MEMS ELECTROMAGNETIC MICRO RELAYS OVERVIEW AND DESIGN CONSIDERATIONS

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***Abstract* :** Miniature electromagnetic relay matrices capable of switching currents up to one ampere range are widely used in commercial applications such as instrumentation and telecommunication. Traditionally these devices have been fabricated from a number of discrete components, however in recent years the emergence of Micro Electro Mechanical System (MEMS) technology has opened up the possibility for batch fabrication of microrelays at much reduced unit cost. While several electromagnetic microrelay designs have been successfully developed and commercialized for use as individual units, development work on electromagnetic microrelay matrices where individual relays can be selectively switched on and off have been fewer and less successful. Due to inherent limitations of the micromachining processes, significant dimensional and material property variations occur among individual relays in a matrix. These variations severely limit the tolerance window and hence the reliability of operation of the device. After reviewing existing designs of electromagnetic microrelays, a set of desirable design features that would make the electromagnetic microrelay more robust are identified. A novel design incorporating these features is proposed and preliminary results of ANSYS[1] simulation studies are presented.

Keywords: *MEMS, microrelay and electromagnetic*

1. INTRODUCTION

Recent trend in the world market shows a continuing demand for the miniaturization of devices. This trend has triggered the emergence of microelectromechanical systems (MEMS) technology in the past few decades. MEMS technologies such as silicon micromachining, bulk micromachining and LIGA (German Acronym for Lithographie, Galvano-formung, Abformung) offer significant advantages in size reduction without sacrificing device performance. Some of the motivating factors are reduced cost, weight and power consumption. MEMS technology is multidisciplinary with its applications ranging from optics, transportation, aerospace, robotics, chemical analysis, and biotechnologies. Comprehensive details on MEMS technology could be referred to Madou [1], Senturia [2] and Pelesko [3]. MEMS pressure sensors, accelerometers are now established commercialized products [4]. Electromechanical microrelay is amongst the predicted MEMS-based products to be commercialized in the next five years [5].

The commercial need for relays up to 2A is projected to be 1 billion units annually. Despite the rapid advances of the semiconductor, the electromechanical relays (EMR) still serves about ninety percent (90%) of the market needs compared to ten percent (10%) by solid state relays (SSR). The major reasons of the continuing use of electromechanical relays are due to its robustness and reliability in harsh environments. In addition, they have large switching range from μV and μA, could handle both DC and AC signals, have low contact resistance (mΩ) and high insulation resistance (MΩ) [6]. Figure 1 shows the miniaturization trend in manufacturing relays during the past 40 years. As can be seen from Fig. 1, the predicted board space for the next generation would be about 30 mm^2, the volume about 100 mm^2. Through MEMS technology, micro sized electromechanical relay, termed microrelay which integrates the merits of both SSR and EMR could be manufactured. MEMS technology offers possibility for exceptional miniaturization of relays, extremely low power consumption and high shock resistance.

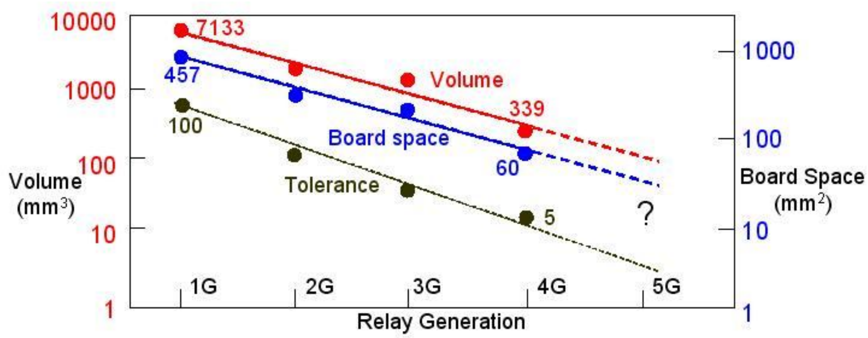


Fig. 1: Ongoing miniaturization of telecom relays during the past 40 years [6]

Pioneered by Petersen [7], realization of microrelay using MEMS technologies has attracted interests of a number of researchers in both academic and industrial field. Relay operation requires sufficient contact force to provide stable contact, reliable opening which involves a lift-off force which exceeds the adherence of sticking contacts and the highest possible breakdown voltage to assure electrical insulation between the open contacts and driving circuit. The basic requirements for microrelay design can be derived as 300 μN contact force to achieve contact resistance less than 100 mΩ, lift-off force greater than 300 μN to overcome adherence, and contact gap in the range of 100 to 250 μm to have a breakdown voltage greater than 500 V [8]. These key parameters are dependable on the contact material, actuation means and mechanical design. From a report by Schimkat [8], $AuNi_5$ is reported as a well suited contact material for microrelays due to relatively high contact force and lower adhesion force. Table 1 summarized the experimental results of the characteristics of several contact materials.

Various actuation methods have been demonstrated successfully; such as electrostatic [9,10,11], thermal [12, 13,14] and electromagnetic [15,16]. The most typical method is electrostatic due to its simplicity, small size and the versatility of integration with the standard integrated circuit (IC) technologies. However, the basic design requirements mentioned above are beyond the operating range of typical electrostatic microrelay. Recently, electromagnetic actuation has generated considerable interest. The feasibility of magnetic materials in MEMS technologies are discussed thoroughly by Busch-Vishniac [17], G. Reyne [18] and D. Niarchos [19].

Table 1: Characteristics Contact Data for Microrelays [8].

	Au	**$AuNi_5$**	Rh
Minimum contact force for stable contact, F_{min} (mN)	<0.1	**0.3**	0.6
Maximum adherence force, F_{ad} (mN)	2.7	**0.3**	< 0.1
Contact resistance, R_c at F_{min} (mΩ)	<30	**<100**	<1000

Though some improvement in magnetic materials properties and compatibility with IC processing still remains a challenge, electromagnetic actuation has been the preferred choice in microrelay applications where larger contact force (few millinewtons) is required to achieve stable electrical contact [20]. Besides, it is also possible to achieve latching by adding permanent magnet or semi-hard magnetic material thereby minimising power consumption [21]. In the case of microrelay matrices, where individual relays will have to be switched on and off selectively, reliability of operation remains an issue owing to the difficulty in achieving sufficient dimensional uniformity among individual relays in the matrix during their manufacture. Authors' research is concerned with the development of a robust design for the microrelay that will be more tolerant to MEMS fabrication imperfections. A novel design of the electromagnetic microrelay is proposed and analysed using ANSYS finite element analysis software.

2. ELECTROMAGNETIC MICRORELAYS

Traditionally electromagnetic relays have been fabricated from a number of discrete components which include an armature made of soft magnetic material, elastic spring, electromagnetic coil, a magnetic core, and special metal contacts [22]. For applications requiring the switch to remain open or closed for relatively long periods of time, a permanent magnet is incorporated into the magnetic circuit to maintain the switch in the closed position even when the control signal is removed. Implementation of magnetic actuation schemes at the micro scale is quite challenging. The most problematic is the design and fabrication of the excitation coil that would provide sufficient ampere-turns. Deposition of magnetic materials and their subsequent patterning and treatment to impart desirable characteristics to them are also difficult in a micro fabrication environment [19]. Micromachined electromagnetic relays reported in early publications [23-26] are simply adaptations of the conventional relay design to suit the microfabrication environment. Planar magnetic coil and flat cantilever spring element have been common features in all of them.

2.1 Principle of operation of the electromagnetic microrelay

Most magnetic microactuators that are reported in publications depend on the attractive force that can be generated between an armature made of ferromagnetic material and a current-carrying coil [27], as shown in Fig. 2. Related to the above microactuators are devices that use a permanent magnet instead of the magnetisable armature as shown in Fig. 3. These devices have the advantage that the actuator can generate both attractive and repulsive forces. More importantly, the relay could be held in its closed state even after the control current is removed.

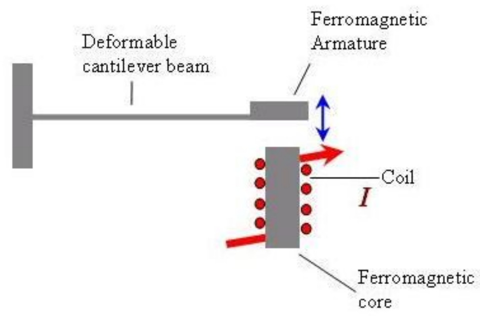


Fig. 2: Magnetization-type actuator.

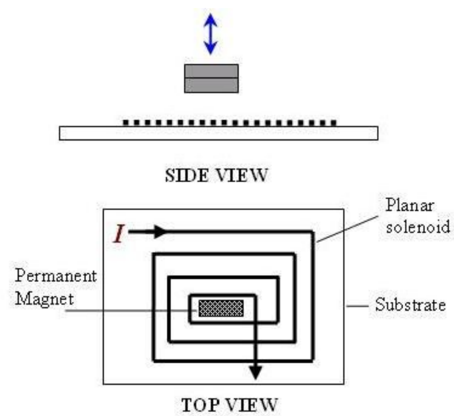


Fig. 3: Planar magnetic microactuator.

The operation of the latching electromagnetic microrelay can best be understood by considering the variations in magnetic, and restoring spring forces with air gap. The relative positions of the spring and magnetic force characteristics for three different states of the relay, namely, unactuated (in either closed or open state), on the verge of closing from the open state, and on the verge of opening from the closed state are shown in Fig. 4, 5 and 6 respectively. Here the spring characteristic is assumed to be linear. Previous studies suggest that the dependence of the magnetic force on the air gap can roughly be described by a power law $F \sim g^n$ with an exponent n in the range -1.4 to -2 [28]. When there is no coil current, the magnetic force will be solely due to the permanent magnet. Depending on the direction of current flow in the coil, the magnetic force can be either enhanced or reduced by the electromagnet. In Fig 4, $F_{s0} = kg_0$, $F_{m0} = Rkg_0$ (say) are the spring and magnetic forces respectively when the air gap, g is zero, k is the spring stiffness, g_1 and g_2 are the air gaps corresponding to the two intersection points of the force characteristics, g_0 is the air gap when the spring is unstressed, and R is the ratio F_{m0}/ F_{s0}. Note that g_1 is a stable equilibrium point whereas g_2 is an unstable equilibrium point. In the unactuated case, either the relay remains open with air gap g_1 or remains closed with contact force $F_{m0} - F_{s0}$.

Figure 5 shows the effect of increasing the magnetic force by applying a coil current. The spring force line is shown to touch the magnetic force curve at the air gap, g_t. Any further increase in the coil current will cause the relay to close. Figure 6 shows the effect of reducing the magnetic force by applying coil current in the opposite direction. Here the magnetic force curve is shown to meet the spring force line at $g = 0$. Any further increase in the coil current will cause the relay to open.

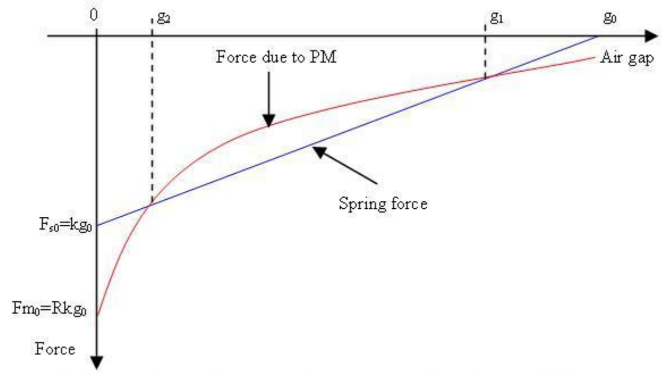


Fig. 4: Spring and Magnetic Forces as functions of air gap.

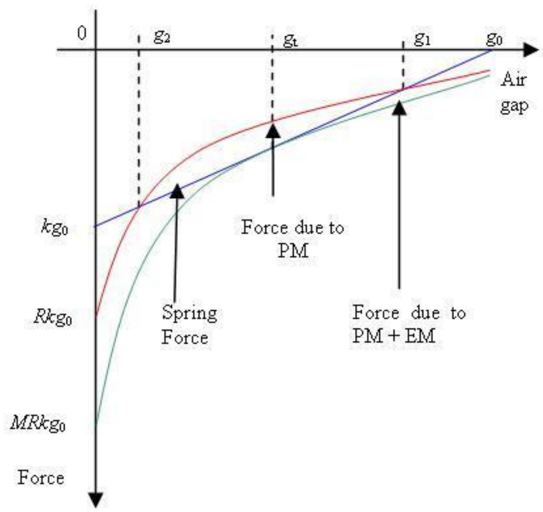


Fig. 5: Relative position of force characteristics.

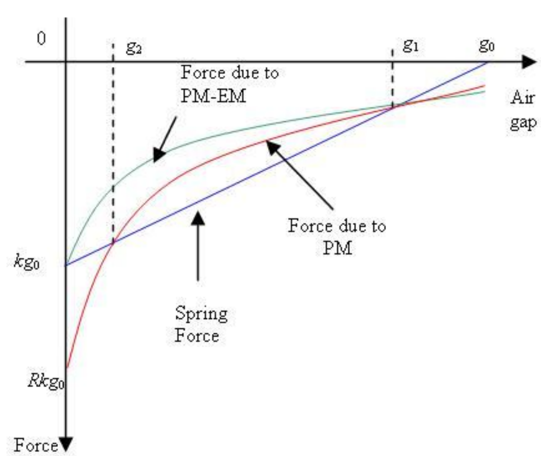


Fig. 6: Relative position of force characteristics of microrelay on the verge of latching of microrelay on the verge on unlatching.

When a current pulse of sufficient amplitude and duration is passed through the electromagnetic coil, the induced magnetic field due to the permanent magnet and the electromagnet in the relay will create sufficient force on the armature to pull the relay closed. The relay will stay closed due to the field from the permanent magnet, which is not strong enough to pull the relay closed by itself, but will hold it there when the air gap becomes small and the flux becomes stronger. To reset the relay, current pulse is applied in the opposite direction which will reduce the resultant flux in the air gap sufficiently so that the beam can spring back to the open position.

Another important practical consideration is the ability of the microrelay to withstand ambient shock and vibration [29]. It can be shown that greater the area of the closed region between the spring and magnetic force characteristics (between g_1 and g_2) in Fig 4, the greater will be the resistance of the microrelay to shock and vibration.

Thus the following four design rules can be formulated for the microrelay.

- For latching to occur, the entire magnetic force characteristics for the case of full positive electromagnetic actuation should be below the spring force line.
- Minimum contact force requirement must be satisfied. That is, the magnitude at zero air gap of the spring force must be less than the magnitude at zero air gap of the magnetic force due to the permanent magnet alone by the minimum contact force required.
- For the switch to unlatch, the magnitude at zero air gap of the spring force must be greater than the magnitude at zero air gap of the magnetic force for the case of full negative electromagnetic excitation.
- The area enclosed by the spring and magnetic force characteristics must be sufficiently large so as to alleviate the detrimental effects of shock and vibration.

Parameters of the spring (k and g_0), magnetic circuit (n), permanent magnet (F_{m0}), and electromagnetic coil (ampere-turns) should be carefully matched to achieve optimum performance. However, manufacturing imperfections associated with MEMS processes are likely to result in significant variations in the values of these parameters and severely limit the tolerance window of the final product.

2.2 Microrelay matrices

While several electromagnetic microrelay designs have been successfully developed and commercialized for use as individual units, development work on electromagnetic microrelay matrix arrays have been fewer and less successful although many commercial applications await them. By combining such relay matrices with electronics, it would be possible to perform multiplexing and to reduce the number of electrical lines required to switch individual relays in the matrix; an 8×8 array for instance would require 16 control lines, as opposed to 64 control lines when the relays are packaged separately without the multiplexing electronics. Such relay arrays have great potential in the telecommunication industry.

While individual microrelays can be made to operate reliably, making micro relay matrix arrays in which individual relays need to be selectively and reliably switched on and off by an appropriate multiplexing scheme presents many challenges. The major problem is the difficulty in achieving the degree of uniformity in the structural dimensions among the individual relays in the matrix. It is difficult to achieve close dimensional tolerances of micro relay structures when cost effective MEMS fabrication methods are used. Due to the inherent limitations of the micromachining processes, significant variations in the dimensions of the micro relay occur across the wafer. For example, each individual microrelay may not have the same thickness of cantilever beam and the initial air gap. Besides, stiction problem, which occurs when two nominally flat surfaces are placed in contact also contribute to unreliability of the switching action [30]. Due to these reasons, each individual relay in a matrix will have varying electrical, magnetic and mechanical properties, and as a result the strength of the control signals required for switching the relays on and off is bound to vary widely. A small variation of $\pm$5% in the thickness of the cantilever, for instance, would result in $\pm$15% variation in the spring parameter *k*. This could cause serious switching errors in the relay matrix. Experience of two of the authors of this paper suggests that micro relay matrix arrays based on microrelay designs outlined in section 2.2 is bound to have very narrow tolerance window and hence very low reliability.

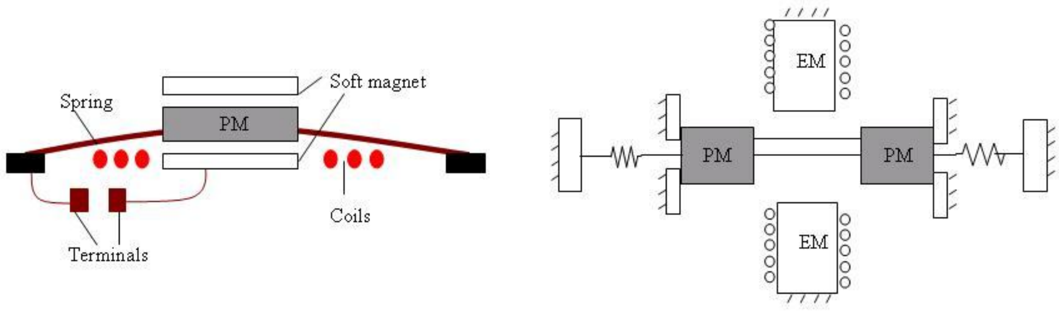
2.3 Alternative design concepts

The most interesting of all electromagnetic microrelay designs that have been reported to date is MagLatch™ which has been commercialised by Magfusion [31]. The major advantage of this relay is the latching mechanism to maintain the non-volatile state without requiring constant current supply. The device is based on preferential magnetization of a permalloy cantilever in a permanent external magnetic field. Switching between two stable states is achieved by sending a short current pulse through an integrated coil underneath the cantilever. However, suitability of this design for the fabrication of integrated microrelay arrays with viable, cost effective row and column addressing scheme is yet to be demonstrated.

A major drawback of the conventional design discussed in Section 2.1 is the variability associated with the initial air gap and thickness of the cantilever. Any stress induced in the cantilever beam during the electroplating process is likely to cause some initial deflection in the cantilever and variable air gap. The stiffness of the cantilever spring varies as the cube of its thickness, implying that the stiffness variation would be about three times the thickness variation. As the heavier armature at the end of the cantilever is not fixed when the relay is in the off state, resistance of the device to shock and vibration is bound to be low.

To alleviate these problems, Roshen *et al.* [32] proposed a micromachined electromagnetic switch with fixed on and off positions using two soft magnets and one permanent magnet as shown schematically in Fig. 7(a). Two soft magnets situated in fixed positions above and below a permanent magnet toggles between two fixed positions by the application of current in an actuator coil for a brief period. The permanent magnet is attached to a micromachined hinge or spring which moves under the action of a net force, thereby opening or closing the switch. Current in the actuator coil changes the relative strength of the magnetic forces due to the soft magnets. In the absence of current in the actuator coil, the switch is kept in the open or closed position by the attractive magnetic force between the permanent magnet and either the upper or lower soft magnet, whereby the stronger force is exercised between the permanent magnet and the nearest soft magnet.

In the conventional electromagnetic microrelay design, the strain energy stored in the spring when the relay is in the closed state is not gainfully utilised. When the relay is switched open from its closed state, the stored energy is transformed into kinetic energy and manifests as oscillations which eventually dies down due to damping.



(a) Fixed on-off position switch | (b) Bistable switch

Fig. 7: Schematic designs of bistable, latching, electromagnetic switch.

Tabat et al. [33] proposed a novel design, shown schematically in Fig. 7(b) that utilises the stored energy in the switch for changing its state. Bistable operation is obtained using a single coil and a magnetic core with a gap. A plunger having two magnetic heads is supported for back and forth linear movement with respect to the gap in the core. The single electrical coil is coupled to the core and is provided with electrical current to attract one of the heads toward the core by reluctance action and drive the plunger to the limit of travel in one direction. The current is then cut off and the plunger returns by spring action toward the gap, where after the current is reapplied to the coil to attract the other head of the plunger to its limit of travel. This process can be repeated at a time when switching of the actuator is required.

While the above two novel concepts have significant merits and are worth pursuing, one has to bear in mind the difficulties of micromachining such devices. To the authors' knowledge, an economically viable design utilizing one or more of these two concepts that is amenable to micromachining remains to be developed.

3. DISCUSSION OF ONGOING RESEARCH AT RMIT UNIVERSITY

A group of researchers at RMIT University are attempting to develop a robust design for an electromagnetic microrelay that can form the building block of microrelay array matrices. The main focus is to develop a relay structure with the following features: easily manufacturable by standard MEMS processes with minimum cost, has fixed on and off positions so that resistance to shock and vibration can be enhanced, utilizes the strain energy stored in the spring for switching from one state to the other resulting in a more positive switching action, uses a permanent magnet to achieve latching as well as push-pull action during switching.

3.1 Proposed design of electromagnetic micro relay

The proposed design under study is shown schematically in Fig. 8(a) and (b). A relatively thick and rigid beam is attached at two points to the free ends of two thin cantilever beams as in Fig. 8(c). These can be made of Silicon or a low permeability material such as electroplated Nickel. An important feature of this mechanical arrangement is that the elastic support provided by the pair of cantilever beams is very stiff for pure vertical movements of the rigid beam (due to axial stiffening of the cantilever beams), but quite flexible for tilting movements as shown in Fig 8(d). Furthermore, in the tilted position the mechanical system once again becomes quite stiff if the lower end of the rigid beam is held against a mechanical stop, as in Fig. 8(e). Two permanent magnets are attached to the ends of the rigid beam and magnetized in a vertical direction as shown. The electromagnet is formed by a number of planar parallel wires all carrying current in the same direction (normal to the plane of the paper). The Permalloy strip is placed underneath the wires to increase the magnetic flux due to the current carrying wires. It is to be noted that, even without the two permanent magnets, bistable operation similar to the device of Fig. 8(b) is possible with this design.

When a current pulse is applied to the coil (in a direction along the outward normal to the paper), the RHS permalloy pole piece will be polarized N and the other S, attracting the LHS end of the rigid beam while repelling the RHS end, and causing the beam to tilt counter clockwise. When the coil current is switched off, the magnetic attraction between the LHS permanent magnet and the LHS permalloy pole piece will be able to hold the rigid beam to remain in the tilted position. A current pulse in the opposite direction will cause the rigid beam tilt to the opposite side.

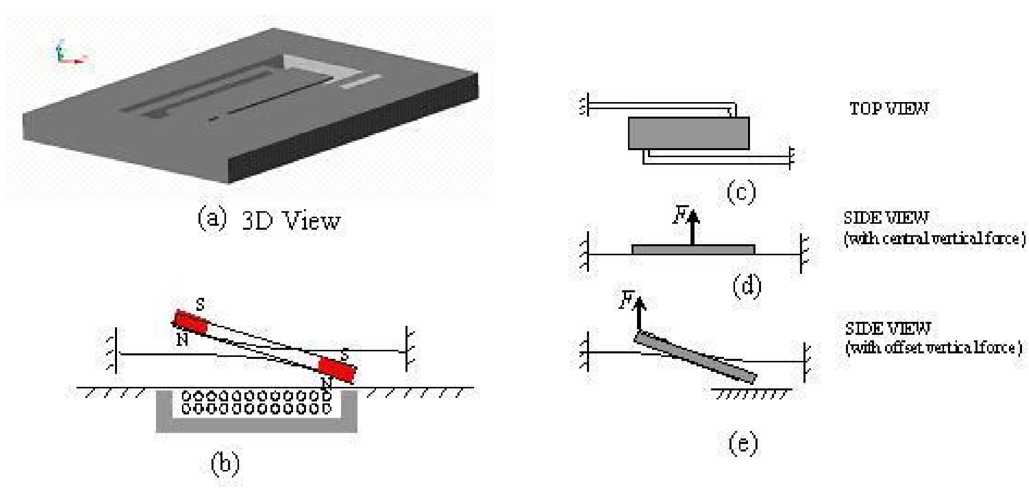


Fig. 8: Schematic of the proposed mechanical system

3.2 Finite Element Analysis (FEA)

To realistically study the mechanical system, a simple linear analysis will not suffice; nonlinear effect of stiffening of the beam caused by deflection will have to be accounted for. Using ANSYS software, a nonlinear finite element analysis is carried out to determine the force-deflection characteristics of the proposed structure. Figure 9 gives the normalized force – deflection characteristics of the LHS end of the rigid beam when the RHS end of the beam is held down against a normalized dead stop distance, d_n below the undeflected position of the beam. At positive normalized forces (upward), the graph demonstrates for higher values of d_n, the characteristics display a very flat region which implies the increasing stiffness of the system. However, beyond a certain threshold values of the applied force, the deflection steadily increases with force. For example, for d_n = 0.042, the graph is nearly constant between the normalized force of 0.00 to 0.02, but when it reached the threshold value at around 0.03, the deflection increase significantly. It appears that buckling of the cantilever beams occur beyond this threshold.

This trend repeats for the negative forces (downward forces) at small value of d_n for example, d_n =0.008. Generally, the FEA results show flat regions in terms of normalized deflection which demonstrates high degree of stiffness when downward forces are applied. It can therefore be concluded that within the limits set be the threshold, the mechanism offers significant disturbance immunity.

Some preliminary analysis of the magnetic circuit of the microrelay has also been done performed to determine the force generated on the rigid beam by the electromagnet at various positions of the rigid beam. The magnetic circuit simulated is shown in Fig. 10(a). In this analysis the permanent magnets are left out and the rigid beam is assumed to be made up of a high permeable material such as electroplated permalloy. The objective is to see whether bistable operation is possible with such an arrangement. The element type PLANE13 is used to model the magnetic circuit, cantilever beam, air gap and the coil, while two-dimensional four node boundary elements, INFIN110, are used to simulate an infinite extension of the surrounding air. The flux patterns for initial horizontal beam position and for a tilted position are shown in Fig. 10(b) and Fig. 10(c). Effect of the tilt angle on the resultant force and its point of application are analysed and the results presented in Table 2.

It can be seen from Table 1 that as the angle of tilt of the rigid beam increases the point of application of the resultant magnetic force moves further to the right of the beam centre. The normalized force and the tilting moment also increase with the angle of tilt. Graph in Fig. 11 demonstrates that bistable operation under electromagnetic excitation is feasible provided the spring force line lies below the magnetic force line.

Table 1: Magnetic force on beam at tilted angle

Tilted angle, θ	Normalised force (F_θ/F_0)	Normalised offset (e/l)	Normalised tilting moment ($F_\theta e/ F_0 l$)
0	1.00	0.00	0
5	1.04	0.17	0.1768
10	1.22	0.33	0.4026
15	1.78	0.54	0.9612

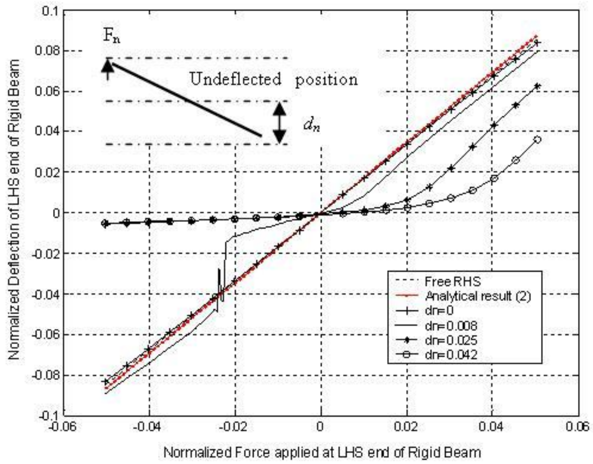
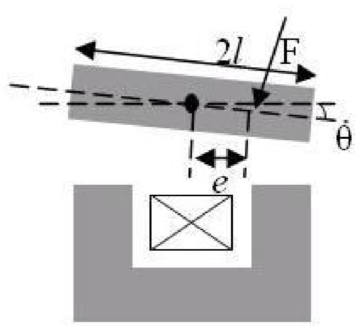
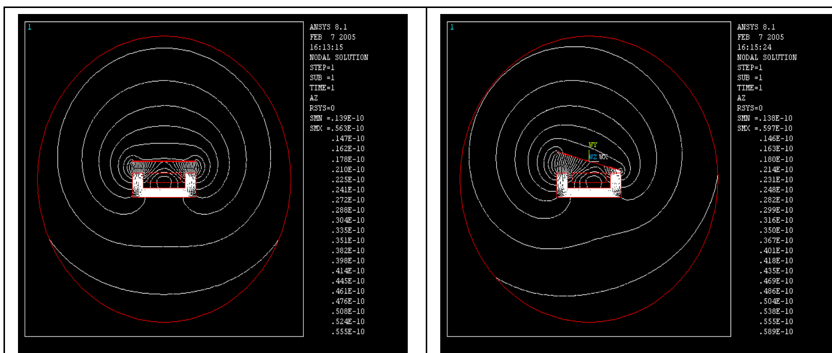


Fig. 9: Force – deflection characteristics of the LHS end when RHS end is pressed down against a dead stop distance *d* below the undeflected position of rigid beam.



(a)



(b)	(c)

Fig. 10: FEA of magnetic circuit and the magnetic flux patterns for horizontal and tilted position

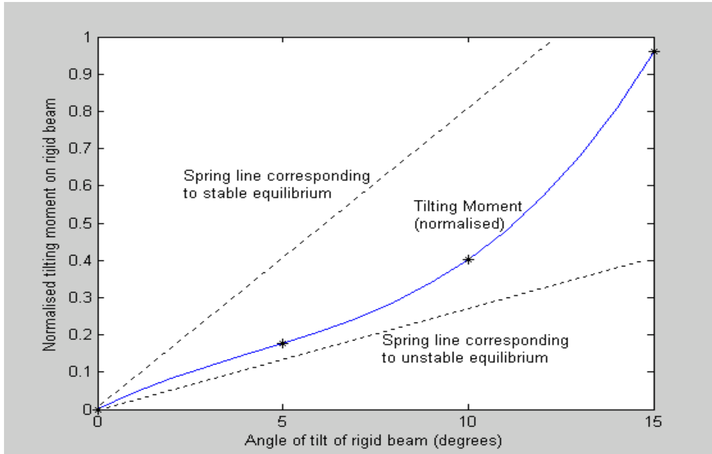


Fig. 11: Tilting moment at different angle

4. SUMMARY

Because of their narrow tolerance window, existing designs of electromagnetic microrelays are proving to be problematic for fabricating microrelay matrices where individual relays are required to be selectively switched on and off by row and column multiplexing. A novel design incorporating a number of desirable features to improve switching robustness is proposed. ANSYS simulation studies are being pursued to demonstrate the advantages of the proposed design. A prototype is to be built and evaluated in the near future.

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