Energy harvesting from vortex induced vibration in MEMS devices using magnetic interaction

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Summary. Energy harvesting from the environment is an emerging field and a better alternative to battery-operated systems such as wireless sensors, IoT and lower power electronic devices. Linear energy harvester has maximum power output near its natural frequency, which restricts its operation in narrow bandwidth. To improve the bandwidth and the power output, a pair of magnets with same polarity is used to induce non-linearity in a cantilever beam subjected to vortex induced vibration. This increases the complexity of the problem in FEA softwares as it will be coupled electrical-fluid-mechanical-magnetic problem. Thus, the magnetic force is replaced with nonlinear spring in ABAQUS and the Fluid Structure Interaction is carried out by reducing the complexity to electrical-fluid-mechanical problem. The magnets are placed at a certain distance so that the beam operates as a bistable system. The analysis was carried out for beam with different natural frequencies by changing the tip mass. Using the pair of repulsive magnets, we have found that the energy harvested in non-linear system is higher than the linear energy harvester.

Keywords: Energy harvesting; Fluid Structure Interaction; MEMS; Nonlinear Dynamics; Vortex Induced Vibration

Introduction

With the rapid development of technology in the field of sensors, IoT more emphasis is made on low power based devices. Wireless Sensor Networks(WSNs), IoT applications demand for low-energy wireless nodes typically powered by non-renewable energy storage units(batteries). But the battery have limited lifetime and it is difficult and expensive to replace them. An energy harvester(EH) operated along with a battery could potentially increase the lifetime of the node and eliminate the need to replace the battery. MEMS devices could be easily integrated with the circuit but the process to develop MEMS devices is complex, time consuming and expensive. Thus, FEA simulation allows to analyze or redesign the harvester according to the need. But FEA packages cannot handle complicated coupled problems which are common in non-linear EH. The major problem to analyze a vortex induced vibration based nonlinear EH involving magnets includes the complexity to solve the electrical-fluid-mechanical-magnetic problem. The magnetic force between two cylindrical magnets used in the MEMS cantilever beam is modeled as a nonlinear spring which has the same behavior as the repulsive magnets. The FE model of cantilever nonlinear EH with nonlinear springs is validated with the theoretical model. Application of phase space, bifurcation diagram, Poincaré maps were used to study the nonlinearity effects to enhance the energy harvested.

Analysis

The axial force and lateral forces between two cylindrical magnets [2] is given in Figure 5 (2a). This nonlinear magnetic force is approximated using piecewise linear segments and given as an input in ABAQUS. The beam with nonlinear spring is simulated in ABAQUS with an acceleration of 2 m/s^2(20 Hz) and validated with the theoretical model using equations shown in Figure 5 (1c and 2c)

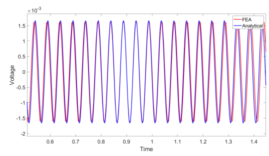

Figure 1: Voltage time history of FEA and theoretical results

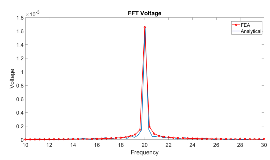

Figure 2: FFT of voltage from theoretical and FE results

Set up

The setup consists of a 2mm cylindrical bluff body and a beam $(5mm \times 0.3mm \times 9\mu m)$ which is placed at a distance of 6mm from the center of the bluff body. The magnets(NdFeB N35 grade) have dimension $\phi 0.1 \times 0.1mm$ placed at a distance of $0.4mm$ from each other. Beam is subjected to a uniform input velocity of 2m/s having vortex shedding frequency of 217Hz. The beam operates in a bistable system, for distance less than 0.4mm as shown in Figure 4.

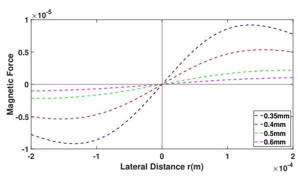

Figure 3: Magnetic force between magnets at different distances

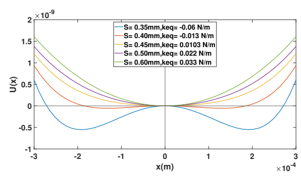

Figure 4: Potential Energy for different magnet distance

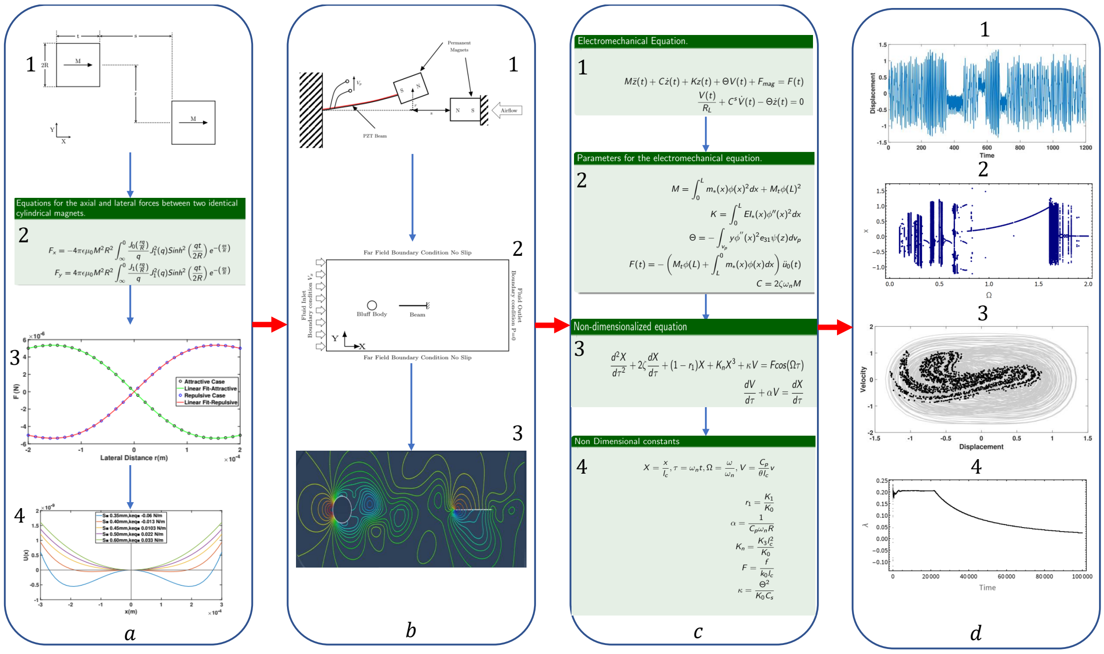

Figure 5: (a) Magnet Design (b) FSI Setup (c) Coupled electromechanical Equation (d) (1) Time history (2) Bifurcation Diagram (3) Phase space (4) Maximum Lyapunov exponents for time series at 131 Hz

The coupled non-dimensionalized equation can be represented as Figure 5 (3c). For beam with natural frequency 131 Hz($\Omega = 1.65$) operates in chaotic range for $\zeta = 0.0275$ as shown in Figure 5 (d)

Discussion

The magnetic force equation was derived with the assumption that the cylindrical magnets are placed axially and there exists uniform magnetization in each magnet. Also, the rotation of the magnet is neglected while simulating magnetic force with nonlinear spring as the rotation of the magnet will be typically below 10° for low base excitation used in energy harvesting applications. Piezoelectric materials are anisotropic by nature. But for our analysis, we have considered both substrate and Piezoelectric material as a linear elastic material model as the strain in the substrate is well below the elastic limit. In HVAC systems airflow is usually unidirectional with operating speeds from 1.8 m/s to 5 m/s. Care must be taken while designing for a bistable system, as adequate forcing is required for the beam to cross the potential barrier.

Conclusion

In this work, we analyzed the nonlinear EH operating as a bistable system using pair of permanent magnets. The bistability causes the beam to cross from one potential to another, thereby increasing velocity and in turn power output. The beam acts as a linear EH when the distance between the magnets is very large. Nonlinear energy harvesters generate more power compared to linear counterparts except at resonance. Beam operating in the chaotic range have higher power output but there is an additional need to design efficient energy harvesting circuit. The system is chaotic for particular values of amplitude, forcing frequency and damping value.

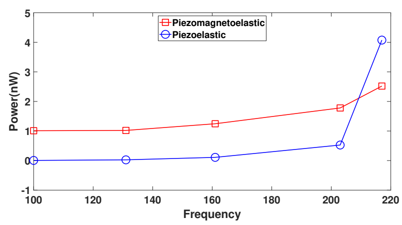

Figure 6: Power ouput of nonlinear and linear harvester

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