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Using artificial gravity loaded nonlinear oscillators to harvest vibration within high g rotational systems

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Abstract. Energy harvesting within rotating environments can help to enable self-powered wireless sensing, which has been motivated in recent years by the advent of legislations mandating tyre pressure monitoring systems for automotive wheels. The centripetal acceleration ($a = \omega r^2$) within such rotational systems can attain 1,000's of g, which manifest as artificial gravity and can adversely suppresses the dynamic motion of oscillators. This paper investigates the possibility of using the high g conditions as a means of introducing nonlinear bi-stability, which can then allow an oscillator to benefit from a broadband response as well as mechanical amplification achieved from the bi-stable snap-through states. An experimental proof-of-concept prototype was designed, built and tested. By controlling the rotational speed ω of the apparatus, the masses of oscillators experienced a g-force of up to 90 g. Purely by increasing ω , an increase in transducer output was observed from the predicted amplification effect. However, beyond a certain threshold, output dropped to minimal as the potential barrier reached an insurmountable level. This work validates the proposed new mechanism that taps into the high g environment and opens a new avenue of design for vibration energy harvesting within rotational systems.

1. Introduction

Vibration energy harvesting have generally given more emphasis to translatory dynamics rather than rotational dynamics. While the core objectives in providing a self-sustaining power source for microelectronics and wireless systems are the same, the mechanism of operation are vastly different [1]. Rotational systems that do exist in the literature report on devices aimed at harvesting human movement, automotive wheels and rotor motion. In recent years, motivated by the mandated TPMS (tyre pressure monitoring system) in Europe and North America [2], there has been a growing interest to develop energy harvesting within high speed rotational systems in order to power sensor instrumentation within these rotating environments.

Generally, linear oscillators have been applied to harvest shocks [3] or noise [4] excitation from these automotive wheel rotating systems. However, for systems with large centripetal acceleration due to either high speed or large radius ($a = \omega r^2$), a significant artificial gravity loading can manifest (1,000's of g). This can in turn statically suppress oscillatory motion and the harvester then becomes minimally responsive to ambient vibration. Therefore, the high g loading within rotational systems have previously been thought as something to avoid by positioning oscillators either parallel to the radial axis or near the centre of rotation [4]. This paper however, aims to deliberately utilise the high g artificial gravity in a specific configuration in order to introduce bi-stability and establish a design pathway towards high g induced mechanical amplification.



2. Theory

In rotational systems, centripetal acceleration results in artificial gravity loading radially outwards from the centre of rotation. A typical linear oscillator can either be stiffened or softened through axial loading [5, 6]. In the case where the oscillator behaves as a vertically upright cantilever, bi-stability can be achieved from the unstable equilibrium at the displacement $x = 0$ position [7]. With potential energy of the oscillator $U(x, t) = -0.5kx^2 + 0.25\mu x^4 - Ax \sin(\omega t)$, dynamic motion can be represented by equation 1 and axially loaded beam by equation 2.

$$m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + \frac{dU(x, t)}{dx} = F(t) \quad (1)$$

$$EI \frac{\delta^4 x}{\delta y^4} + \rho B \frac{\delta^2 x}{\delta t^2} - \rho I \frac{\delta^4 x}{\delta y^2 \delta t^2} + \frac{\delta}{\delta y} [F(y, t) \frac{\delta x}{\delta y}] = 0 \quad (2)$$

where, $U(x, t)$ is the potential energy given by $-0.5kx^2 + 0.25\mu x^4 - Ax \sin(\omega t)$, x is the displacement, k is the spring stiffness, μ is the geometric nonlinearity, A is the input displacement amplitude, m is the proof mass, c is the damping, F is the driving force, E is the elastic modulus, I is the area moment of inertia, ρ is the mass density, B is the cross-sectional area of the beam, y is the axis along the beam length where $0 < y < L$, L is the beam length and t is time domain.

The terms ρB , EI and ρI denotes mass per unit length, flexural rigidity and rotatory inertia of cross-sectional area respectively. Taking into account the varying artificial gravity induced from centripetal acceleration, the forcing term $F(y, t)$ is given by $\pm \rho B (-\omega [r(x, t)]^2) (L - y)$; where, ω is the angular velocity, and r is the radial distance between the effective mass of the oscillator and the centre of rotation. This parameter itself modulates as a function of $x(t)$.

Figure 1 illustrates the modulation of the potential barrier as F varies. Instantaneous energy release can be achieved as the oscillator hops from one potential well to another. The modulation in the potential barrier helps to promote the potential barrier hopping.

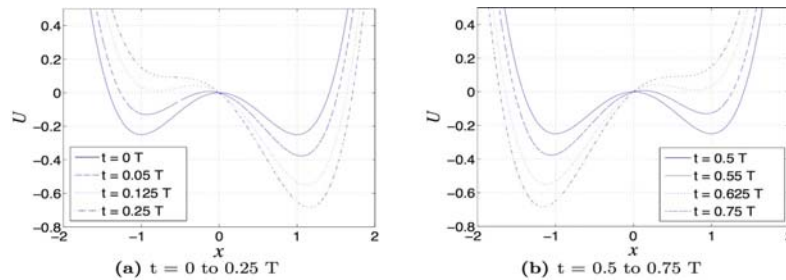


Figure 1: Periodic modulation of the bi-stability potential barrier in order to promotion intra-well hopping. U is the potential energy, x is the displacement of the oscillator, t is the time domain and T is the unit normalised time period.

3. Design and method

An embodiment of the proposed mechanism is shown in figure 2 with the cantilever tip mass radially directed towards the rotatory centre. A lab prototype is shown in figures 3 and 4.

Piezoelectric cantilevers made from PVDF, stainless steel substrate and mild steel end mass (~ 3 grams) were anchored onto a 3D printed frame, and attached to a rotor. The rotor system is both statically and dynamically balanced to minimise lateral vibration. Electrical connections from the piezoelectric transducer were routed out using a basic commutator mechanism, in order to electrically measure the oscillation of the cantilevers by a digital oscilloscope. The apparatus was mounted on a shaker to simulate ambient vibration, the shaker was programmed by a



Figure 2: An embodiment of the proposed system: cantilever inversely upright (mass towards the centre) in the artificial gravitational field.

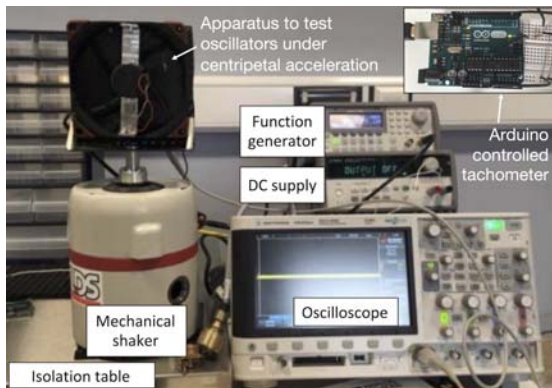


Figure 3: Experimental setup: the voltage controlled rotor with the cantilever oscillators, shaker apparatus controlled by function generator, measurement kit and an Arduino controlled tachometer.



Figure 4: Experimental system in operation with the cantilever oscillators in the rotor. The piezoelectric cantilevers are wired to two metal rings at the centre of the rotor and the electrical signals are interrogated by two flexible springs serving as the commutator.

function generator and vibration monitored by an accelerometer, the rotor speed was controlled by a high precision DC supply, and the rotor speed of rotation was measured by an Arduino controlled tachometer.

4. Results and discussion

Figure 5 presents the time domain outputs and their respective FFT. The results illustrate examples of the system driven at different rotational speeds, which manifest as varying levels of artificial gravity loading on the proof masses. It can be seen that at a higher g level, response has fewer but higher frequency peaks. This is because the potential barrier becomes taller with higher g force, and the instantaneous energy release thus becomes greater once hopping takes place. However, after a certain threshold (>63 g), the response amplitude diminishes. This suggests that the potential barrier has attained an insurmountable level for the available ambient vibration.

Figure 6 summarises the average voltage output from the piezoelectric transducer at varying levels of g . An increase in output can be initially seen with larger g due to the greater energy release from crossing the higher bi-stable potential barrier. Beyond 63 g, the output returns to base levels as the bi-stable potential barrier becomes too high to cross over and the oscillator is trapped within the potential intra-well.

Conclusion and future work

This paper presents for the first time a centripetal acceleration induced bi-stable nonlinear oscillatory mechanism for vibration energy harvesting. A proof-of-concept prototype, with g -force up to 90 g, has experimentally validated the theoretical framework of utilising artificial

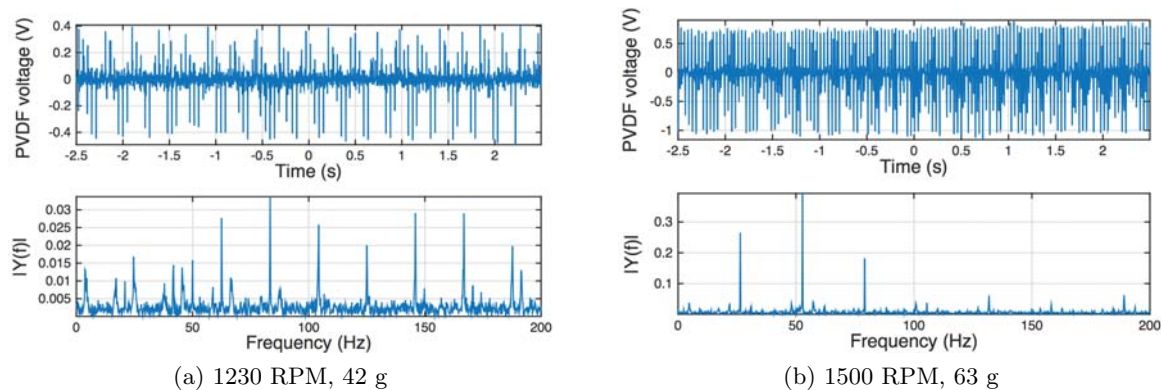


Figure 5: Time domain and FFT response of the piezoelectric oscillator at various rotational speeds, resulting in varying levels of artificial gravity experienced by the proof mass.

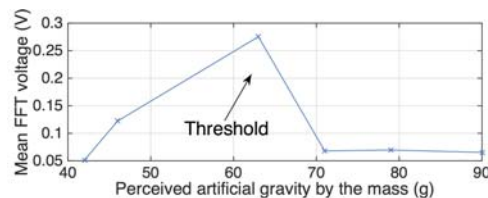


Figure 6: With higher gravity (g), the response increases from snap-through amplification. However, beyond a threshold, gravity loading traps the oscillator in one potential intra-well.

gravity as a means to introduce modulated bi-stability. Therefore, this study opens up new avenues of oscillator design to make use of the high g environments within rotational systems as a means of mechanical amplification for VEH. Future work will involve active and passive control of this nonlinear vibratory phenomenon, as well as experimentation with higher g scenarios.

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