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Investigation of Piezoelectric Vibro Impact Energy System

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Abstract: *The paper deals with theoretical and experimental investigation of vibroimpact energy harvester. This harvester consists of two parallel piezoelectric discs disposed into cylindrical case. The design of the harvester allows the gap between the discs to be varied. The case of the energy harvester is driven by a vibrational shaker. As a result of case motion a sphere moves between the discs and impacting onto a disk surface produce electric energy. The laws of sphere motion and impact energy are determined theoretically and the obtained results are proven by experiments. The aim of the paper is by the optimal dimensions, mass parameters, piezoelectric and elastic properties of the harvester to be determined in order the maximum energy to be produced*

Keywords: *vibroimpact energy harvester, vibrational energy harvester, shock energy harvester, MEMS*

1. Introduction

Vibrational shock energy harvesters are micro electro-mechanical systems (MEMS), which generate electrical power from impacts. The source of the vibrational energy necessary for the impacts is derived from unutilized vibrations of the surrounding environment.

A good approximation of a traditional harvester is the mass – spring – damper system with limiting motion edges. Such a design has a typical behaviour of clipping the resonance peak in the frequency sweeps due to imposed motion limit [7],[18].[21]. The jump phenomenon also occurs in higher frequencies for the side of the clipped peak. With increasing the amplitude of the vibrations from the external source the power output from the device reaches a saturation point, at least to a given approximation [1],[2],[11],[12],[13].

The power output saturation is a negative consequence from the imposed restriction on the motion [14][16]. Whether or not the impacts are totally elastic is irrelevant for the power output when the vibrations are sinusoidal and the device is subjected to its resonant frequency [3],[17],[20]. The goal of the article is to examine the characteristics of an impact energy harvester for sinusoidal type vibrations and to determine the conditions for optimal performance concerning the maximum of energy yield.

2. Problem Definition

Simplified schematic of the vibrational impact harvester is shown in Figure 1. A metal sphere 1 with radius r located inside a cylindrical housing is moving freely between the housing`s membranes. The membranes are the mechanical end stops limiting the sphere`s motion. These membranes are made of elastic brass substrate and thin piezoelectric layer of PZT disposed at the brass substrate. The housing undergoes periodic oscillations. Its position with respect to the fixed reference system is denoted as y2. The relative position of the material sphere center with respect to the housing base is denoted as y12. The instant absolute position of the sphere with respect to the fixed base is denoted as y. The periodic motion of the housing is assumed to be a sine law of the type, where is the amplitude, is the angular frequency, and is the time.

In the initial position the sphere lies at the bottom membrane until the inertial force overcomes the weight of the sphere. At the instant of separation of the sphere from the bottom membrane there is no relative motion between the sphere and housing i.e. y=y2 and y12=0. When the inertial forces overcome the weight of the sphere a jump occurs.

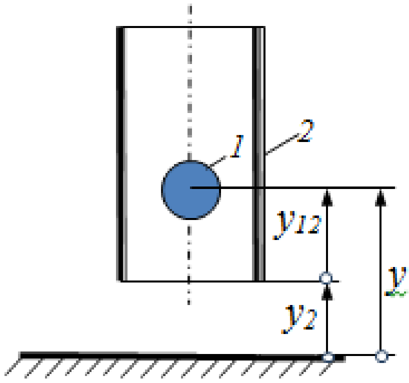

Fig1. *Simplified schematics of the vibrational impact harvester*

This leads to a free motion of the sphere between the upper and lower piezoelectric membranes of the housing. If the initial velocity is high enough the sphere impacts the upper piezoelectric membrane. After the impact at the upper membrane, the sphere reverses its direction of motion towards the bottom piezoelectric membrane. Due to the deformations imposed on the membranes from the impact with the sphere, an electric voltage is produced on their surfaces.

3. Basic Relationships for Sine Motion of Housing

If the housing moves by sine law the initial force can be expressed by the formula

$$\Phi = -m\ddot{y}^2 = mA\omega^2 \sin \omega t, \quad (1)$$

Where m is the mass of the metal sphere, .

The weight of the sphere G is defined as

$$G = mg, \quad (2)$$

Where g is the gravity acceleration. The condition for a jump of the sphere from the bottom housing is

$$\Phi > G \quad (3)$$

Taking into account eq. (1) and eq. (2) it leads to

$$A\omega^2 \sin \omega t > g. \quad (4)$$

This condition can only be fulfilled in the first quarter of the period for a sine function, since then the inertial force ? is directed upwards, i.e. in the opposite to the direction of the weight. It is assumed that if a jump is not initiated at the peak of the inertial force then the sphere will not separate from the housing and it will continue contact with the bottom membrane. The peak inertial force is achieved when

$$\omega t_m = \frac{\pi}{2} \text{ or} \quad (5)$$

$$\sin \omega t_m = \sin \frac{\pi}{2} = 1, \quad (6)$$

Where tm is the time elapsed the sphere to reach the maximum force. From the above argument we can conclude that, if the sphere does not jump before the first quarter from the period of the oscillations it will continue to be relatively immovable on the bottom disc.

Equation (4) can be written in the form

$$\sin \omega t > \frac{g}{A\omega^2}. \quad (7)$$

Since , this leads to the following condition for a jump to occur

$$\frac{g}{A\omega^2} \le 1. \tag{8}$$

It is not possible for a relative displacement of the sphere to occur, if the product of the amplitude and the square of the frequency is less than the gravitational acceleration.

Equation (7) can be rewritten in the form

$$A > \frac{g}{\omega^2 \sin \omega t} \tag{9}$$

Taking into account that the maximum value of is 1, this leads to a restriction on the peak amplitude for the vibrations on the housing

$$A_m \ge \frac{g}{\omega^2}. \tag{10}$$

This is the minimal amplitude, under which a jump from the bottom will not occur for a given angular velocity.

Let assume that the housing vibrate with amplitude $A \ge A_m$. In this case, in accordance with equation (4) the jump has to appear at instant time t_0 , $\left(0 \le t_0 \le \frac{\tau}{4}\right)$ following from the expression

$$t_0 = \frac{1}{\omega} \arcsin \frac{g}{A\omega^2}. \tag{11}$$

If the membrane deformations during this moment are ignored the sphere separates from the bottom membrane with initial velocity

$$v_0 = A\omega \cos \omega t_0. \tag{12}$$

The initial absolute displacement of the sphere is

$$y_0 = A \sin \omega t_0. \tag{13}$$

If it is assumed, that the sphere moves in vacuum than the differential equation describing its motion takes the simple form

$$m\ddot{y} = -mg. \tag{14}$$

Taking into account the initial conditions (12) and (13) the solution of differential equation (14) is found in the form

$$y = -\frac{1}{2} g t^2 + \left(A\omega \cos \omega t_0 + g t_0\right) t \; + A \sin \omega t_0 - \frac{1}{2} g t_0^2 - A\omega t_0 \cos \omega t_0. \tag{15}$$

Taking in account equation (11) it can be written

$$\cos \omega t_0 = \frac{g}{A\omega^2} \sqrt{\frac{A^2 \omega^4}{g^2} - 1}, \tag{16}$$

Taking in account equation (10) and on substituting equation (16) in 15 it follows that

$$y = -\frac{1}{2} g t^2 + \left(\omega \sqrt{A^2 - A_m^2} + g t_0\right) t + A_m + \frac{1}{2} g t_0^2 - \omega t_0 \sqrt{A^2 - A_m^2}. \tag{17}$$

In order to have a sufficient high kinetic energy it is reasonable to take vibrations which have a relatively high amplitude A, many times surpassing the minimal required value of Am. This assumption can simplified the equation (17) in the form

$$y = -\frac{1}{2}gt^2 + \left(A\omega + gt_0\right)t + A_m + \frac{1}{2}gt_0^2 - A\omega t_0. \tag{18}$$

The relative displacement of the sphere with reference to the housing in accordance with Figure 1 is described by

$$y_{12} = y - y_2. \tag{19}$$

Or

$$y_{12} = -\frac{1}{2}gt^2 + \left(A\omega + gt_0\right)t + A_m + \frac{1}{2}gt_0^2 - A\omega t_0 - A\sin\omega t. \tag{20}$$

The condition for impact on the upper membrane is

$$y_{12}(t_1) - r = d, \tag{21}$$

Where d is the distance between the bottom and upper membranes, t1 is the moment when the impact occurs.

On applying Taylor series and after simple transformations, we get

$$\sin\omega t \approx \omega t - \frac{1}{6}\omega^3 t^3 + O\left[\left(\omega t\right)^5\right] \tag{22}$$

$$y_{12} = -\frac{1}{2}gt^2 + \left(A\omega + gt_0\right)t + A_m + \frac{1}{2}gt_0^2 - A\omega t_0 - A\omega t + \frac{1}{6}A\omega^3 t^3. \tag{23}$$

$$-\frac{1}{2}gt_1^2 + \left(A\omega + gt_0\right)t_1 + A_m + \frac{1}{2}gt_0^2 - A\omega t_0 - A\omega t_1 + \frac{1}{6}A\omega^3 t_1^2 - r + d = 0. \tag{24}$$

If it is assumed that $\sin\omega t \approx \omega t + O\left[\left(\omega t\right)^3\right]$ then

$$t_1 \approx t_0 + \frac{\sqrt{2}}{\sqrt{g}}\sqrt{d - r - A\omega t_0 + A_m} \tag{25}$$

In this moment the sphere impacts the upper membrane with speed

$$v_{12}^{(I)} = -gt_1 + gt_0 - A\omega\sin\omega t_1. \tag{26}$$

Equation (26) is derived by differentiating equation (20) and on substituting t with t_1 .

According to the elementary impact theory, in an infinitely small amount of time the sphere velocity changes direction and reduces its value

$$v_{12}^{(II)} = -kv_{12}^{I} = kgt_1 - kgt_0 + kA\omega\sin\omega t_1. \tag{27}$$

Where k is the restitution coefficient which depends on the impacting materials. To exhibit a velocity reversal the following relation must apply

$$v_{12}^{(II)} = kgt_1 - kgt_0 + kA\omega\sin\omega t_1 < 0 \tag{28}$$

$$t_1 - t_0 + \frac{A\omega}{g}\sin\omega t_1 < 0 \tag{29}$$

If conditions (28), (29) are not satisfied, the sphere will continue to move with the upper membrane until condition (29) is satisfied.

4. Results and Discussion

Using a steel sphere with mass of 440mg and available traveling distance of 3,59 mm. The sphere radius is r=2,38 mm, and the gap d=8.35 mm between the membranes.

The harvester was subjected to sine oscillations with different frequencies to observe the induced voltages on the piezoelectric membranes. The assembled harvester and experimental setup with simplified block scheme is depicted on Figure 2 and Figure 3.

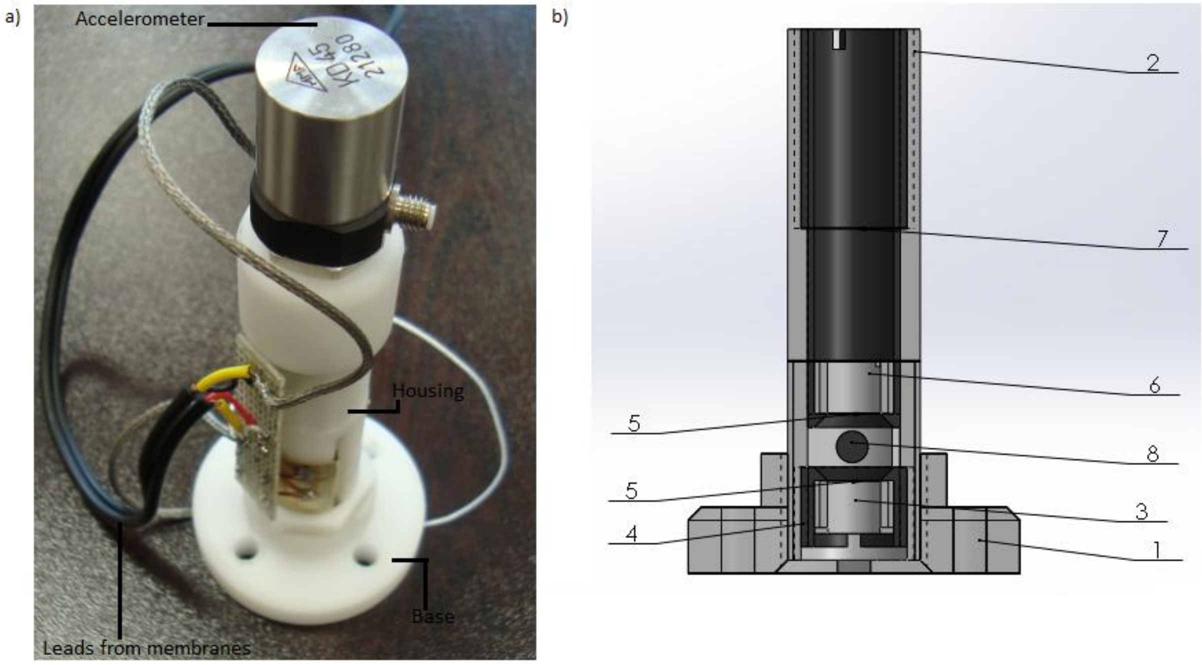

Fig2. *Vibro impact harvester design: a) -Assembled harvester b) – Modeled assembled harvester with section view, 1 – flange, 2- housing, 3-piezoelectric disk holder, 4- supporting piezoelectric disk holder, 5-piezoelectric membrane, 6-mobile piezoelectric disk holder, 7- mobile piezoelectric disk supporting holder, 8- metal sphere;*

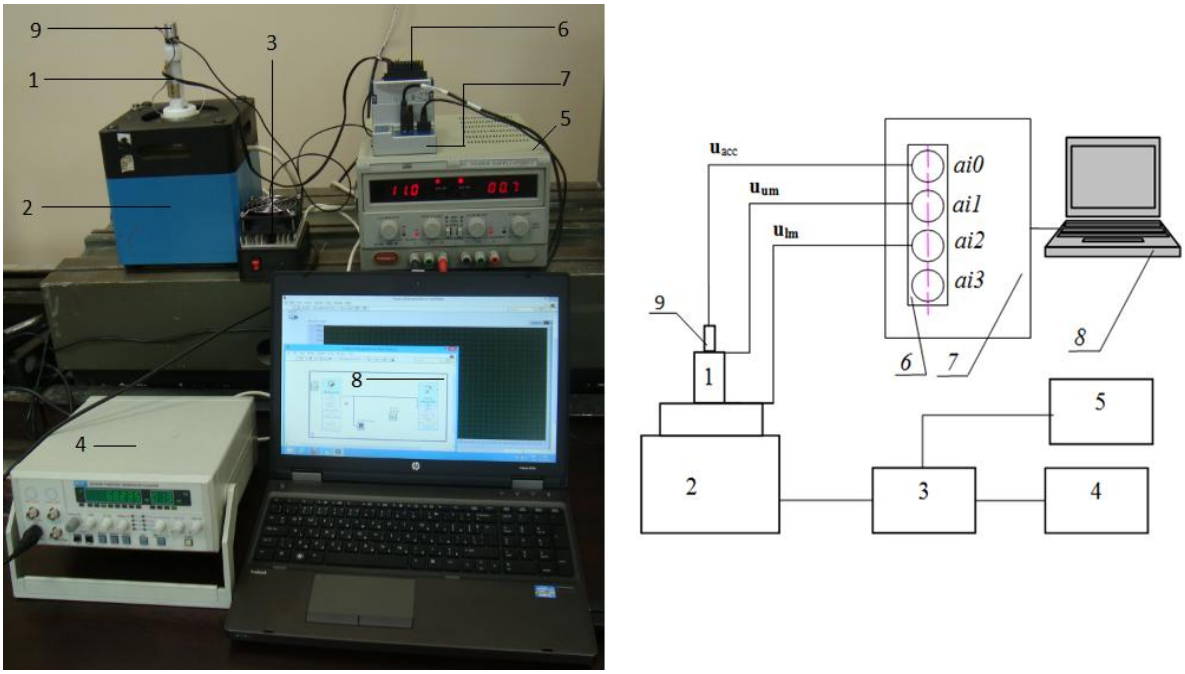

Fig3. *Experimental setup apparatus a) 1- Impact Harvester, 2- Vibration generator (shaker), 3- Amplifier, 4- Frequency generator , 5- Power supply, 6- National Instruments DAQ 9201, 7- National Instruments DAQ 9174, 8- Computer with LabView software, 9- Accelerometer – b) Simplified block scheme of the experimental setup*

In order to eliminate noise the data was sieved and analysed for signals that generate above/below +/- 0,5V. The number of impacts that generate above/below +/- 0.5V is depicted on Figure 4.

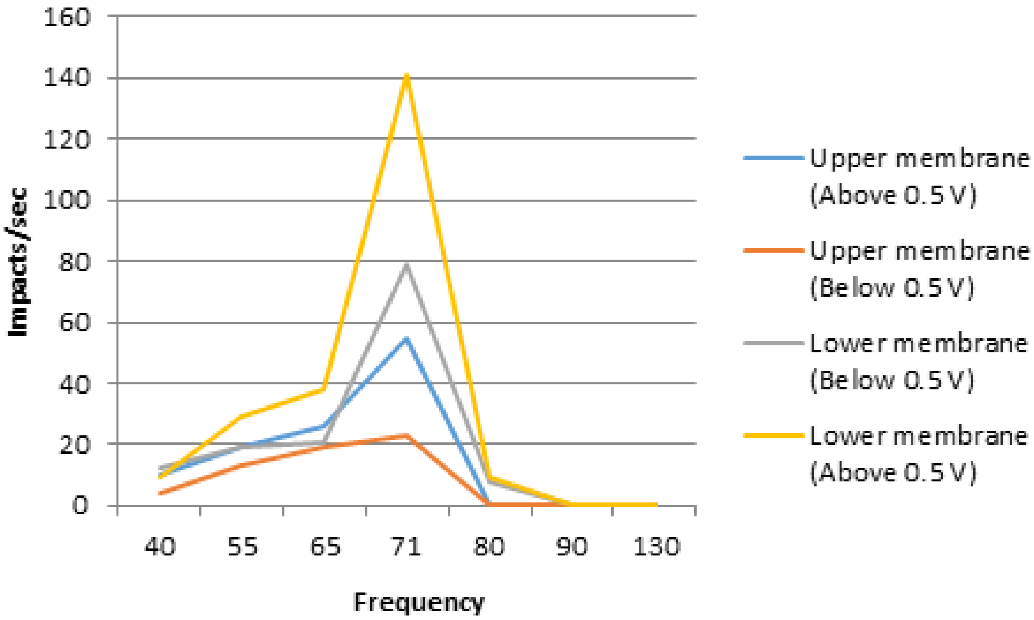

Fig4. *Number of impacts per second that generate above/below 0.5 V on the membrane*

It can be seen that the number of impacts steadily increase until the system reaches its quasi-resonant state. Further increase in the frequency leads to steeper decrease of the number of impacts on both membranes. From fig. 4 it can be concluded that the system reaches a state in which the impact frequency surpasses the external driving frequency by a factor of 3.

On Figure 5 the maximum and minimum generated voltages are shown. There is a saturation point for maximum voltage on the lower membrane due to equipment set up parameters. There is a tendency for the maximum and minimum voltages to increase in magnitude towards the quasi-resonant frequency. We suspect that the increase in induces voltage is due to the decreased time between impacts, where the sphere impacts the membranes before the impact oscillations from the previous impact have not ceased.

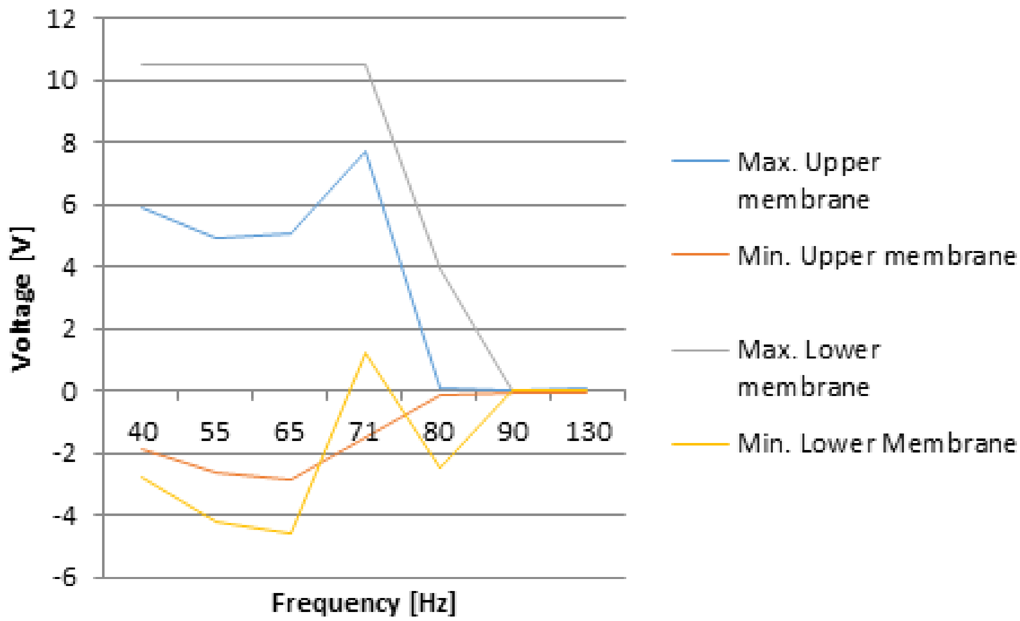

Figure 5. *Maximum and Minimum induced voltages from impact on the membranes;*

On Figure 6 is shown the average and maximum acceleration measured on the harvester during vibrations. While the average acceleration remains relatively unchanged, the maximum acceleration shows a plateau at the quasi-resonant frequency

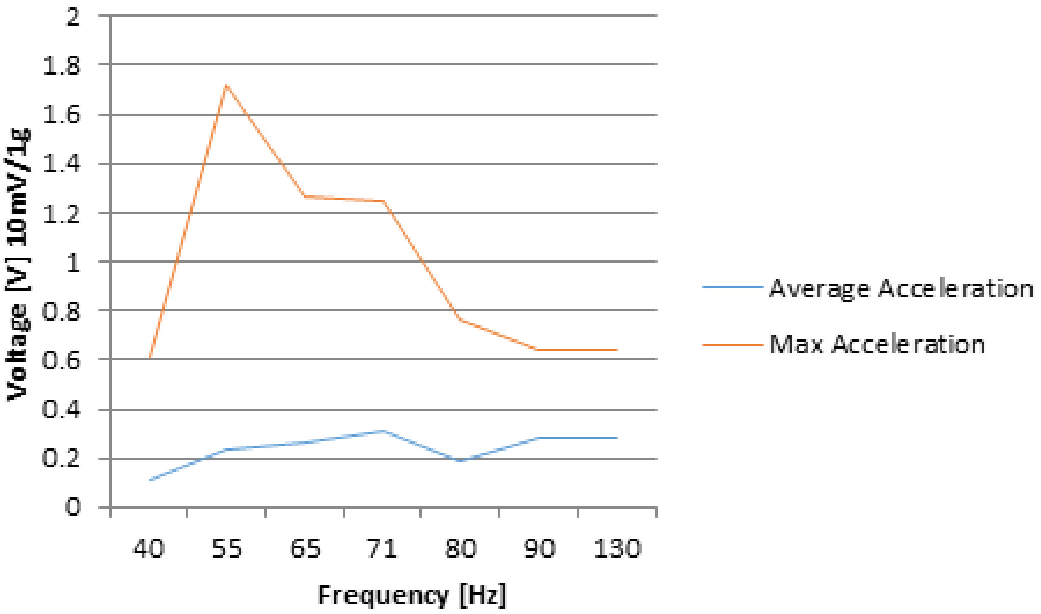

Fig6. *Average and maximum acceleration during impacts on both membranes*

This discrepancy can be explained from the time elapsed between two successive impacts on the same membrane (Figure 7).

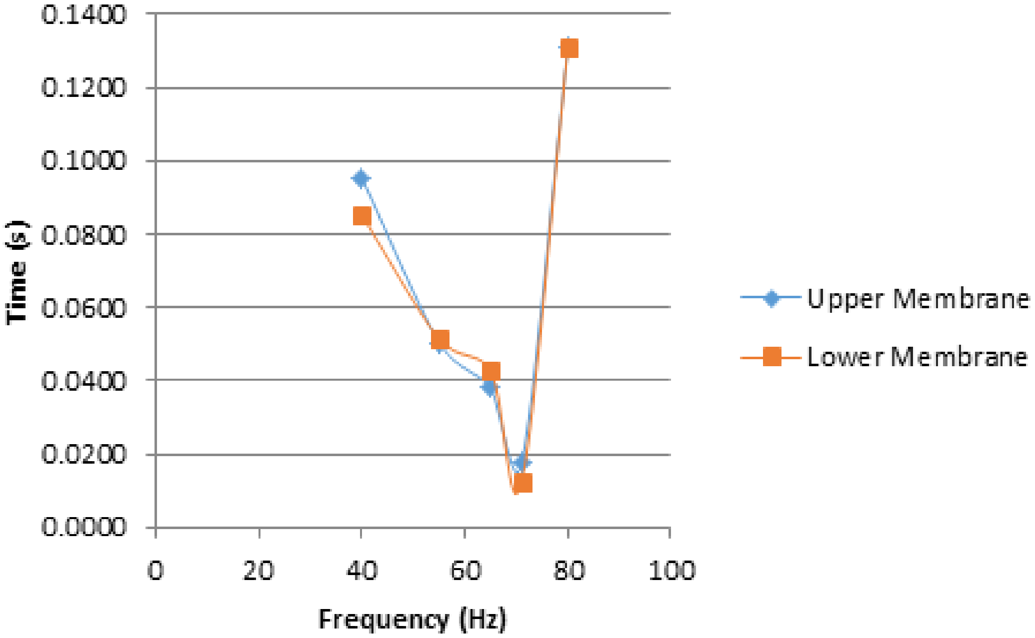

Fig7. *Time between successive impacts on the upper and lower membrane*

As the driving frequency reaches the quasi-resonant frequency of the system, the time spread between two successive impacts starts to decrease which leads to less spreading out of the time intervals for the output generated voltages and more predictable induced output voltage on the membrane. On fig. 7 the average period on impact is shown. It can be concluded that the most of impacts occur in the range

$$T \in \left[\frac{\pi}{2}; \frac{3}{2}\pi\right] \tag{30}$$

From figure 8 it can be derived that the period ratio between two impacts on the membranes is u≈0.5 or its inverse 1/u≈2 (Figure 9).

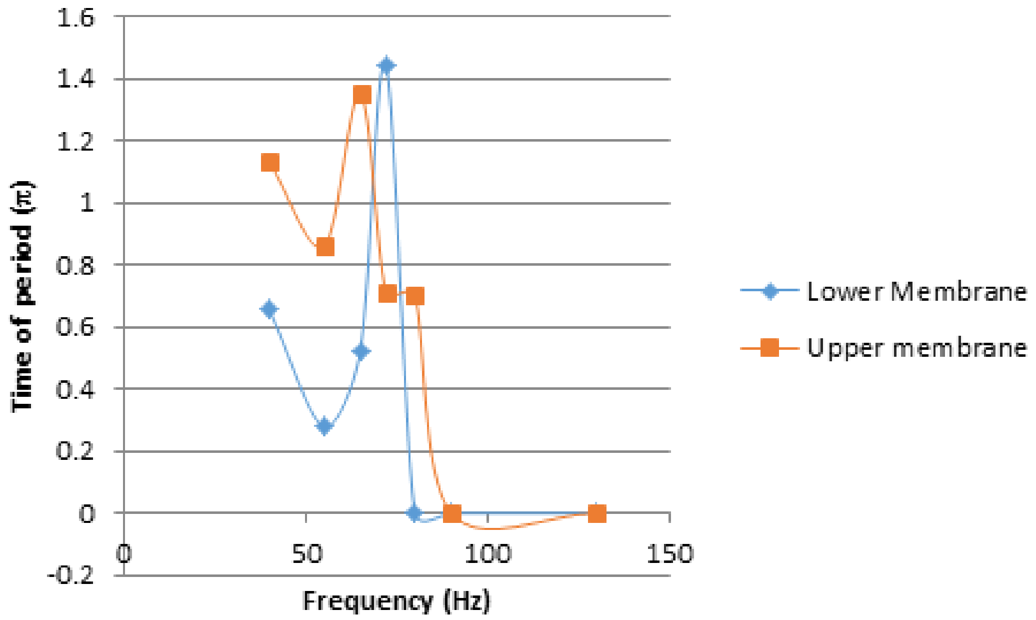

Fig8. *Average period time of impact*

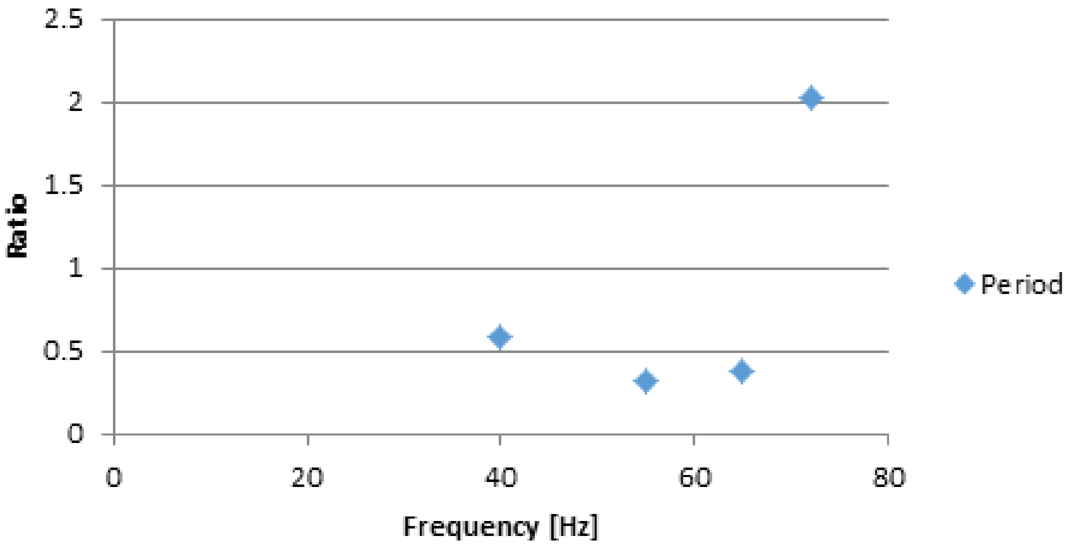

Fig9. *Period ratio between two impacts from one piezoelectric membrane to the other*

The output from the membranes, for a period of one second, is shown on Figure 10. The number of saturated output peaks steadily increases until it reaches a maximum at the resonant frequency of 71.25 Hz. Using the equation for maximum energy in quasi-resonant state of an impact harvester [6].

$$E = \frac{mk^2 A^2 \omega^2}{2} \cdot \frac{(u+1)^2 \cos^2\left(\omega t_0 + \frac{2\pi}{u+1}\right)}{(1+ku)^2} . \tag{31}$$

where k is the coefficient of elasticity for the piezoelectric membranes, u is the period ratio and t_0 is the time before the initial impact. Assuming the sphere has an initial velocity $A\omega$ (maximum possible velocity for harmonic vibration), it can be assumed that $t_0 = \frac{y}{A\omega}$, thus $\omega t_0 = \frac{y}{A}$. Taking y=3,59mm and A=2mm from equation 30 it can be concluded that the maximum energy will achieved for u$\approx$0.4, which is in agreement with experimental results.

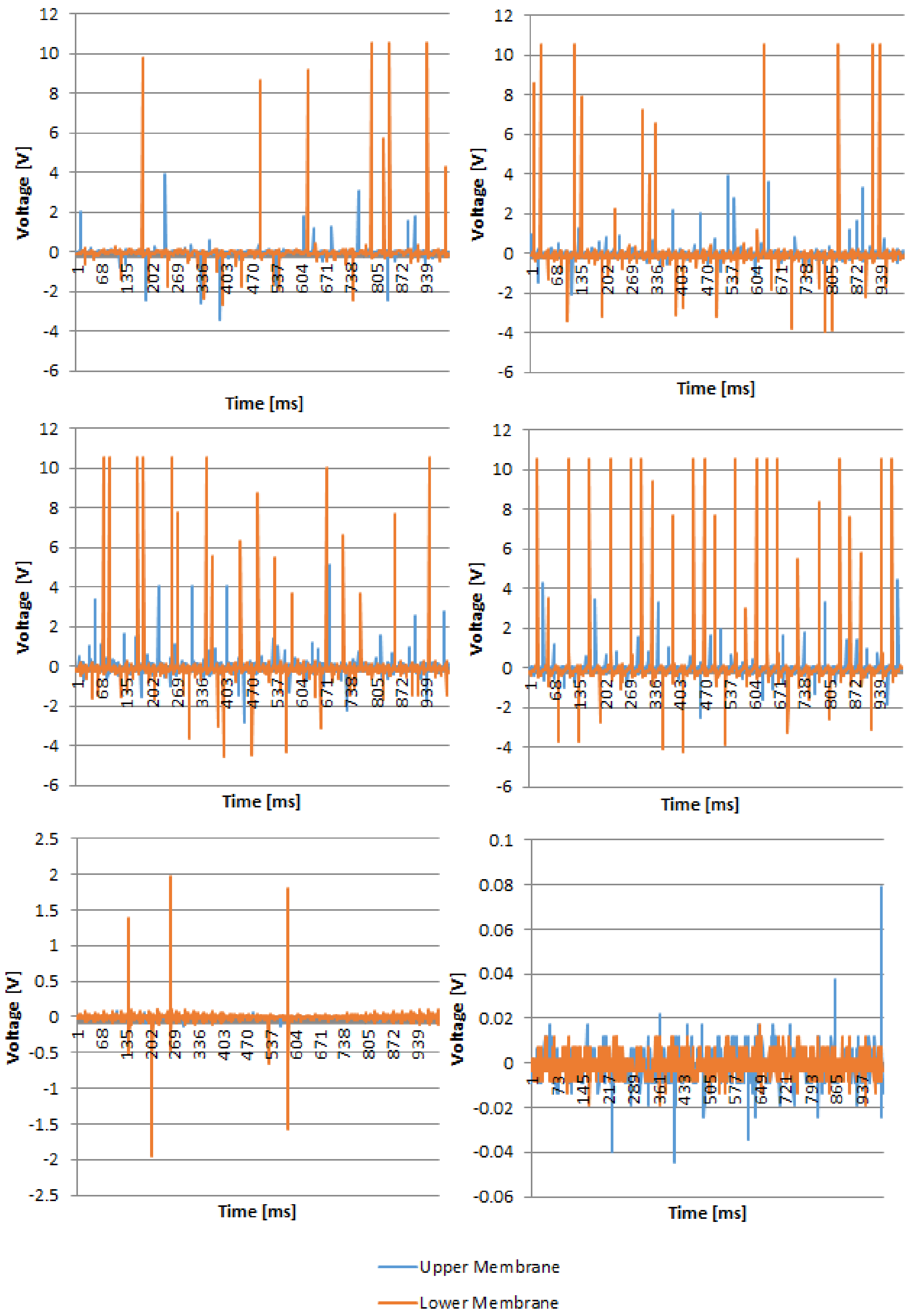

Fig10. *Output voltages from the piezoelectric membranes for a period of 1 sec.(1st row – Left 40 Hz, Right – 55 Hz; 2nd row – Left 65 Hz, Right – 71.45 Hz, 3rd row – Left 80 Hz, Right 90 Hz)*

It is important to note that the maximum amplitude is limited by the strength of the piezoelectric membranes. The typical damages are shown in Figure 11. It is seen that the weakest point of the membranes is the impact strength of the piezoelectric ceramic layer. The bending stress of the elastic substrate is the next crucial element which limits the maximum energy harvested

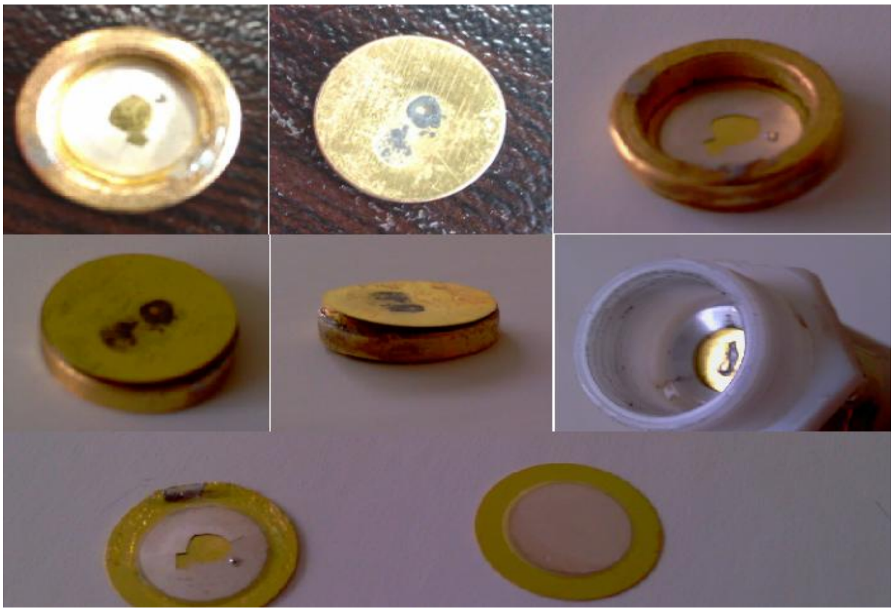

Fig11. *Piezoelectric membrane damage after a few minutes of operation at quasi-resonant frequency*

5. Conclusion

The basic equations which describe the impact energy of the harvester are worked out.

The experiments by vibroimpact harvester with variable parameters are done in order to validate the theoretical results.

By experiments it is found that the maximum energy will be achieved for the period ratio u≈0.4, which proofs the experimental results.

Although impacts lead to complex system description and chaotic behaviour [15],[16],[17],[18], under certain conditions the response of the system tends toward more repetitive behaviour with more stable output parameters [19]. In this state the impact frequency surpasses the driving frequency by a factor of 3.

This can be exploited to build energy harvesters which can supply apparatus that is hard to reach and/or maintain but is known to be subjected to sinusoidal type vibrations [8]-[11],[12],[13],[14].

The current results were made on the basis of sine vibrations. Future experiments will be conducted to study the behaviour of the system under other type of repetitive vibrations to determine the behaviour for quasi-resonant state of the system.

The main disadvantage of impact energy harvester is that involves impacts which generate bigger forces and loads than other types of harvesting systems [1]-[4],[22],[23]. Thus the life expectancy of the impact energy harvester depends on the mass of the sphere used [5].

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