An Accurate Computation Model for Magnetic-mechanical Based Penta-stable Mechanism

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(Summary) Different from multistable mechanisms relying on the complex multiconnected bistable structures, a novel penta-stable mechanism is designed by utilizing magnetic-mechanical coupled structures. The pentastability mainly originates from the nonlinear interactions among the four spatial arranged magnets and the large deflection parallel supporting beams. Considering the relative axial displacement attributed by the large deformation of the parallel beams, an accurate computation model for analyzing the pentastable behaviors is established according to the pseudo-rigid-body model and magnetic charge model, which is useful to the optimization of the PM-based multistable mechanisms. The simulation results are in good agreement with those by the finite element method.

Introduction

Bistability and multistability are nonlinear phenomena that can maintain two or several different stable states without any external forces, which are really attractive in deploying the compliant mechanism of the satellite-antenna, switching of capacitor banks in filters or impedance matching networks, and maintaining the required states of valves, relays, positioners, and reconfigurable robots.

Traditionally, multistable characteristics always originate from geometric nonlinearity of compliant mechanisms [1-3] or multi-connected bistable structures [4, 5] following with the storage and release processes of strain energy of the flexural members. However, one disadvantage of such mechanisms is that the number of auxiliary components increases with the stable states, which will make them more complex, and more importantly prevent their miniaturization. To simplify the structure configuration, high performance magnetic blocks are introduced in designing multi-stable mechanisms. Zhao[6] have designed both bistable and tristable mechanisms by utilizing the nonlinear force to hold the structure in stable states, whose motion trajectory can be controlled by changing the arrangement of the magnets. Limited by the magnet geometry, the bistable or tristable mechanisms can only be realized in a short range of linear motion, and it is difficult to achieve four or more stable states without a large range of linear motion.

Therefore, the authors mainly provide an accurate model for precisely designing of magnetic based multistable mechanisms. And the nonlinear relationship between the threshold snapping force and the structural parameters such as the traveling range, stable positions, relative distances among the four magnets and beam dimensions is obtained. The simulation results are in good accordance with the finite element model and thus useful to the optimization design of the PM-based multistable mechanisms.

Magnetic-mechanical penta-stable mechanism

As a new application in designing multi-stable mechanisms, magnets are used to provide necessary forces for maintaining the stable positions. In Fig.1, we proposed a novel penta-stable mechanism, which mainly consists of four spatial arranged magnets and one elastic supporting beam with an orientation constraint on the free end.

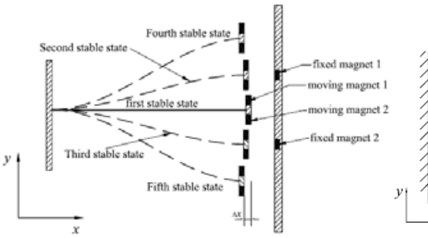

Fig.1 Penta-stable mechanism

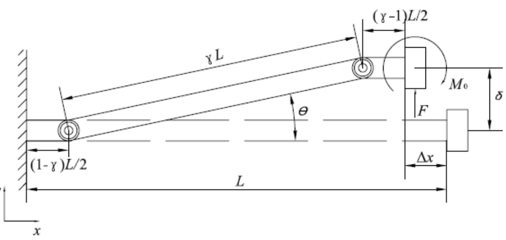

Fig.2 Simplified fixed-guided beams

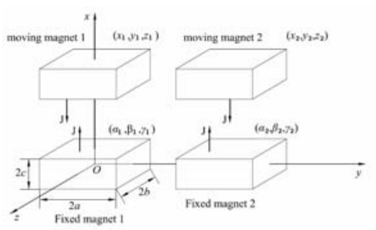

Fig.3 the arrangement of the four magnets

According to the PRBM theory, the mechanism can be simplified to the rigid body connected with rotating springs[7], as shown in Fig.2. To analyze the nonlinear interactions, four magnets are set to have same magnetization direction, same magnetization intensity J, and same geometrical sizes of $2a\times2c\times2b$. $(\alpha_1, \beta_1, \gamma_1)$, $(\alpha_2, \beta_2, \gamma_2)$, (x_1,y_1,z_1), and (x_2,y_2,z_2) are the coordinates of the central positions of the fixed magnets and moving magnets, as shown in Fig.3. And the relationship among the two relative coordinates can be expressed as $d_1=\alpha_2-\alpha_1$, $d_2= x_2-x_1$, $\beta_1=\beta_2$, $\gamma_1=\gamma_2$, $y_1= y_2$, and $z_1=z_2$. d_1 and d_2 represents the distances between the two magnets on the same plane.

Based on the magnetic charge model and the superposition principle of magnetic force, considering the axial displacement (Δx) of the free end, the total force acting on the moving magnets can be obtained as

$$\begin{aligned} F_{total}\left(x+\Delta x, y\right) &= F_k\left(x,y\right)+F_m(x+\Delta x, y) \\ &= \frac{4\theta K_\theta EI}{L^2\cos\left(\arcsin\left(\dfrac{y}{\gamma L}\right)\right)} + \sum_{\substack{n=1\\m=1}}^{2}\frac{J^2}{4\pi\mu_0}\left(\sum_{i=0}^{1}\sum_{j=0}^{1}\sum_{k=0}^{1}\sum_{l=0}^{1}\sum_{p=0}^{1}\sum_{q=0}^{1}(-1)^{i+j+k+l+p+q}\phi_{mx}(u_{mn}, v_{mn}, \omega_{mn}, r_{mn})\right) \end{aligned} \tag{1}$$

where F_k is the elastic force of the large deformation fixed-guided beam, F_m the magnetic force, E the Young of the material, I is the inertia moment, L is the length, K_θ is the stiffness coefficient, θ the rotation angle, y the transverse displacement of the free end, μ_0 the magnetic permeability.

In accordance with the geometric relationship, the axial displacement attributed by the large deformation of the fixed-guided beam can be deduced.

$$\Delta x = \gamma L - \gamma L \cos(\arcsin(\frac{y}{\gamma L})) \tag{2}$$

Meanwhile, the intermediate variables appearing in equation(1) for computating the magnetic force are

$$\begin{cases} u_{mn} = (x_m - \alpha_n) + (-1)^j a - (-1)^i a \\ v_{mn} = (y_m - \beta_n) + (-1)^l b - (-1)^k b \\ \omega_{mn} = (z_m - \gamma_n) + (-1)^q c - (-1)^p c + \Delta x \\ r_{mn} = (u_{mn}^2 + v_{mn}^2 + \omega_{mn}^2)^{1/2} \\ \phi_{mx} = \frac{1}{2}(v_{mn}^2 - \omega_{mn}^2)\ln(r_{mn} - u_{mn}) + u_{mn}v_{mn}\ln(r_{mn} - v_{mn}) + u_{mn}v_{mn}\tan^{-1}\frac{u_{mn}v_{mn}}{r_{mn}\omega_{mn}} + \frac{1}{2}r_{mn}u_{mn} \end{cases} \tag{4}$$

where n ={1, 2}, m={1, 2}, Δx is the axial displacement, (i, j, k, l, p, q)=$\{0, 1\}^6$, r_{mn} the distance between two interactive magnets, (x_m,y_m,z_m) is the coordinate of the central position of the moving magnet.

Simulation

Considering the axial displacement induced by the large deformation fixed-guided beam, the nonlinear force characteristic of the penta-stable mechanism is obtained, as shown in Fig.4. Fig.5 shows the magnetic field distribution of the mechanism simulated by software. There are nine force balanced positions along the traveling range of the moving magnets. Based on the energy variation principle, the second -order derivative of the whole energy at the stable position should be greater than zero. Therefore, five positions can fulfill the stability requirement, which means that the proposed mechanism owns five stable states. Meanwhile, from the comparison of the two force curves, it can be found that the axial displacement is of great importance in determining the amplitude of the threshold snapping force to the fourth or fifth stable states. From the simulation results, we can see that the computation model considering the axial displacement compensation is much more accurate in predicting the force behaviors of the penta-stable mechanism.

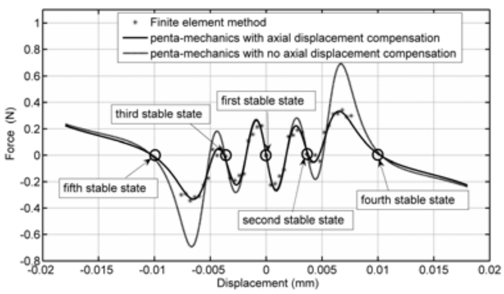

Fig.4 Force-displacement curve of the penta-stable mechanism

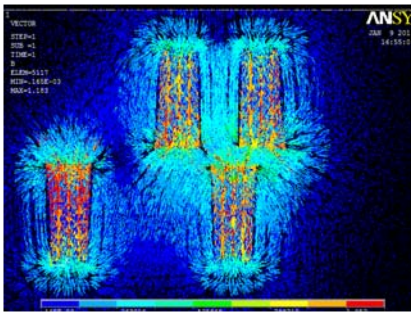

Fig.5 The magnetic field distribution of mechanism

Conclusion

In this paper, a novel penta-stable mechanism is proposed by utilizing the magnetic-mechanical coupled structures. Considering influences of the nonlinear large deflection on the axial displacements, an accurate model for calculating the penta-stable behaviors is established. The simulation results show that the proposed mechanism has five different stable states with different snapping threshold forces, which are in good agreement with those obtained by finite element method. Finally, the feasibility of design methodology for penta-stable mechanisms is validated, which are useful in simplifying the traditionally multistable mechanisms such as satellite-antennas, switches, valves, relays, positioners, sensors and reconfigurable robots.

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