Design, Development and Testing of Compliant Mechanism for Amplification of Energy Generated in Vibration Energy Harvester.

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Abstract - This paper presents, a unique flexure-based mechanism known as 'Compliant Mechanism', for amplification of displacement of inertia mass in vibration-based electromagnetic energy harvester (VEH). The Electromagnetic energy harvester used in this work is proposed to power sensors used for condition monitoring of industrial centrifugal pumps. The flexure-based compliant mechanism is used to amplify displacement in the system. Pugh selection criteria is used to find the optimum design from four designs. The selected design is further used to amplify the output of an electromagnetic harvester by amplifying the displacement in that system. The use of compliant mechanical amplifier gives satisfactory results.
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***Key Words*:** Compliant Mechanism, Condition Monitoring, Pugh selection criteria, Electromagnetic harvester

1.INTRODUCTION

Energy harvesting technologies that can collect energy from the surroundings (e.g. solar power, thermal energy, wind energy, mechanical energy, and so on) and store it for small autonomous devices have been making rapid progress recently [1]. Energy harvesters provide very small amount of power for low-energy electronics. Energy harvesting devices converting available ambient energy into electrical energy have attracted much interest in sectors like military. Some systems convert motion, such as that of ocean waves, into electricity that can be used by monitoring sensors. These can be used in cases such as high-power output devices deployed at remote locations to serve as reliable power source for that system.

The sensors used for condition monitoring of any heavy machinery consumes power in milli-Watts (mW). Usually, vibrations are present in any sort of rotary machinery, due to imbalance in rotating parts. One promising technology is to provide power to structural health monitoring sensors to reduce their reliance on batteries or to eliminate the installation costs associated with running power cables across sensor nodes [2]. The dynamic response of various structures, such as railway tracks, buildings, and bridges provide a ubiquitous source of mechanical excitation that can be tapped into to provide sustainable power for a wide variety of sensors and devices [2]. Generally, the apparatus used for condition monitoring runs on batteries. The batteries that are used to fulfil the power requirement of the sensors, deplete within 3–5 years [3]. Therefore, an interruption is caused each time a battery needs to be replaced, resulting in the restriction of the vibration monitoring process. It is also hectic to replace the batteries. needed to operate these devices is a major concern. An alternative type of energy source to conventional batteries must be considered. The electrical energy required to run these devices can be obtained by tapping the thermal, light, or mechanical energies available in the ambient environment. This process helps in providing unlimited energy for the lifespan of the electronic device. The design of electromagnetic system can be done with the help of method given by Dirk Spreemann et.al [4] and Tom J. Ka´zmierski et.al. [5].

The output from the energy harvesting devices can be increased to satisfy useful power requirement with the help of 'Compliant Mechanism'. These Mechanism are flexure-based mechanism which amplify either force or amplitude in a system. This can be achieved due to flexibility provided by hinges at the joints in any particular mechanism. Compliant mechanism can be simple in construction, but generally compliant mechanisms are complex in term of geometry. The construction of compliant mechanism can be done with the help of procedure given in handbook of compliant mechanism given by Larry Howell [6] and Midha [7].

In this work, Compliant Mechanism is designed to amplify the displacement of inertia mass in an electromagnetic harvester which is previous work of Syed Faizan-ul-Haq Gilani et.al [3]. In electromagnetic harvester the output is depend upon the displacement of Inertia mass. In this work, inertia mass consists mass of two coils on which copper coil is wound. A compliant mechanism is designed to amplify the displacement of inertia mass which will help to increase the output from electromagnetic harvester. Operating frequency for this application is 150Hz to 250Hz [3]. And the resonating frequency of model is 200 Hz [3]. Hence to get maximum displacement the design is made at resonating frequency. The modelling of Compliant mechanism is discussed in sections below.

2. METHODOLOGY

In this section, methodology of developing compliant mechanism is discussed. In first step, various possibilities for compliant mechanism are generated, and out of those options most suitable mechanism is selected. For selection of suitable mechanism, a selection method called Pugh concept selection criteria [8] is used. This selection criteria include two steps. Those steps are, 'concept screening' and 'concept scoring'.

2.1 Pugh selection criteria

2.1.1 Concept screening

In this, selection criterion grouped together which satisfy the requirements of working conditions. The selection of those criterion is depending upon the conditions in which the final component is going to operate. Strength, durability, ease of manufacturing some of the examples of these selection criterion. The concept screening stage includes three steps which are:

2.1.1.1 Preparation of Selection matrix:

In this step, the criterion which are required for the working of mechanism are specified. A table is prepared which includes selection criterion, all the proposed concepts. By using this table, a comparison between the proposed concept becomes easy.

2.1.1.2 Rating the concept:

The code used for rating the concepts (+ for "better than," 0 for "same as," – for "worse than").

2.1.1.3 Rank the concept:

In this step, addition and subtraction of + ves and –ves are done. Based on those values, rankings are assigned which will give basic idea about selection of one or more suitable concepts. If more than one concept is selected in this process. Then concept scoring is used to clearly distinguish most suitable concept from other one.

2.1.2 Concept scoring:

This method uses a weighted sum of the ratings to determine concept ranking. The method is used to get most suitable concept from concepts which are finalized in concept screening. This stage consists of following steps:

2.1.2.1 Prepare the selection matrix:

In this stage, a table is prepared which consists of selection criterion previously specified in concept screening stage. After the criteria are entered, importance weights are added to the matrix. Several different schemes can be used to weigh the criteria, such as assigning an importance value from 1 to 5.

2.1.2.2 Rate the concepts:

Rating to concept can be done by assigning values from 1 to 5.

2.1.2 Concept scoring:

From table 1 we can clearly see that there are two suitable concepts of compliant mechanism are present. Thus, to get most suitable between those two, concept scoring method is used.

Step 1: Prepare the selection matrix:

After the criteria are entered, importance weights are added to the matrix. Several different schemes can be used to weigh the criteria, such as assigning an importance value from 1 to 5 which is adopted here.

Step 2: Rate the concepts

A recommended scale is from 1 to 5.

Step 3: Rank the concepts

Once the ratings are entered for each concept, weighted scores are calculated by multiplying the raw scores by the criteria weights. The total score for each concept is the sum of the weighted scores:

$$S_j = \sum_{i=1}^{n} r_{ij} \times w_i \tag{1}$$

here,

r_{ij} = raw rating of concept j for the ith criterion.

W_i = Weighing for ith criterion.

n = number of criteria.

S_j = Total score for concept j.

Step 4: Select best concept

The highest-ranking concept is finalized as compliant mechanical amplifier. The weight selection criterion and concept rating criterion are given in Table-3 and Table-4. The total score decides the best concept. Then selected concept is considered for further design procedure which includes flexural hinge selection.

By using above mentioned method, a suitable geometry for mechanism is decided. Then the design of compliant mechanism is made starting from hinge groove. The hinges are designed on the basis non dimensional equations provided by Schotborgh et.al [9]. The compliant mechanism is designed for amplification of 5 times and with design restrictions for length not more than 60 mm. The Modelling of Compliant mechanism and results are discussed in next section.

3. MODELLING AND ANALYSIS

In this section, few concepts of compliant mechanism are discussed. Here, four concepts are used to find the most suitable among them. The selection of most suitable concept is done on the basis of Pugh selection criteria [8]. The procedure to find best concept is discussed below.

3.1 Concepts

Concept A: Symmetric Five bar Mechanism

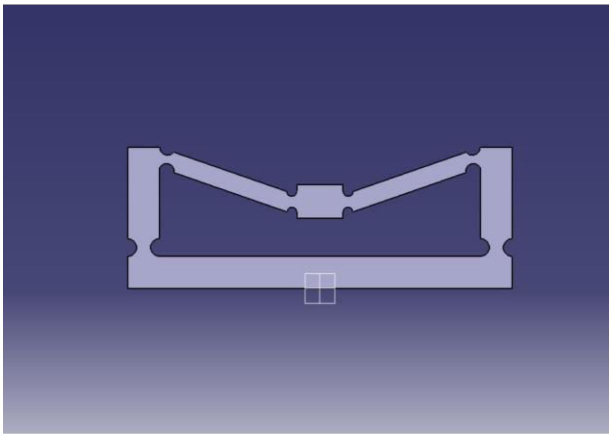

Fig-1: Symmetric Five bar Mechanism

Concept B: Combination of Scissor type

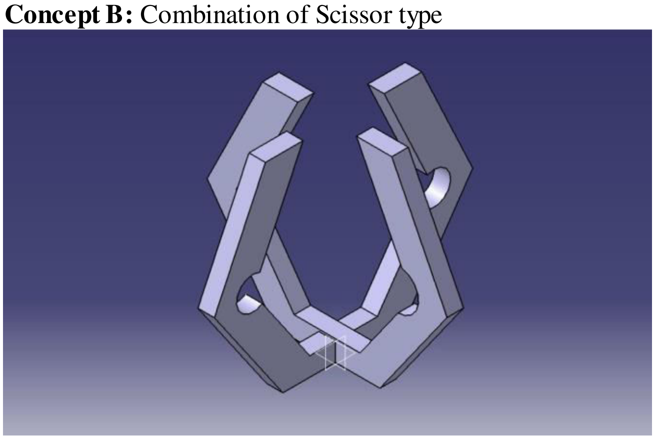

Fig-2: Combination of Scissor type

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Concept C: Bridge type

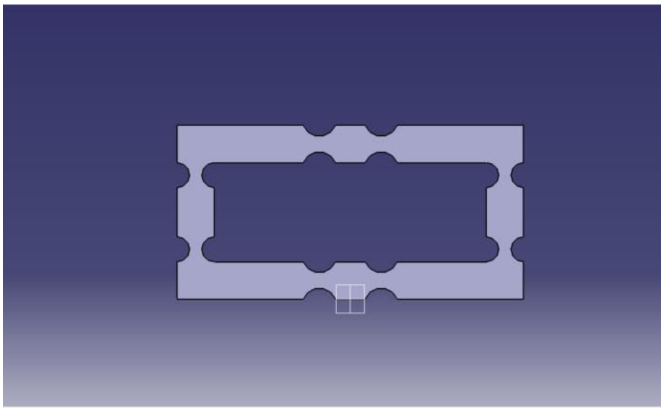


Fig-3: Bridge type

Concept D: Simple Beam

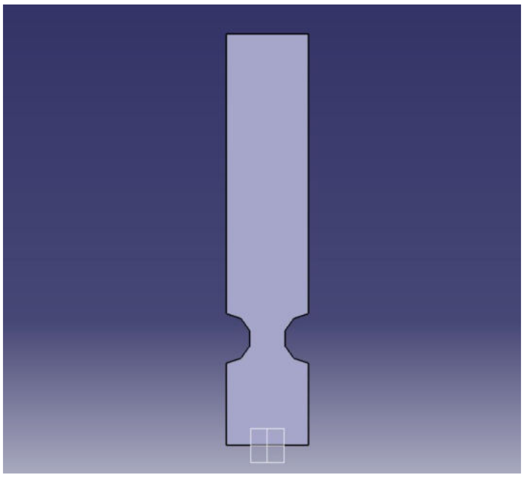


Fig-4: Simple Beam

3.2 Pugh Selection Criteria

In this section, Pugh selection criteria is applied for all above concepts. The procedure is discussed below.

3.2.1 Concept Selection matrix

3.2.1.1 Preparation of Selection matrix

The criterion selected for screening process are as follows**.** These criteria are selected according to requirements of working conditions. Concept selection criterion are specified here,

1 Strength
2 Durability
3 Ease of manufacture
4 Amplification
5 Range of motion and rotation
6 Stress concentration
7 Axis Drift
8 Compactness.

By following steps mentioned in previous section we get final results are shown in **Table-1.**

From **Table-1** we can clearly see that there are two suitable concepts of compliant mechanism are present. Thus, to get most suitable between those two, concept scoring method is used.

In concept scoring method steps, which are mentioned in **sec.2** are followed. The final results are mentioned in **Table-2**.

Table -1: Concept selection matrix for compliant mechanical amplifier

No	Criteria	Concepts			
		A	B	C	D
1	Strength	0	0	+	+
2	Durability	0	0	+	+
3	Ease of Manufacture	+	0	-	+
4	Amplification	0	0	0	0
5	Range of motion and Rotation	0	0	+	+
6	Stress Concentration	-	-	0	-
7	Strength	0	0	+	+
8	Durability	0	0	+	+
Sum '+' s		**2**	**0**	**4**	**5**
Sum '0' s		**5**	**7**	**3**	**2**
Sum '- 's		**1**	**1**	**2**	**1**
Net score		**1**	**-1**	**2**	**4**
Continue		X	XX	+	+
X- Discontinue		**XX- Strongly Discontinue**		**+ - Continue**	

Table-2: Concept Scoring matrix

Criteria	Weight (w)	C		D	
		Rating (R)	Score (w × R)	Rating (r)	Score (w × r)
Strength	15%	3	0.45	4	0.6
Durability	15%	3	0.45	4	0.6
Ease of Manufacture	20%	2	0.4	4	0.8
Amplification	20%	3	0.6	3	0.6
Range of motion and Rotation	5%	3	0.15	3	0.15
Stress Concentration	10%	2	0.2	3	0.3
Strength	5%	4	0.2	3	0.15
Durability	10%	2	0.2	4	0.4
	Total		2.65		3.6

	Rank		2		1
	Continue		x		+

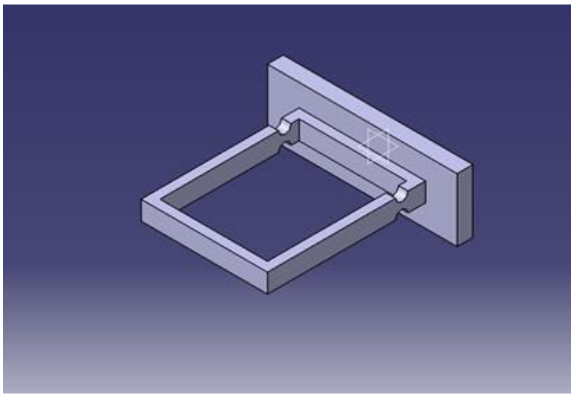
Table-3: Weight Selection criterion

20%	More Importance
10% to 15%	Medium Importance
0 to 10%	Not that Important

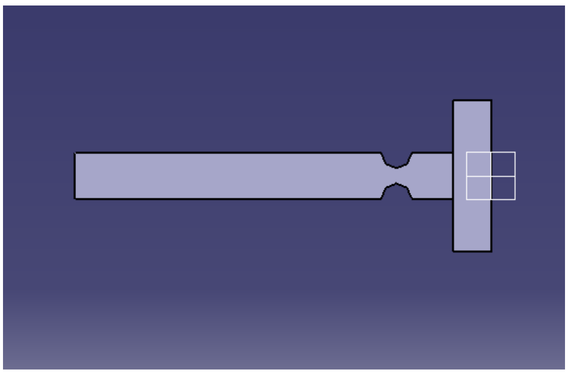
Table-4: Concept rating

Worse	1
Worse than	2
Same as	3
Better than	4
Better than	5

From **Table-2** it is concluded that, concept D which is a simple beam is scored highest rating and the mechanism is developed based on that design. Based on requirement of working condition final model developed is shown below.



(a)



(b)

Fig-5: Catia model of Proposed compliant mechanism

(a) Iso-View (b) side view.

(b)

3.3 Modelling and Design of Compliant Mechanical Amplifier

This section includes design of circular notch flexural hinge of compliant mechanical amplifier. The force acting in the system is around 50 N, the frequency is 200 Hz. Acceleration in system is nearly 1 g. Here, the mechanism is designed to amplify the displacement of inertial mass in Electromagnetic harvester by 5 times previous value. The requirements of compliant mechanism are, maximum length not more than 60 mm. (design restrictions) and amplification ratio 5.

3.3.1. Flexure hinge design:

The material selected for design for compliant mechanism is PLA (polylactic acid). The material is selected to achieve ease in manufacturing, non-magnetic property and achieving required complexity (if any).

Material Properties:

PLA (Polylactic Acid)

Sut = 35 MPa, **Poisson's ratio**= 0.36,

E (Youngs modulus) = 3.5 GPa.

The hinge in a compliant mechanism is a designed on the basis of non-dimensional equation given by Schotborgh [9]. The equations are as follows,

Dimensionless stiffness in x-direction:

$$\frac{K_{xx}}{E\times t} = \left[0.0010 + \left(0.4256 \times \sqrt{\frac{h}{D}}\right) + \left(0.0824 \times \left(\sqrt{\frac{h}{D}}\right)^2\right)\right] \quad (2)$$

Dimensionless stiffness in y-direction:

$$\frac{K_{yy}}{(E\times t)} = \left[0.0040 - \left(0.0727 \times \sqrt{\frac{h}{D}}\right) + \left(0.3417 \times \left(\sqrt{\frac{h}{D}}\right)^2\right)\right] \quad (3)$$

Dimensionless stiffness in z-direction:

$$\left(\frac{K_{\varphi\varphi}\times 12}{E\times t\times h^2}\right) = \left[-0.0089 + \left(1.3556 \times \sqrt{\frac{h}{D}}\right) - \left(0.5227 \times \left(\sqrt{\frac{h}{D}}\right)^2\right)\right] \quad (4)$$

By using above equation dimensions of beam calculated as:

Length(l) = 50 mm.

Width(b) = 3 mm.

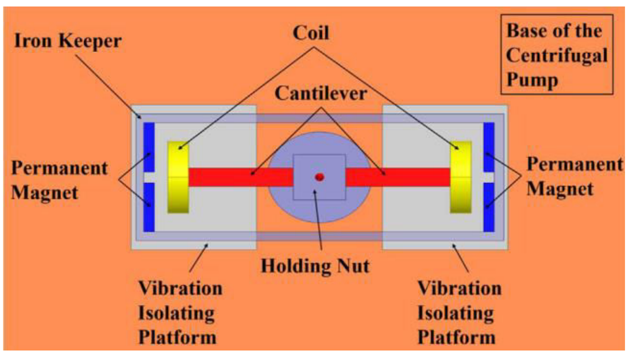
Depth(d) = 6 mm.

Dimension of hinge:

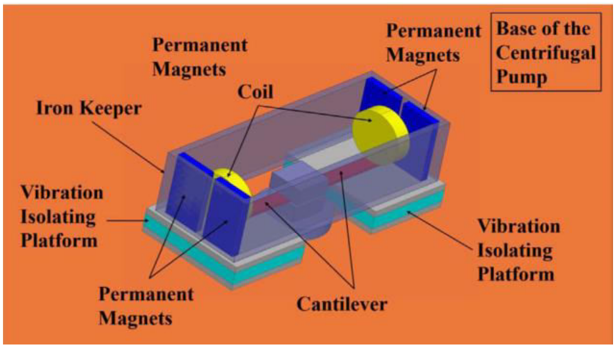
D (diameter of hinge) = 4 mm.

h (distance between two hinges along depth) = 2 mm.

3.4 Electromagnetic system properties:



(a)



(b)

Fig-6: Proposed design of the VEH (a) Top view (b) 3D View of the VEH [3].

Properties of Electromagnetic system are as follows:

m_1 (mass of both coils) = 18 gm

m_2 (mass of magnetic assembly) = 38 gm.

Magnet size = 25×12×5 mm

ε (open loop voltage) = 3.48 V.

B= 0.4 T.

Power = 3.48 mW.

Resonant frequency=200 Hz.

Acceleration (g) = 1 g

No of magnets used = 4.

Final model of whole system:

The final model is consist of electromagnetic proposed by [3] and above compliant mechanism in Sec 3.

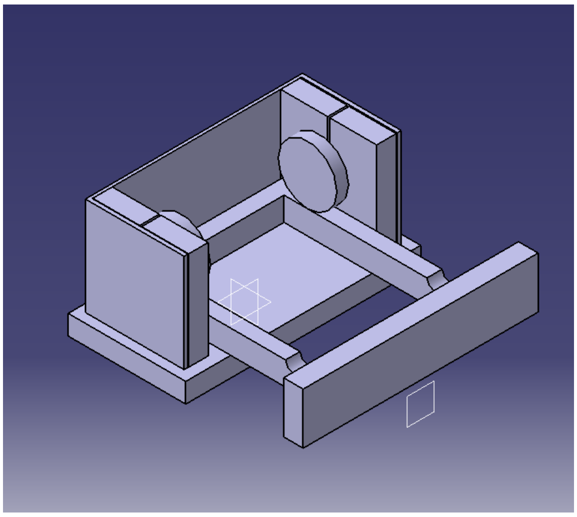


Fig-7: Final model of system with compliant mechanism in Catia.

3.5 Analysis of Compliant mechanism:

Analysis of the compliant mechanism has been made in Ansys 18.1. From that it is concluded that the mechanism can work in the given specified range 150 Hz to 250 Hz. The first five result are as follows:

SN.	Mode	Frequency (Hz)
1	1	552
2	2	675
3	3	1078
4	4	2136
5	5	3715

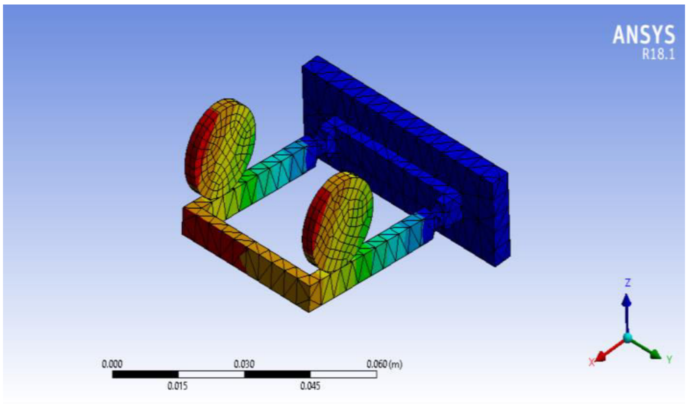


Fig- 8: Analysis result at 552 Hz frequency (mode 1)

3.6 EMF generated in Electromagnetic harvester (with compliant mechanism)

The Open loop voltage generated in electromagnetic harvester is given by Faraday law of electromagnetic induction which is,

$$emf = N \cdot l \cdot B \frac{dv}{dt} \tag{5}$$

here,

emf = Open loop voltage. B = Flux linked to coil.

$\frac{dv}{dt}$ = Ratio of change in velocity to change in time.

l = length of coil in a turn. N = No. of turns.

From above equation emf in system can be calculated as value of no. of turns (N), length of coil (l), flux in coil (B), is known. Hence, by using above equation the value any unknown quantity can be calculated, provided that all other quantities are known. The calculated output emf for given amplification is comes out to be 10.43 V. The output specified in previous work is 3.48 V. Here the output obtained is amplified with the help of Compliant Mechanical Amplifier.

4.RESULTS AND DISCUSSION

From the results of above sections, it is clearly observed that, the compliant mechanical amplifier used for the purpose of amplification gives satisfactory output. Pugh selection criteria gives most suitable design concept of compliant mechanism. From results obtained in section 3.4.3, it is seen that the compliant mechanism is suitable to work in frequency range of 150 Hz to 250 Hz. The result obtained in section 3.4.4 suggests that the compliant mechanism can be used to amplify the voltage from electromagnetic harvester. Resulting output (open loop voltage) with compliant mechanism obtained is 10.43 V which is almost 3 times the previous results [3] without compliant mechanical amplifier i.e., 3.48 V. The testing of the prototype will give actual results.

5.CONCLUSION

The issue of condition monitoring of equipment which are located at remote location can be tackled with the help of energy harvesters. Which extracts the un-used useful energy from the equipment which in most cases present in the form of vibrations. The problem of depletion of batteries which are used in condition monitoring equipment can be solved with energy harvester. Above work shows the output from the energy harvester get amplified with the use of compliant mechanical amplifier. Compliant mechanism developed in above sections in specifically designed for an electromagnetic harvester. The harvester was designed to power sensors that are used in condition monitoring of centrifugal pump. The fabricated prototype is able to achieve open loop voltage of 3.48 V and with the use of compliant mechanism the output is amplified to 10.43 V. From these results it can be concluded that the compliant mechanism can be used to increase the output in a system. Further work will be using the prototype in actual working condition. Real life working conditions presents different challenge, which can be solved after testing the prototype in actual working conditions.

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