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To cite this article: D.J. Clarkson *et al* 2019 *J. Phys.: Conf. Ser.* **1407** 012105

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Feasibility of a V-Shaped Magnet Rotor to Convert Vibration into Rotation

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Abstract. Majority of the reported kinetic energy harvesting mechanisms involve translatory transduction mechanisms, which diverges from the long established rotary design for electromagnetic generators. A rotary design can offer a much smaller magnet-coil air gap and clearance guidance that translatory transducers simply cannot physically attain. Therefore, this research investigates the feasibility of implementing a V-shaped magnet rotor for the purpose of coupling base point excitation into rotation, which can eventually be coupled to a generator motor. It was also previously theorised that the nonlinear magnetic coupling can give rise to broadband nonlinear resonant behaviour. The resultant device aims to enhance the overall power conversion efficiency of the captured vibration energy.

1. Introduction

Vibration energy harvesting (VEH) has predominantly been achieved by translatory mechanisms, such as cantilever amplifiers, to accumulate kinetic energy [1]. However, the traditionally established design of choice for electromagnetic generator is that of a rotary mechanism rather than translatory. In contrast to linear oscillators, magnetic rotors can achieve exceptionally small magnet-coil spacing within a guided track in order to maximise change in flux density and minimise wear from unconstrained vibrational modes.

This paper investigates the feasibility of implementing a V-shaped magnet rotor to harvest base point excitation to be fed into a conventional generator motor. The V-shaped magnet track configuration on the rotor, coupled with a magnetic spring mechanism, helps to radially couple in translational vibration every revolution. With a slightly eccentric centre of mass, the rotor behaves like a compound pendulum and radial excitation can trigger either direct resonance or Mathieu instability [2, 3]. This establishes a pathway to experimentally implementing a previously theoretically simulated rotary auto-parametric oscillator [4] for extending the bandwidth of resonant vibratory motion.

2. Theory and design

Figure 1 summarises the basic degrees of freedom of the proposed mechanism, where base point excitation is fed into a magnetic spring that is in turn coupled to a rotor by the magnetic V-track. In the schematic shown in figure 2, the directions of motion are shown by the white arrows. The magnetic spring is made up by two pairs of opposing magnets levitating the top bar mass and vertically guided by linear ball bearings within the columns (not visible in the diagram).



As shown by the model diagram in figure 3 and summarised in equations 1 and 2, as the magnet bar vibrates vertically, translatory motion is coupled into the rotor radially via the V-shaped magnet arrangement track on the rotor. The nonlinear magnetic coupling force is simplified by cubic approximation, which is accurate for small displacements [4]. As the magnet bar couples linear motion to rotational motion through the V-shaped magnet circumferential arrangement on rotor, a vertical input is internally fed to the rotor as a torque signal.

$$\ddot{y} + 2\zeta_1\omega_0\dot{y} + [\omega_0^2 + \mu y^2]y|_{y_{min}}^{y=0} - g = a \cos(\omega t) + W(t) \tag{1}$$

$$\ddot{\varphi} + \zeta_2\dot{\varphi} + \left(\frac{g}{l} + \alpha\frac{\ddot{y}}{l}\right) \sin \varphi = \beta\frac{\ddot{y}}{l} \tag{2}$$

where, y is the vertical motion, ζ is damping ratio, ω_0 is the natural frequency of the levitated magnetic spring in the columns, g is acceleration due to gravity, a , ω and W are acceleration amplitude, excitation frequency and noise intensity respectively, ε is the angular motion, α and β are the coupling coefficients of the V-shaped magnetic track for the vertical and horizontal direction respectively, t is the time domain, and l is the effective length of the eccentric pendulum for the rotor, which should be a very small value (~ 1 's mm).

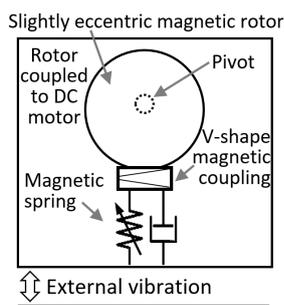


Figure 1. Base point excitation drives magnetic spring. Repulsive force pushing the stator along per revolution, until it reaches the end of the circle.

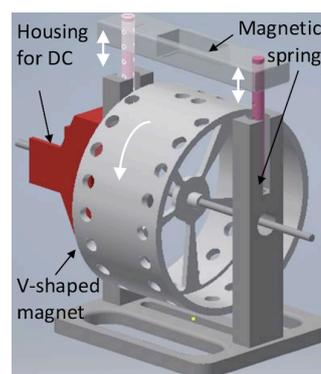


Figure 2. Prototype schematic, white arrows show direction of motion. Top bar is magnetically levitated in the columns.

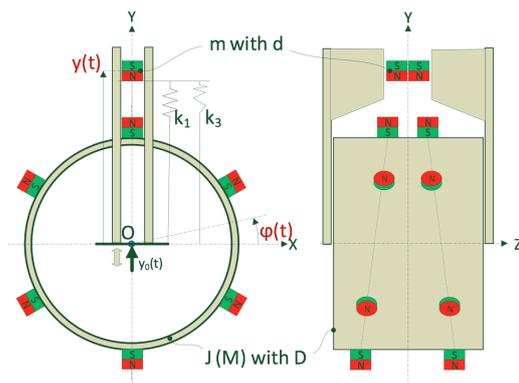


Figure 3. Model diagram of the V-shaped magnet rotor, showing coupling of vertical vibration (magnetically levitated column springs) into the rotational direction (top bar magnet and magnet V-track).

3. Simulation

The magnetic coupling force along the V-shaped magnet track is simulated in figure 4. As the top opposing magnet bar sits between the V-shaped magnet track, the rotor is pushed along the potential slope until it reaches the bottom of the V after nearly 1 revolution, at which point it hits a potential barrier. In the absence of periodic vertical motion to lift the magnet bar, torque will dissipate as the potential barrier prevents further rotation.

When continuous vibration couples in at a frequency equivalent to the rotational velocity of the rotor, the magnet bar is vertically lifted and allows the V-shaped magnet track to guide the rotor along another revolution. Figure 5 shows the simulation of the displacement and energy signals during the coupling of translatory motion into the rotary motion. It can be seen in the energy diagram that a potential barrier needs to be overcome per revolution, which can be achieved by the periodic vertical motion of the top magnet bar levitated on the magnetic springs in the columns. As the top magnet bar lifts, the system hops across the potential barrier.

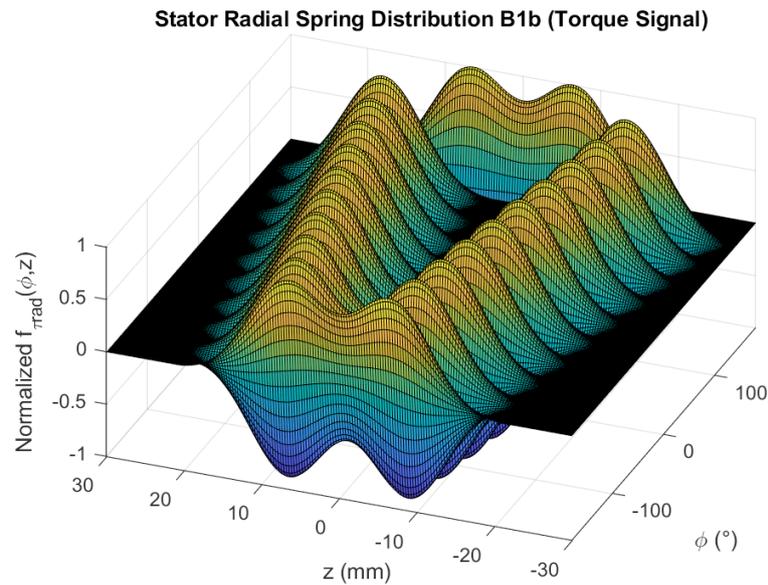


Figure 4. Simulated torque signal along the V-track illustrating the propelling force on the rotor per revolution. As the rotor hits the potential barrier at the end of each revolution, base point excitation can be employed to help the system hop across the potential barrier and continue a new revolution along the V-track.

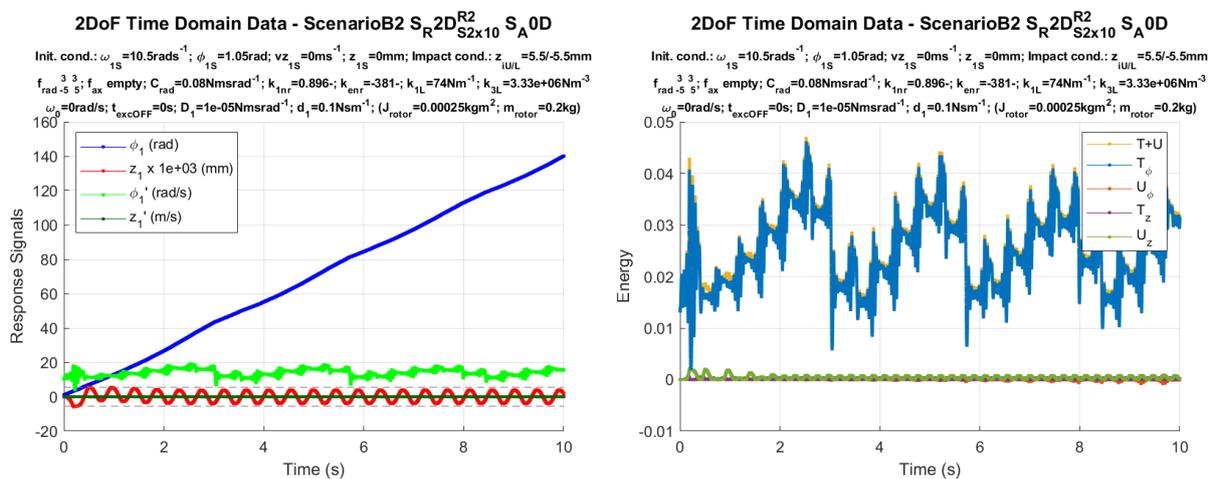


Figure 5. Simulated displacement signals (left) and energy behaviour (right) of the V-shaped magnet rotor. It can be seen that with base point excitation to lift the system across the potential barrier every revolution, the magnet V-track drives the rotor within each revolution.

4. Experimental validation

A proof-of-concept prototype is shown in figure 6. Most of the parts were 3D printed using an engineering grade polymer. Disk N42 magnets of 5 mm radius and 5 mm thickness were used to form the V-track. Repulsive pairs of similar disk magnets were employed as the magnetic spring embedded within the two columns. The columns supporting the top magnet bar (proof mass) is guided by linear bearings to minimise friction. The assembled prototype was mounted on a shaker platform to induce base point excitation. The V-shaped magnet rotor is coupled to a DC generator motor at shaft of the centre axis in order to electrically characterise the device.

Vibration excitation at varying frequency and excitation levels were tested. Figure 7 summarises the experimental result of the prototype operating at varying conditions and assembly configurations. The voltage signal from the DC motor was recorded on a digital oscilloscope and can be seen in the plot, serving as an analogous to the torque of the rotation.

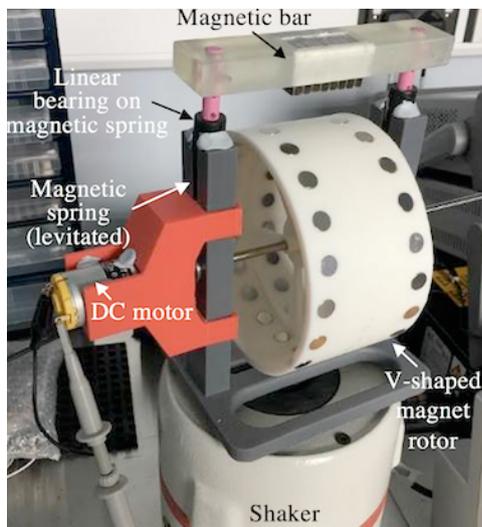


Figure 6. Prototype on a shaker.

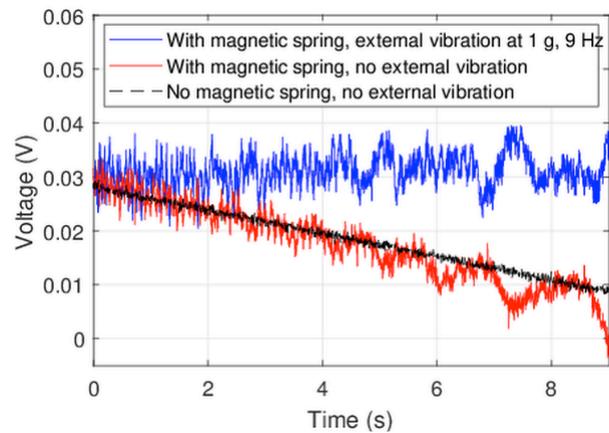


Figure 7. Voltage output from the prototype, given a fixed initial rotational velocity (initial torque), tested at different excitation and physical setup configurations.

With a given initial rotational velocity (initial torque), the angular output from the rotor can be sustained when the external excitation is set at 1 g and 9 Hz. This frequency was around twice the resonant frequency of 4.5 Hz, suggesting the onset of parametric resonance [3]. At lower acceleration levels, rotation cannot be sustained as the vibration amplitude fails to overcome the magnetic potential barrier at the bottom of the V-track. At other frequency ranges, higher acceleration is required. On the other hand, when no external vibration was present, either assembled with magnetic spring or without it, rotation from the initial torque decays away to zero after a few revolutions. This preliminary validation establishes the feasibility of this proposed mechanism for converting mechanical vibration into rotary motion and electrical energy that has the potential to employ established generator motors and capture broadband spectra [4].

Conclusion

This paper validated the feasibility of implementing a V-shaped magnet rotor mechanism for converting base point vibrational excitation into rotation, which can then be harnessed by a conventional electromagnetic rotary generator. External vibration was fed into a first magnetic spring, which then couples in the vertical translatory motion into rotation via the magnetic V-track. The periodic vertical oscillation of the top magnet bar induced by the first magnetic spring helps to sustain the rotation of the V-shaped magnet rotor. This opens up a new avenue of mechanical energy conversion mechanism, which can potentially bridge the gap between vibration energy harvesting and the long established electromagnetic rotary motors.

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