SW1$ turns on and $V_{var}$ is held at $V_1$.

The area within the closed curve in Figure 5 equals the mechanical vibration energy converted to electrical energy and delivered to the battery.

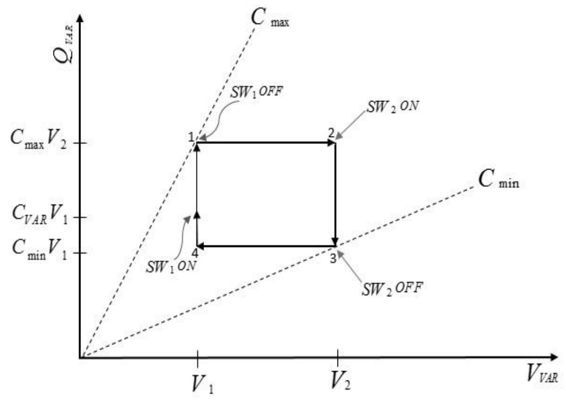


**Figure 5** $Q - V$ Plane contour representing one energy harvesting cycle

## 3. THE NUMERICAL SOLUTION

In order to investigate the mechanical behaviour of the capacitive energy harvester, a rectangular micro plate is considered with geometrical and material properties as listed in Table 1.

**Table 1** Geometrical and Material Properties of the Micro-Plate

| **Width** (µm) | **Thickness** (µm) | **Length** (µm) | **Young's modulus** ($GP_a$) | **Density** (Kg/m3) |
|---|---|---|---|---|
| 10 | 2 | 30 | 169 | 2330 |

The other properties of the system are listed in Table 2.

**Table 2** Other Properties of the System

| **Initial gap** (µm) | $V_1$ (volt) | **Shuttle Mass** (gr) | $V_2$ (volt) | **Permittivity of air** ($F/m$) | **Spring constant** (N/cm) |
|---|---|---|---|---|---|
| 2 | 8 | 7 | 20 | 8.85e-12 | 0.3 |

Time history of the shuttle mass and micro-plate undergone vibration are illustrated in Figure 6 (see appendix). It must be noted that after several cycle vibration of the plate, it reaches to stability and regular cycles, as expected.

Figure 6 plots the relationship between the electrical Power output as a function of the excitation frequency and other parameters of the system when they are fixed.

It can be inferred that the maximum electrical Power occurs at resonance frequency and when damping ratio is low.

Here, $f_n$ is 65 Hz. Figure 7 (Appendix) illustrates the relation of the electrical Power output as a function of the excitation frequency when $\varsigma_m$is different. As shown in Figure 7, generated electrical Power increases with decreasing value of $\varsigma_m$. In addition, the maximum electrical Power output occurs when $\varsigma_m$ is as low as possible.

It should be noted that by controlling the damping ratio values, an optimized electrical Power generator for a given geometry can be attained.

Figure 8 (appendix) shows variation of Power extracted versus $d$ for various $d_m$ s.

At a certain distance between plates, $d$ SW1 turns on. As shown, if $d$ increases, more charge goes on the capacitor and the amount of output power increases.

In Figure 9 (appendix), different curves are plotted for output Power versus excitation frequency at different accelerations. When the amplitude of the frame movement increases, the maximum electrical output Power increases.

## 4. CONCLUSION

In this work, a new method to harvest small bits of energy from the environment vibrations for use by low Power electronics. A capacitive energy harvester was employed which combines charge constrained and voltage constrained cycles for that purpose. Dynamic simulation revealed that more than 0.019 $\mu W$ as an output Power of the system is possible from a vibration source of 2.5 m/s$^2$ at 65Hz. Finally, these results as the most significant ones can be pointed out:

1. A glance on Electrical Power versus excitation frequency for $\varsigma_m$ various shows that decrease in $\varsigma_m$ causes output Power to increase.
2. For various $d_m$ s by increasing the value of $d$ extracted Power increases.
3. The acceleration of the frame has a considerable influence on the output Power in a way that giving rise to acceleration triggers a dramatic increase in output Power.

As a matter of fact what was expected at the beginning is in a broad agreement with what was revealed through the simulation.

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## APPENDIX

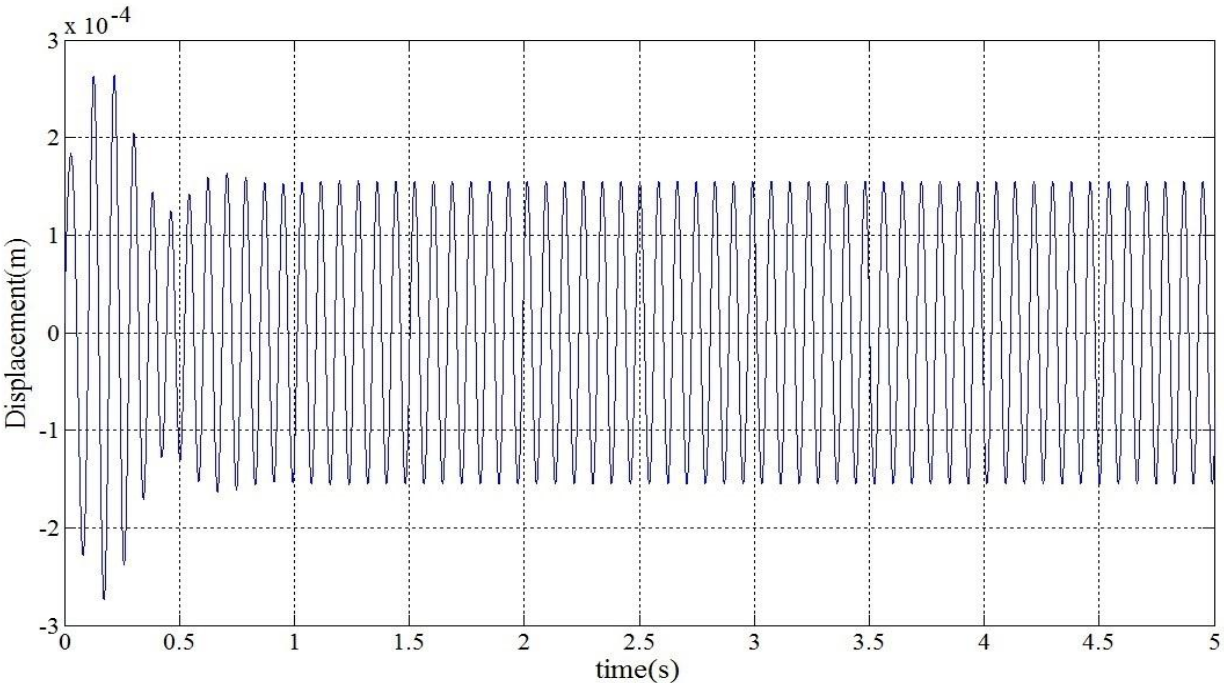


**Figure 6** Displacement of the plate versus Time

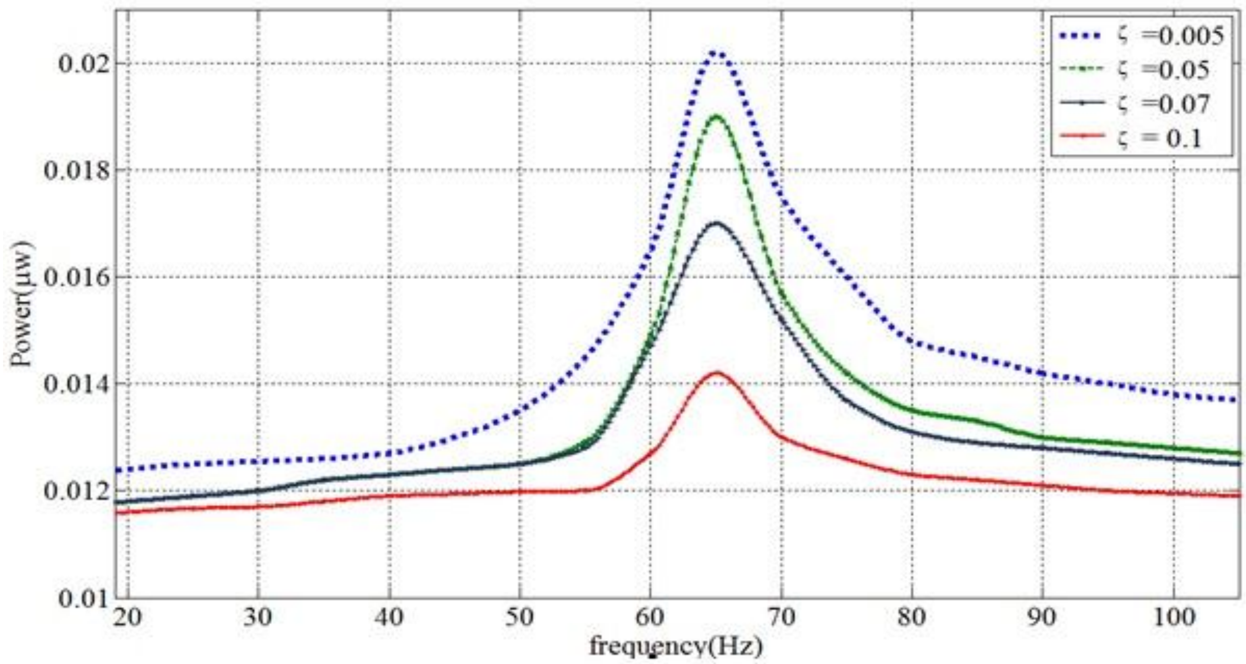


**Figure 7** Electrical Power versus excitation frequency for $\varsigma_m$ various

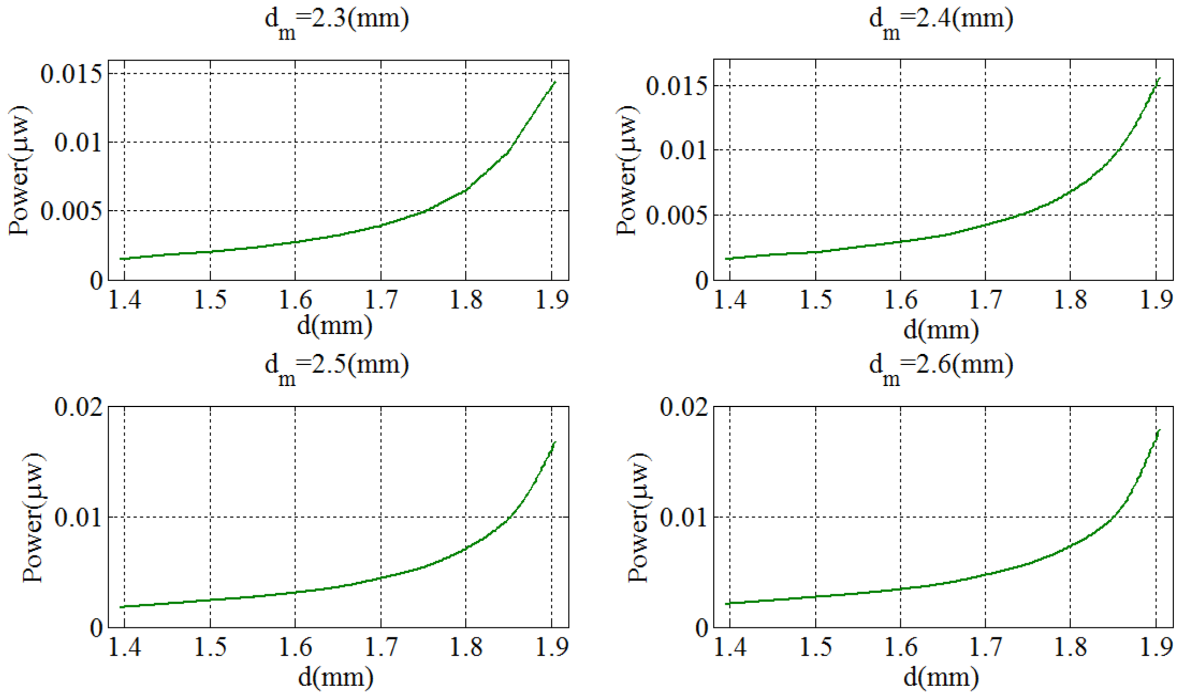


**Figure 8** Power extracted versus $d$ for various $d_m$.

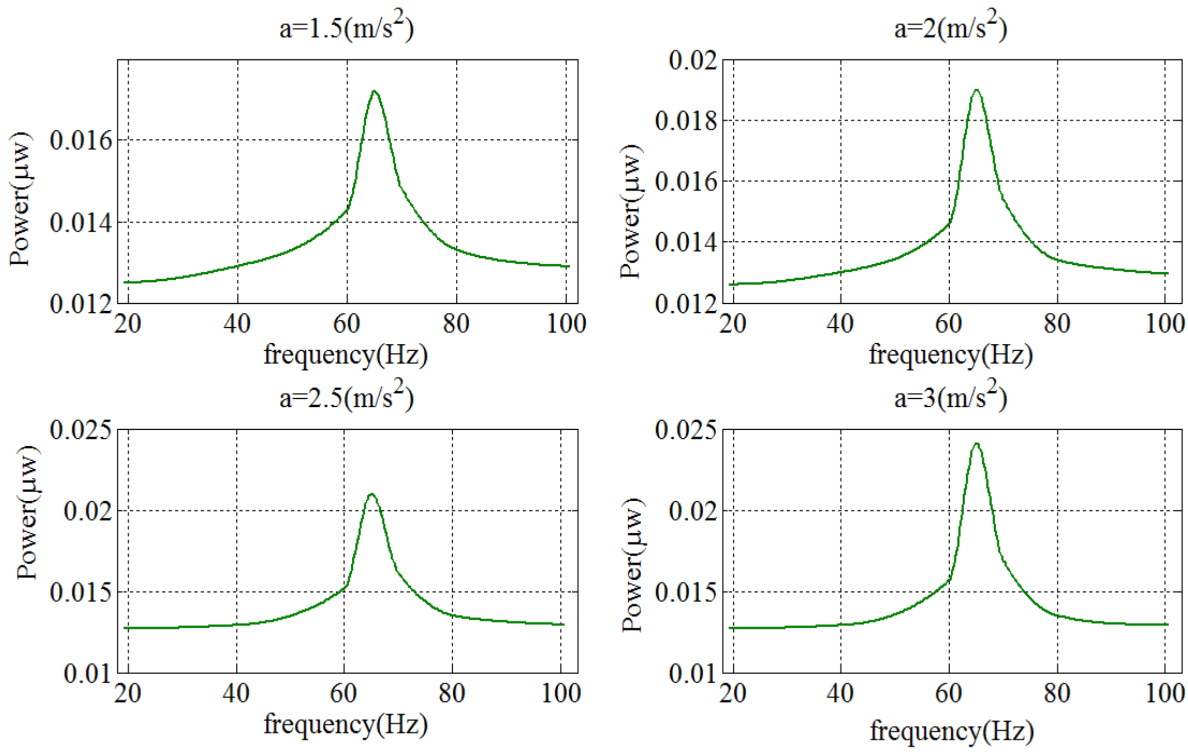


**Figure 9** Output power versus excitation frequency at different acceleration.