A tristable mechanism using combination of magnetic mechanisms and compliant beams

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(Summary) As a new application of PMs for providing necessary positioning forces, a novel magnetic-fields-based tristable mechanism with two parallel beams and four magnets is designed and fabricated. Based on the magnetic-charge model, the nonlinear snap-through mechanics of the tristable structure is analyzed theoretically, which is in accordance with results obtained by finite element method and experiments. And the nonlinear relationship between the threshold snapping force and the design factors such as the travelling range, stable positions, relative distances among the four magnets and beam dimensions is deduced. Finally, the design methodology of introducing magnetic elements in the multistable mechanisms is validated, which is really useful in the ultra-low energy consumption systems and high accuracy positioning instruments.

Introduction

A tristable mechanism has three force-balanced positions within its range of motion, where the stable states can be maintained without input power. With the advantages of high repeatability and positioning accuracy, the multistable mechanisms have a large number of potential applications in ultra-low power consumption systems such as satellite-based modules, capacitor banks in filters, fast switching valves [1-3].

Traditionally, tristable mechanisms always originate from three main categories of bistable mechanisms such as latch-lock mechanisms, hinged multisegment mechanisms, and residual-compressive-stress buckled beams[4-8]. As a new application for providing necessary positioning forces, permanent magnets are used as the main structural elements to construct multistable mechanisms. In this paper, a novel symmetrical tristable mechanism incorporating the permanent magnetic mechanism and compliant beams is proposed, as shown in Fig.1.

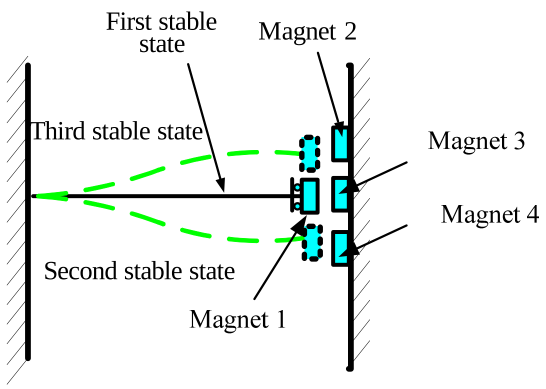


Fig.1 The tristable mechanism with four PMs

Tristable mechanism design

Different from the tristable structures based on the fully compliant structures, four permanent magnets are included in the tristable mechanism, three of which are fixed in the case and the other one is fixed in the moving point of the compliant parallel beams. Hence, at the stable positions, the nonlinear interaction magnetic force between the moving magnet and the three fixed magnets is used to balance the elastic force from the compliant beams. Also there is an orientation constraint on the end of the parallel beams to keep a constant relative distance between the moving magnet and the fixed magnets while the stable states changed. Based on the magnetic-charge model and material mechanics theory [1, 2], the nonlinear snap-through mechanics of the tristable structure is analyzed theoretically, which is in accordance with results obtained by experiments. And the nonlinear relationship between the threshold snapping force and the design factors such as the travelling range, stable positions, relative distances among the four magnets and beam dimensions is deduced.

As shown in Fig.1, the tristability of the coupled structure directly depends on the resultant force of the elastic force and the magnetic force.

$$F_{total} = kx + F_m(x) \tag{1}$$

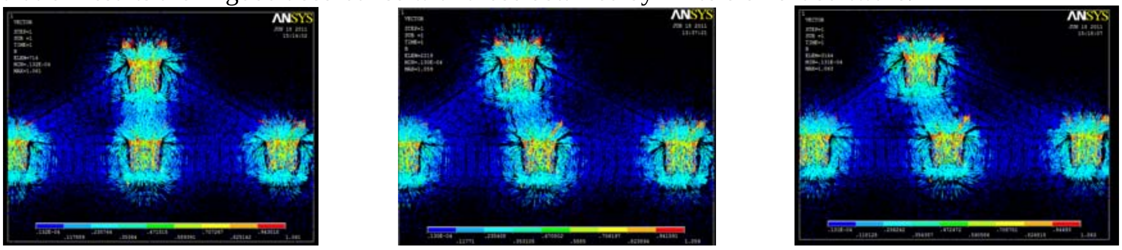
where k is the stiffness of the compliant beam, the magnetic force Fm applied by the three fixed magnets to the moving magnet can be expressed as

$$F_m = \sum_{n=1}^{3} \frac{J^2}{4\pi\mu_0} \left(\sum_{i=0}^{1} \sum_{j=0}^{1} \sum_{k=0}^{1} \sum_{l=0}^{1} \sum_{p=0}^{1} \sum_{q=0}^{1} (-1)^{i+j+k+l+p+q} \phi_x(u_n, v_n, w_n, r_n) \right) \tag{2}$$

And the variables in equation(2) are

$$
\begin{cases}
u_n = (x-\alpha_n) + (-1)^j a - (-1)^i a \\
v_n = (y-\beta_n) + (-1)^l b - (-1)^k b \\
w_n = (z-\gamma_n) + (-1)^q c - (-1)^p c \\
r_n = (u_n^2 + v_n^2 + w_n^2)^{1/2} \\
\phi_x = \frac{1}{2}(v_n^2 - w_n^2)\ln(r_n - u_n) + u_n v_n \ln(r_n - v_n) + u_n v_n \tan^{-1}\frac{u_n v_n}{r_n w} + \frac{1}{2} r_n u_n
\end{cases}
\tag{3}
$$

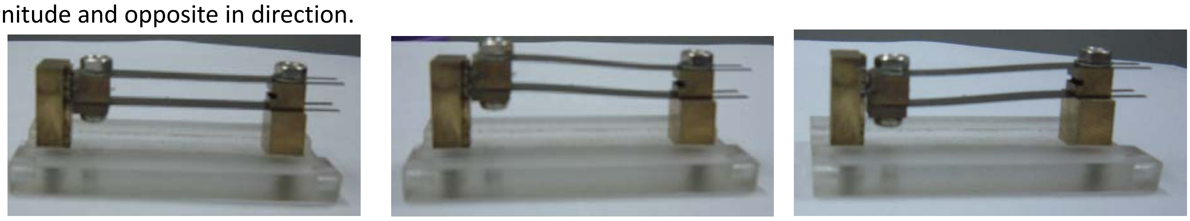
where n=3, is the number of the fixed magnets, r_n the vertical distance between two interactive magnets, and μ_0 the magnetic permeability, $a\times c\times b$ the geometrical size of the magnets. The three points (α_1, β_1, γ_1), (α_2, β_2, γ_2), and (α_3, β_3, γ_3) are the central positions of the three fixed magnets, and (x,y,z) the position of the moving magnet. Considering the boundary conditions of the proposed structure, the variable x changes with the displacement of the moving magnet and the coordinates of y and z are constant values. Fig.2 shows the magnetic fields distribution of the tristable mechanism, and simulation results are in good accordance with those obtained by finite element software.



a. Original position b. 0.41mm displacement c. 0.5mm displacement

Fig. 2 FEM model of the four magnets

According to the relationship between the elastic force and the magnetic force, a miniature sample of the tristable mechanism is designed and fabricated, which is shown in Fig.3. At the stable position, there is no external force needed to maintain the stable state. At the second and third stable states, the elastic force and magnetic force are equal in magnitude and opposite in direction.



（a） the first stable state (b) the second stable state (c) the third stable state

Fig.3 The miniature structure of the tristale mechanism

Conclusion

Besides the traditional tristable mechanisms with compliant structures, a novel magnetic-fields-based tristable mechanism with two parallel beams and four magnets is designed and fabricated. Based on the magnetic-charge model and material mechanics theory, the nonlinear snap-through mechanics of the tristable structure is analyzed theoretically, which is in accordance with results obtained by finite element method and experiments. And the nonlinear relationship between the threshold snapping force and the design factors such as the travelling range, stable positions, relative distances among the four magnets and beam dimensions is deduced. Finally, the design methodology of introducing magnetic elements in the multistable mechanisms is validated, which is really useful in the ultra-low energy consumption systems and high accuracy positioning instruments.

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