TUNING RESONANT ENERGY HARVESTERS USING A VARIABLE RELUCTANCE LINK

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Abstract: The use of a Variable Reluctance Link (VRL) to control a tuning mechanism for a vibrating energy harvester is introduced here for the first time. Magnetic flux from a tuning magnet creates a virtual spring by interacting with a magnet on the cantilever of the vibrating harvester. To vary the flux strength, a variable reluctance link is inserted between the two magnets. A macro-scale mechanically operated system has been constructed and tested in order to validate the concept and a tuning range of ±7% at a centre frequency of 110Hz achieved. A MEMS VRL incorporating thick, low stress electroplated nickel magnetic components has been designed, a fabrication process developed and fully released prototype MEMS VRL devices successfully fabricated. The MEMS VRL has electrostatic comb drives made of the same thick nickel as the magnetic components. Movement of the shuttle brings the magnetic teeth into alignment to continue the magnetic flux path. Because the moveable link will be attracted to the position of least reluctance, the actuation force may be of similar magnitude to the desired magnetic force in the vicinity of the proof mass. In order to reduce this effect, and thus to allow a lower actuation voltage and power, the magnetic attraction has been balanced against the actuator's own spring force in the design of the device.

Keywords: Frequency tuning, vibrating energy harvester, variable reluctance.

INTRODUCTION

In order for a vibration energy harvester to operate well in many practical scenarios, the resonant frequency of the mass-spring system should be tunable. Most energy harvesting devices developed to date, irrespective of their transduction mechanism, have a single resonant frequency, and while recent efforts have been made to broaden the frequency range of such devices, compact, robust and low power tuning techniques are still desirable.

There are a number of techniques through which the resonance frequency of a harvester can be tuned. Conceptually, the easiest ways to change the resonant frequency of the device would be to alter the mass, length, or thickness of the vibrating structure; however, in practice it would be challenging to alter these parameters while the device is operational. Earlier, an active tuning technique was demonstrated that applied an electrical input to a piezoelectric bimorph to alter the resonant frequency by altering its mechanical properties [1].

An alternative method of tuning a resonant system has been demonstrated in which the reactive electrical load on a generator is adjusted by electronically synthesizing variable inductive or capacitive components which in conjunction with the mechanical components determine the resonant frequency. The synthesized reactive load can then be altered dynamically to maintain resonance [2]

It has also previously been demonstrated that changing the distance between an oscillating magnet mounted on a vibration harvester and an additional tuning magnet can sufficiently change the effective spring constant and thus modify the resonant frequency [3]-[4]. We report here work to develop a MEMS magnetic tuning system for an energy harvester using the concept of a variable reluctance link (VRL). This has the advantage that the permanent magnet does not need to be moved, and can be located at some distance from the harvester.

EXPERIMENTAL VRL

To validate the principle of the VRL, a discrete macroscopic experimental arrangement with separate piezoelectric driven and sensing elements was constructed. Fig.1 shows the setup with the variable reluctance link situated in between the oscillating cantilever beam with magnetic proof mass and the fixed tuning magnet.

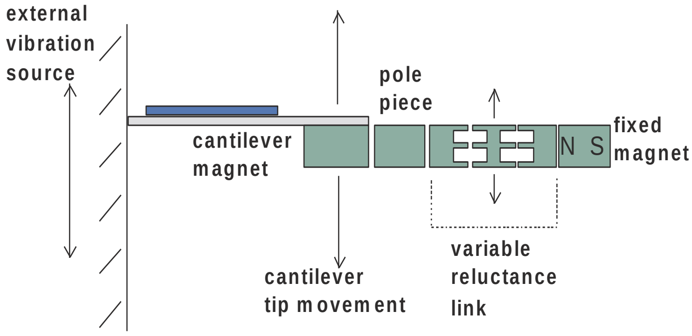

Fig.1: Tuning concept including variable reluctance link.

The method we have adopted is to place a variable flux path between a tuning magnet and the cantilever magnet. By varying the reluctance of this path, the flux density near the proof mass can be changed, so altering the resonant frequency of the cantilever beam. Electrical excitation of the driven elements and measurement of the response of the sensor element allows measurement of the oscillation amplitude at any frequency and thus determination of the resonant frequency.

The variable flux link comprises a moveable steel bridging piece. As the bridging piece is mechanically moved by means of a micrometer to vary the reluctance, the change in resonant frequency of the cantilever can be observed.

Measurement

Figs. 2 and 3 show the details of the experimental setup. The vibrating cantilever with the four piezo driving elements and one middle sensing element can be seen on the left side of Fig 6. The variable flux link comprises a neodymium permanent magnet on the right hand side to provide magnetic flux and a moveable steel bridging piece above which can be moved in a vertical direction. As the top bridging piece is moved, the reluctance changes and hence the resonant frequency also changes.

A programmable 10MHz DDS function generator was used to supply the drive voltage to the piezo generator. The mechanical response of the cantilever was measured by applying a 10.5V peak to peak driving voltage and measuring the voltage from the sensor as a function of frequency using an oscilloscope. The resonant frequency is then taken as the frequency of peak response.

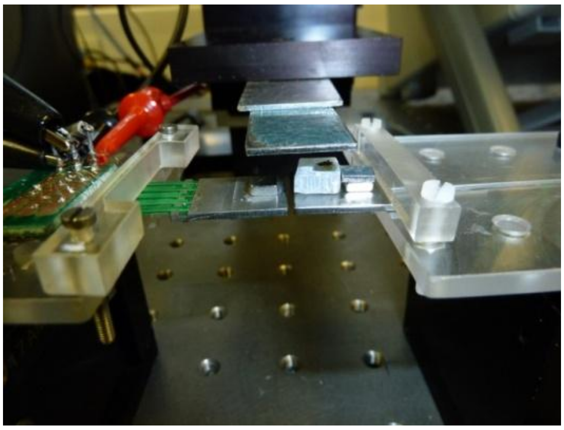

Fig. 2: Experimental setup for variable reluctance tests.

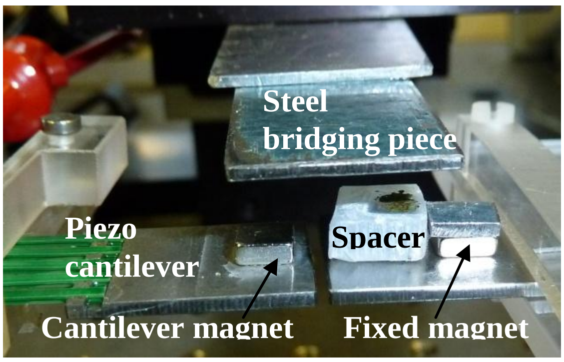

Fig.3: Enlarged view of the variable reluctance test setup.

RESULTS AND DISCUSSION

Fig 4 shows how the action of the macro-scale VRL alters the resonant frequency of the cantilever by varying the magnetic flux. A variation of 15Hz at a centre frequency of 110Hz was achieved by a movement of the magnetic link of 0.75mm, therefore it can be seen that a tuning range of ±7% is available.

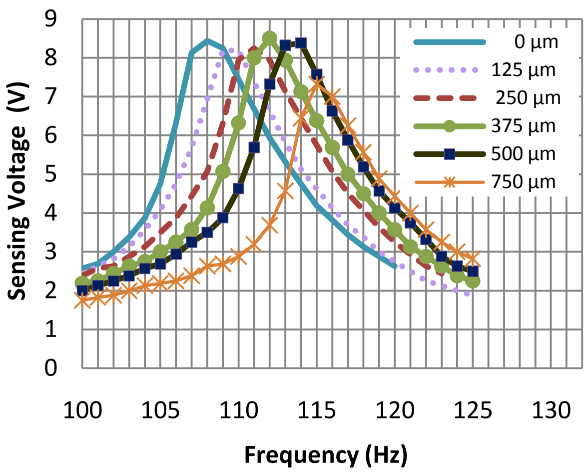

Fig 4: Frequency response for different link positions as indicated.

The horizontal movement of the tuning magnet in [6] has one undesirable side effect as it produces an uneven distribution of the flux across the gap between the tuning magnets. This effect may introduce undesirable forces onto the moving elements of the harvester, unbalancing it and causing misalignment of the fixed and moving parts. In comparison to this our variable reluctance link technique provides an essentially laterally uniform magnetic flux. In addition, in a practical system it potentially provides a lower power and higher bandwidth means of varying the magnetic flux by balancing the magnetic forces against the restoring forces from the flexure springs in the VRL device.

MEMS VRL

In order to more easily utilize this advantage in a practical vibration harvester, it is desirable to have a more compact and integrated system. One way of achieving this would be to use this VRL technique in a MEMS system. This work was therefore extended to the design and fabrication of a MEMS version of the VRL. The design incorporates electrical actuation using a MEMS comb drive, to avoid macroscopic position control and thus to increase the speed and ease of tuning. Because the moveable reluctance link will naturally be attracted to the position of least reluctance, there is a possibility that the required actuation force will be of similar magnitude to the desired magnetic force in the vicinity of the proof mass. In order to reduce this effect, and thus to allow a lower actuation voltage and power, we have balanced the magnetic attraction against the actuator's own spring force. The design adopted is shown in Fig 5.

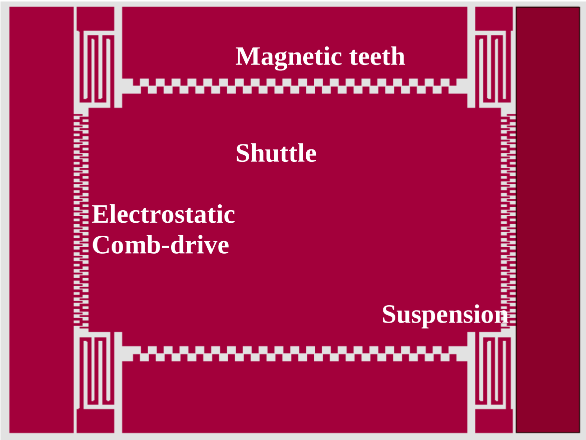

Fig.5: MEMS variable reluctance link.

The entire device is built on a silicon wafer and incorporates thick electroplated nickel for the magnetic structures needed. It has a horizontal electrostatic comb drive structure and movable shuttle made of thick nickel. The comb drive has the suspension, also fabricated of nickel, attached to anchor points, and the fixed parts have an electrode to apply the operating voltage. This voltage causes movement of the shuttle in a lateral direction. This movement of the shuttle brings the vertical combs to alignment to continue the magnetic flux path. Any displacement of the shuttle flexes the suspension anchors and generates an opposing force to restore the initial position of the mass. The die size is 3mm × 3mm.

The folded flexure design strongly reduces the development of axial forces and exhibits a much larger linear deflection range compared to clamped-beam or crab-leg designs. The stiffness ratio for small deflections is equal to the stiffness ratio of a clamped–clamped beam. This design is therefore very suitable for large deflection actuators [5].

MEMS Fabrication

Fig. 6 shows the process flow used to fabricate the MEMS VRL. This process required the development of 45 µm thick low stress electroplated magnetic components, and permits reliable release of the moving parts.

The process starts with a standard silicon wafer. The first step is 48 hours dry oxidation at 1100^{0}C to grow a 1µm thick oxide layer to act as isolation of the nickel structure from the silicon substrate. Step (ii) in Fig. 6 is to form the nickel VRL by electroplating at a current density of 8 mA/cm^2 on a Cr/Cu seed layer. This is the first layer of nickel electroplating to form the full VRD on the silicon substrate. Step (iii) completes the 45 µm thick nickel structure for the magnetic path while the comb-drive structures are protected with a resist mask. Step (iv) is to deposit gold to form pads to make electrical connections. Step (v) is to sandwich the device wafer on a pre-prepared backing wafer ready for releasing the nickel structures. The backing wafer has a 2 mm wide ring with 300 µm deep cavity formed by deep reactive ion etching (DRIE). The wafer is then oxidized for 48 hours at 1100^{0}C to grow a 1 µm thick oxide layer all over the backing wafer. This oxide ensures that during the release process the backing wafer is not attacked by the DRIE release etch.

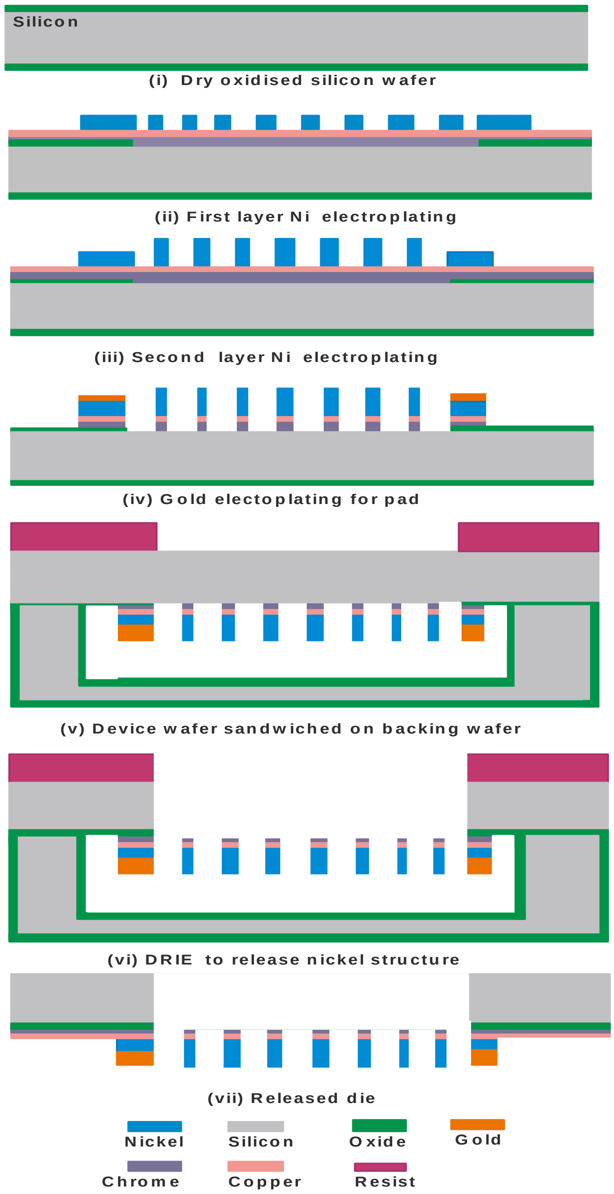

Fig. 6: MEMS process flow for VRL.

The device wafer with the nickel structures on it was then suspended upside down on the backing wafer with Cool Grease (zinc oxide compound) on the ring area only as shown in Fig. 6(v). The next step is DRIE to release the movable nickel structures from the silicon substrate as shown in Fig. 6(vi). The final stage of the process is to separate the die from the backing wafer as shown in Fig. 6(vii).

Fig. 7 shows an SEM image of the prototype fully released MEMS VRL. Movement of the reluctance link by application of an actuating voltage to the electrostatic combs will bring the teeth of the combs into alignment to continue the magnetic flux path. Any displacement of the mass flexes the suspension anchors and generates an opposing force to restore the initial position of the mass.

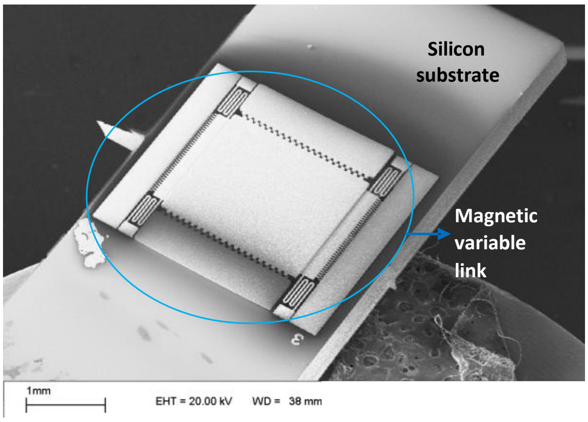

Fig.7: SEM photograph of fully released MEMS Variable Reluctance Link.

Following successful fabrication of the prototype MEMS VRL device, work to characterize its mechanical and magnetic behavior by measuring the movement of the shuttle and variation of the linked magnetic flux is underway.

CONCLUSION

It has been shown that a VRL device can be used to tune the resonant frequency of a vibration-driven energy harvester. Here we have described results from a macro-scale tuning mechanism where the reluctance link is operated mechanically and a tuning range of ±7% has been achieved.

A process methodology for fabrication of a MEMS VRL structure has been successfully developed, which required the development of low stress, thick (45um) nickel films with good adhesion to the underlying Si substrate. The same nickel electroplated layer has been used for the magnetic flux-path structures and the suspension flexures. This avoids the necessity of providing separate electrical conductors to the comb drives, which would be necessary if silicon was used for the suspension due to its low electrical conductivity.

Fully released MEMS devices have been successfully produced and characterization is in progress. Future work will include integration into a vibration harvester system to enable active tuning to maximize energy extraction from the environment.

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website: www.holistic.ecs.soton.ac.uk.

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