Design of a Low-Frequency Linear Motion Testbed for Electromagnetic Kinetic Energy Harvesters in JumboNet

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***Abstract*—Kinetic energy harvesting on animals is an emerging technology that could facilitate real-time monitoring of wild elephants. Real-time monitoring is a proven solution to the Human-Elephant Conflict, a problem that has spread across Asia and Africa. However, when designing electromagnetic harvesters, it is essential to accurately model the voltage produced due to electromagnetic effects.**

In this paper, we present the design, development and the complete simulation of a simple and low-cost linear motion testbed that estimates the generation of an electromagnetic harvester.

We integrated the dynamic non-linear flux linkage across the coil with an analytical model that accurately estimated the motion of the moving magnet. The experimental measurements from the testbed were better than 80% in agreement with the simulation results within the frequency range of 1Hz to 2Hz.

I. Introduction

The search for effective measures to deal with Human–Elephant Conflict (HEC) is one of the most significant challenges for elephant conservation globally. Real-Time Monitoring (RTM) of positional data using tracking units attached to animals is emerging as an effective tool for ecological monitoring and wild life conservation. As an example, Wall et al. [1] have performed real-time monitoring of proximity, geofencing, movement rate and immobility detection on 94 elephants to prove its effectiveness compared with traditional slow and often inaccurate monitoring techniques. Their system is composed of an elephant-mounted collar that uses satellite and GSM networks to transmit GPS and auxiliary sensor data to a cloud based storage where analysis is performed and necessary alerts are generated within 5 minutes.

In [2], authors demonstrated the feasibility of electromagnetic kinetic energy harvesting on elephants in order to perform real-time monitoring. Using acceleration data recorded on an elephant, they analyzed the frequency and amplitude distribution of motion on each of the 3 axes. This provided some vital information on the best harvester orientation and the optimal dimensions that maximizes energy generation while maintaining a size and a weight that could be practically mounted on an elephant.

Designing elephant mounted kinetic harvesters involves a number of steps. Firstly, the estimated energy requirement per day is obtained assuming a basic source to sink transmission protocol. The minimum requirement for real-time monitoring is an hourly transmission of position to the monitoring system. We also assume that these updates are transmitted to a sink that is less than 114km (line of sight) away from the elephant. Secondly, using a simulation based analytical model of the kinetic harvester, it is possible to estimate the daily energy generation for the recorded motion on the elephant. If the simulated daily energy generation is more than the estimated daily energy requirement, the harvester design is considered feasible.

The simulation includes two key components. The first is the mechanical system simulation and the second is the electromagnetic simulation. The electromagnetic simulation provides the radial flux density and the flux linkage distribution of the magnet as it interacts with the coil. The mechanical system simulation approximate the forced forced oscillation of the moving magnet as described in [3].

This paper presents a method to experimentally verify the flux linkage in the electromagnetic simulation. Using a simple slider-crank mechanism, a controlled periodic linear motion is produced. A permanent magnet is mounted on this mechanism and made to travel through the coil with a motion similar to what results from an external acceleration on the kinetic harvester. The voltage induced across the coil is compared with that of the simulation.

The cost of a laboratory grade linear motion testbed range between $2000 to $4000 depending on the load, acceleration and amplitude of the motion required [4] [5]. The solution presented in this paper is both low-cost and easy to implement, and it provides a better than 80% accuracy.

The work presented in this paper is part of JumboNet [6], a collaborative effort between University of Rochester and Sri Lanka Institute of Information Technology to explore solutions to HEC using wireless communication technologies.

The rest of the paper is organized as follows. In Section II, we present the analytical model of the harvester. In Section III we present the simulation model of the system. In Section IV we compare the experimental results with the simulation results. Finally, Section V concludes the paper.

II. Analytical Model

A. Modeling and Analysis of SDOF Electromagnetic Harvesters.

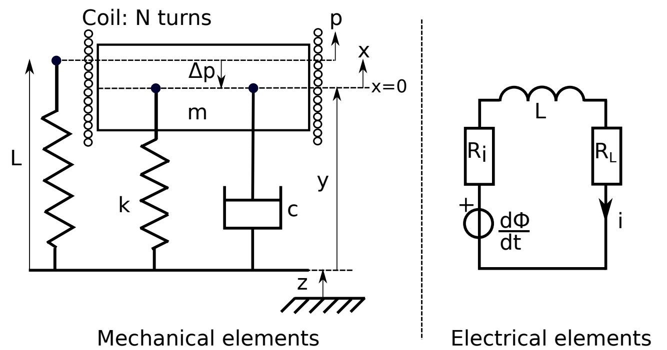

Figure 1. Electrical and mechanical elements of the kinetic energy harvester.

A simple kinetic harvester has a permanent magnet of mass m which is placed on a spring of natural length L. Due to gravitational acceleration g acting on mass m, the spring will come to equilibrium with a displacement of Δp from its natural length. An electromagnetic harvester of such properties can be modelled as a Single Degree of Freedom (SDoF) spring-mass-damper with external excitation as illustrated in Figure 1.

The equation of motion for this model can be expressed as given in Equation 1.

$$m\ddot{p} = -c(\dot{p} - \dot{z}) - k(p - z - \Delta p) - mg \tag{1}$$

It is assumed that the center of the coil is adjusted to coincide with the center of the moving magnet at equilibrium. If x is defined as the displacement from equilibrium, p in Equation 1 can be replaced using Equation 2.

$$x = p + \Delta p \tag{2}$$

Hence, the equation of motion from equilibrium can be expressed as shown in Equation 3.

$$m\ddot{x} = -c(\dot{x} - \dot{z}) - k(x - z) - mg \tag{3}$$

In the equations 1,2 and 3, $\ddot{x}$, $\dot{x}$ and x correspond to acceleration, velocity and displacement of the moving magnet with respect to the center of the coil as depicted in Figure 1. $\ddot{z}$ corresponds to the external acceleration applied to the harvester where g represents gravitational acceleration. The constants m, k and c are mass of the moving magnet, spring constant and the viscous damping coefficient respectively.

When the coil is connected to a load, due to the current that flows through both the coil and the load, two phenomena give rise to damping [3].

First effect is due the magnetic field generated by the coil resulting from self-inductance. This magnetic field interacts with the field of the moving magnet resulting in damping.

The second is the resulting Lorentz's force on the coil due to the interaction between the current and the magnetic field of the moving magnet.This effect is more prominent compared to the first.

In order to calculate the effect of Lorentz's force, radial component of the moving magnets magnetic field and the induced voltage in the coil V_{ind} are required.

The induced voltage in the coil can be expressed as the the derivative of flux linkage Φ through the coil . Here, Φ is a function of x.

$$V_{ind} = \frac{d\Phi}{dt} \tag{4}$$

The work reported in this paper focuses on determining V_{ind} using a simulation based on an analytical model and verification the simulation results experimentally.

B. Flux Linkage (Φ)

The relationship between the displacement x of the magnet and the Flux Linkage (Φ) through the coil is determined using a magnetic simulation using the FEM software Flux2D.

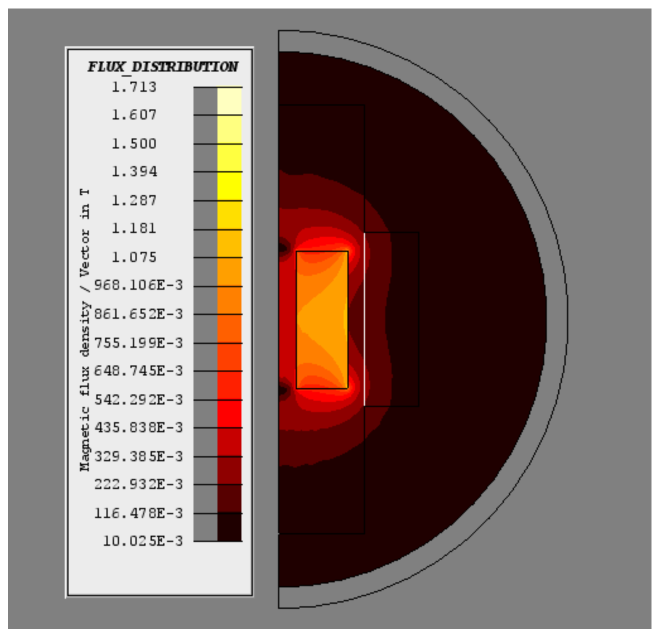

Figure 2. Flux Representation of the Testbed

The magnetic simulation results were obtained by defining the Flux2D project as a Magneto-static 2D axisymmetric problem as both coil and magnet used in the experiment were cylindrical in shape. The simulation provides the flux linkage through the coil at different static positions of the moving magnet with respect to the coil.

The simulation parameters were set to match the implementation that is presented in Section II-D and are listed in Table I.

The geometric view of a model with the magnet aligned with the coil at $x = 0$ after the solving process is depicted

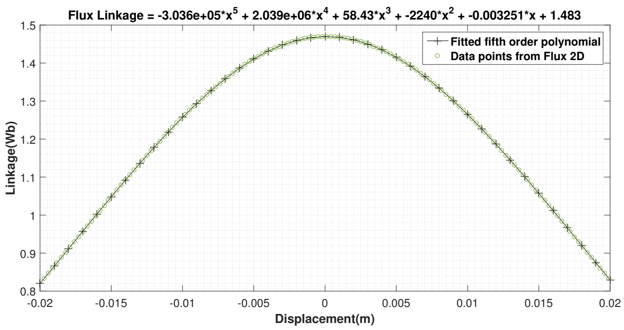

Figure 3. Simulated Flux Linkage Through Coil vs. Displacement of Magnet

in Figure 2. Figure 3 illustrates the flux linkage Φ across the coil for all displacements of the moving magnet.

C. Design of the Testbed

In order to determine the induced voltage in the coil V_{ind}, the magnet must be moved through the coil with a known velocity.

A practical approach to achieve a controlled motion is to utilise slider-crank mechanism,that converts rotary motion to linear motion. The rotary motion of a DC motor with a motor controller is connected to two rods of length r and l, which are hinged at either end and the end of the second rod is restricted to move in a straight line as illustrated in Figure 4.

The advantage of this mechanism is that the velocity of motion can be controlled by controlling the rotational speed of the motor. The amplitude of motion can be controlled adjusting the length r. The distance y between the motor shaft and the end of the second rod where the magnet could be mounted, is defined by the Equation 5.

$$y = r\cos(\omega t) + \sqrt{l^2 - r^2\sin^2(\omega t)} \qquad (5)$$

Here, ω is the angular velocity and t is time.The resulting motion of the slider-crank mechanism is only approximately sinusoidal. However, this does not affect the intended measurements.

D. Implementation of the Testbed

Figure 5 shows the implementation of the testbed. The DC motor used in the testbed is a Pololu [7] 19:1 37Dx68L metal gear motor with built-in encoder with 64 counts per rotation.

The encoder attached to the motor facilitated the accurate monitoring of the frequency of forced oscillations. A 18V7 Pololu Simple Motor Controller was used to drive the DC motor at required speeds. The motor speed was monitored in real-time using the encoder feedback.

The slider was adopted from the simple camera slider from Inventables [8]. The mounts and spool for the generating coil were 3D printed.

Tamiya [9] 70156 Long Universal Arm Set was used as the rods. Tamiya 70155 3mm Push Rivets were used to hinge the rods.

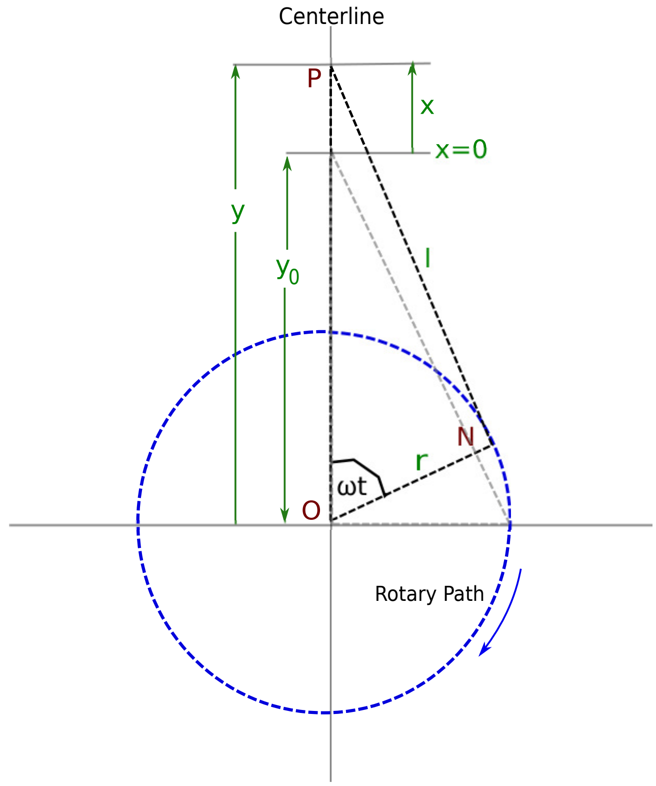

Figure 4. Slider-Crank Motion

Table I
SIMULATION PARAMETERS FOR FLUX2D

Simulation Parameter	Magnet	Coil
Geometry of Component	Ring Type	Ring Type
Type	N42 Neodymium	32 AWG Copper
Thickness	1"	1.26"
Inner Diamater	1/4"	1.24"
Outer Diameter	1"	2.03"
Strength	Br_{max} of $1.32T$	Not applicable

III. DEVELOPMENT OF THE SIMULATION MODEL

A Matlab Simulink model shown in Figure 6, was developed combining the flux linkage function obtained from the Flux2D simulation and motion model of the slider-crank introduced in Equation 5.

As illustrated in Figure 4, O is the center of the rotary path of the first rod ON of length r. The second rod NP of length l is hinged to the first rod at N. The moving magnet is hinged at P and is made to move linearly along the centerline OP. When the motor rotates, the distance between O and P changes oscillating between the minimum $l - r$ and the maximum $l + r$. As the generating coil is centered at mid point of the oscillation, the displacement of the moving magnet x is measured from $y = y_0$.

The parameters l and r in the model control the amplitude of oscillation of the magnet while the frequencies of cos and sin signals control the frequency of motion. The value of

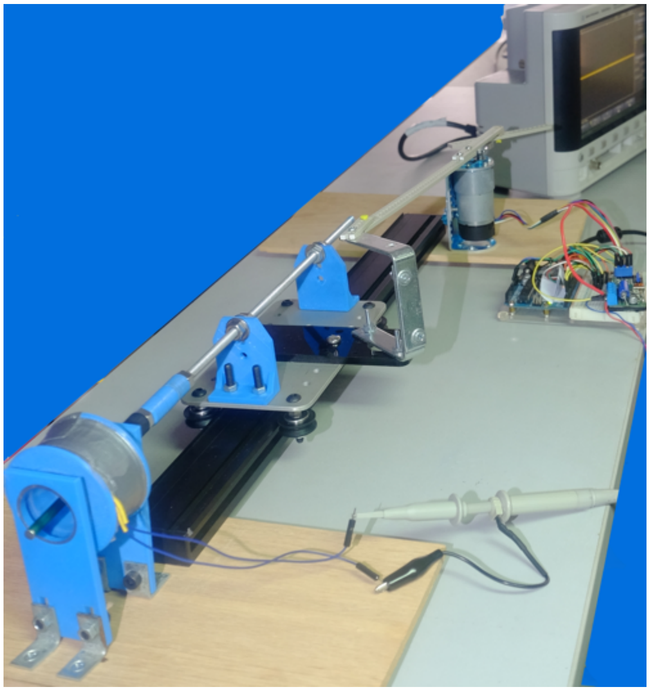

Figure 5. Linear Motion Testbed Implementation

Table II
SIMULINK MODEL PARAMETERS

Parameter	Value
Frequency	$1Hz$, $1.25Hz$, $1.5Hz$, $1.75Hz$, $2Hz$
r of ON	$0.01m$
l of NP	$0.275m$
y_0	$0.275m$

y_0 was calculated and deducted from the output of the first stage, so that the displacement corresponds to relative displacement x. The Flux Linkage vs. displacement relationship obtained using Flux 2D was fit to a fifth order polynomial using regression and applied to the Flux Linkage block. The resultant polynomial had a Root Mean Square Error (RMSE) of $3.303 * 10^{-5}$, which is an extremely low deviation from the data points obtained from Flux 2D.

Once the parameters are set according to Table II, the outputs produced at 1 Hz with an amplitude of $\pm 1cm$ are in Figure 7. It must be noted that for each oscillation of the moving magnet, produces two periods in the induced voltage waveform.

IV. RESULTS

The simulation results and the experimental results were compared for a series of frequencies between 0.5 Hz and 2 Hz. The results of both the simulations and the experiments are displayed in Table III and the Figures 8 - 11.

As observed in Figures 8 - 11, the experimental results closely match the experimental measurements with better than 80% accuracy. While the deviation is 1% at $1Hz$, the deviation increases with increasing frequency. As the stresses

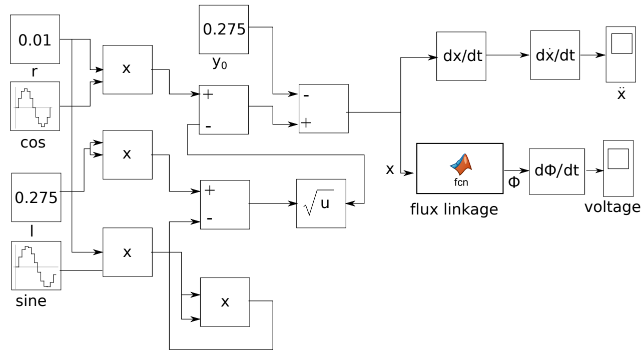

Figure 6. MATLAB Simulink Model of the Testbed

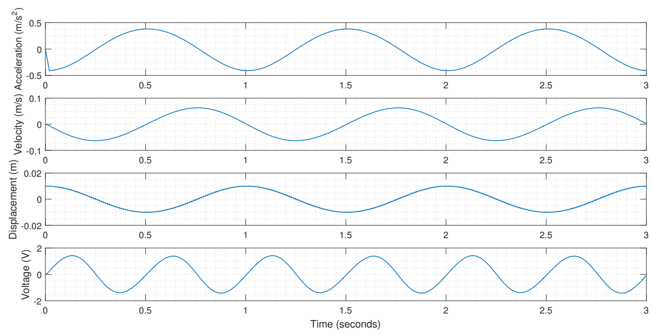

Figure 7. Displacement, Velocity, Acceleration and Voltage vs Time at 1Hz using the Simulink Model

on the mechanical system increase with increasing frequency, mechanical imperfections produce a higher overall displacement, velocity and acceleration than what is predicted by the simulation. The minor distortions in the shape of the curve is due to the motor speed variations as it overcomes the opposing force from Lorentz's force.

Table III
CONSISTENCY BETWEEN SIMULATED AND EXPERIMENTAL RESULTS

Frequency	$p_k - p_k$ **Measured**	$p_k - p_k$ **Simulated**	**%Deviation**
0.5Hz	1.11V	1.30V	14%
1.0Hz	2.63V	2.60V	-1%
1.25Hz	3.36V	3.25V	-3%
1.50Hz	4.23V	3.90V	-8%
1.75Hz	5.24V	$4.54V$	-15%
2.00Hz	6.20V	5.20V	-19.23%

V. CONCLUSION

In this paper we introduced a low-cost low frequency linear motion testbed that can be utilised for designing electromagnetic harvesters energy harvesters. Using the proposed system, it is possible to verify the flux linkage vs displacement obtained via Flux 2D.

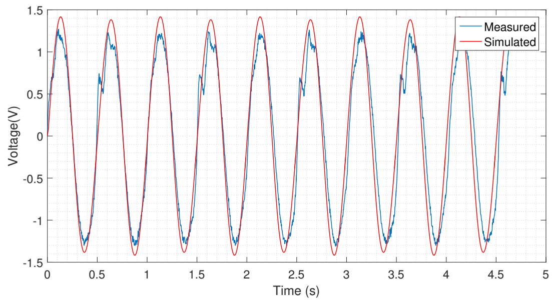

Figure 8. Measured vs Simulated Voltage @1Hz

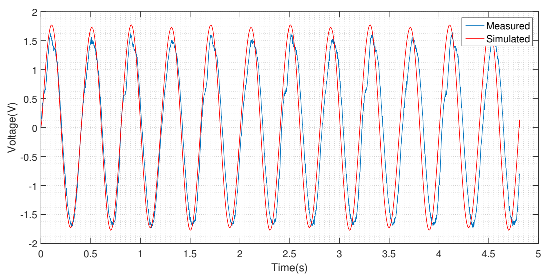

Figure 9. Measured vs Simulated Voltage @1.25Hz

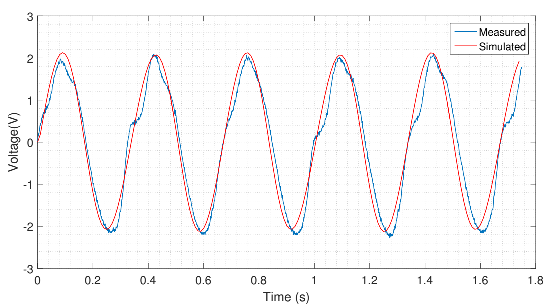

Figure 10. Measured vs Simulated Voltage @1.5Hz

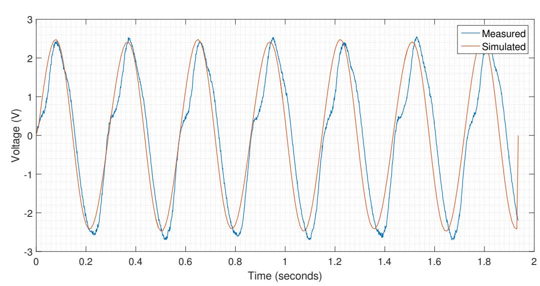

Figure 11. Measured vs Simulated Voltage @1.75Hz

A simple slider-crank system was developed in order to produce a controlled motion to drive the magnet through the coil. The induced voltage across the coil was measured and compared with a simulation of the system using Simulink. The results were better than 80% in agreement within the measured frequency range.

The methodology proposed is extremely low cost compared to laboratory grade linear motion testbeds. Although there were minor imperfections and deviations, overall outcome was accurate enough to verify that the magnetic flux vs displacement produced by Flux 2D simulation was accurate. This output also shows that assuming an average linkage across the length of the coil could lead to erroneous results as the linkage curve is non-linear.

Our ongoing work is focused on to accurately modelling and verifying the electromagnetic damping produced due to Lorentz's force.

References

[1] J. Wall, G. Wittemyer, and B. Klinkenberg, "Novel opportunities for wildlife conservation and research with real-time monitoring," *Ecological Applications*, 2014.

[2] M. Wijesundara, C. Tapparello, A. Gamage, Y. Gokulan, L. Gittelson, T. Howard, and W. Heinzelman, "Design of a kinetic energy harvester for elephant mounted wireless sensor nodes of jumbonet," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec 2016, pp. 1–7.

[3] E. Dallago, M. Marchesi, and G. Venchi, "Analytical model of a vibrating electromagnetic harvester considering nonlinear effects," *IEEE Transactions on Power Electronics*, vol. 25, no. 8, pp. 1989–1997, Aug 2010.

[4] "Labworks Inc." [Online]. Available: http://labworks-inc.com/

[5] "ACA Motion." [Online]. Available: https://www.ancamotion.com/

[6] "JumboNet." [Online]. Available: http://www.jumbonet.lk

[7] "Pololu Inc." [Online]. Available: https://www.pololu.com/

[8] "Inventables, Inc." [Online]. Available: https://www.inventables.com/

[9] "Tamiya, Inc." [Online]. Available: www.tamiya.com