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Configuration compliant tristable mechanism based on characteristics of differential compliant bistable mechanisms

Ngoc Dang Khoa Tran*

Faculty of mechanical engineering, Industrial University of Ho Chi Minh City, Vietnam

*Corresponding Author Email: tranngocdangkhoa@iuh.edu.vn

ABSTRACT: Compliant tristable mechanisms have many applications in the future. However, predict the characteristic of the mechanism is the challenge for the engineers because of the nonlinear behavior. This paper introduces the design of a tristable mechanism which is comprise from the two stable mechanisms. These mechanisms are connected through a frame mass. The combination of their behaviors is assisted to predict the function of the tristable mechanism. In the investigating, the peak forces of bistable mechanisms are close to the peak force of the tristable mechanism. Their characteristics are indicated by the finite element method. The finite element method is implemented to prove the results. Strain energy is studied to explain the discrepancy of tristable and bistable behavior. The influence of parameters of frame mass is investigated. Several cases are executed to varified the consequence.

KEYWORDS: nonlinear behavior, bistable mechanism, tristable mechanism, frame mass.

INTRODUCTION

Many applications of tristable mechanisms have been potentially used in the modern industry. These mechanisms dominance that they can maintain three stable equilibrium positions with no power input and high integration. They employed in design switches, positioners, sensors, energy harvester, microactuators and many devices. However, most of the researches interested in design bistable mechanism devices [1-5].

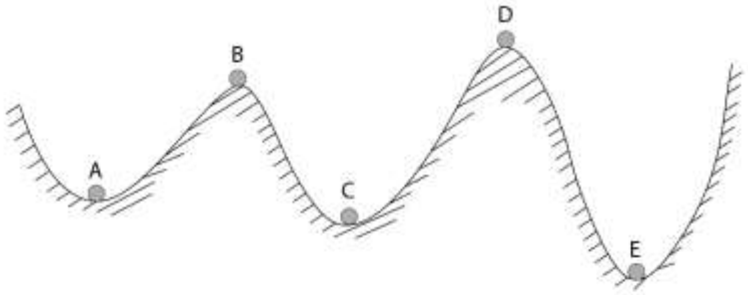


Figure 1. “Ball-on-hill” tristable mechanism [3].

The tristable mechanism has three stable equilibrium positions, figure 1 demonstrates the “Ball-on-hill” analogy for a tristable mechanism, introduced [6]. Ball at A position is the first stable equilibrium position, at this position, the ball is in the valley, it is very hard to move to the B position. In order to move to the B position, the ball need a external force to push the ball go to the B position. When the ball come to the B position, the ball is unbalanced, freely go down A or C point. When the ball moves to point C, gain the second position. When external force applies to the ball and pushes the ball go to point D, achieves the second unstable position, and continually move to the F position which is the third stable position. The property of the tristable mechanism is the relation between the force and dispalcement. Figure 2 show the behavior of the simple tristable structure. In the figure, the tristable mechanism have two maximum force F_{max1} and F_{max2} and two minimum force F_{min1} and F_{min2}. The P_0, P_1, P_2 is the three stable positions and U_1, U_2 are the two unstable postion of the mechanism.

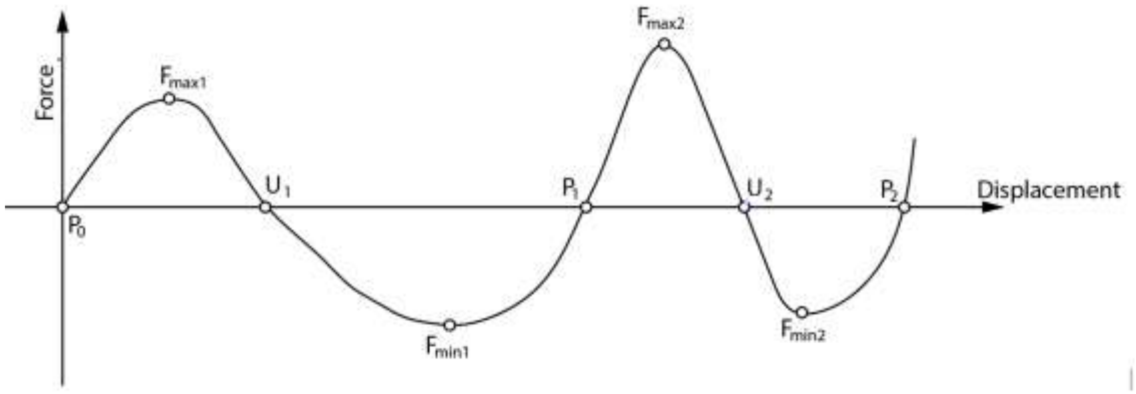


Figure 2. Typical force-displacement of the tristable mechanism.

Recently, many researcheres studied the tristable mechanisms. Oberhammer et al. designed an electrostatic actuator based on a tristable mechanism [7]. The mechanism has one input stage and two output states, these states are stable by the latching mechanism. Depend on the Young bistable mechanism, Chen and Yu developed a tristable device, the configuration of this mechanism can be performed by pseudo-rigid-body model [8]. The configuration of the tristable mechanism has been solve by the numerical method. This method also applied in predicting nonlinear characteristics of a fully compliant double tensural tristable mechanism [6]. The study interests the synthesis of compression, bending, and tension of flexible members. A three stable equilibrium mechanism formed on geometric symmetry, introduced by Pendleton and Jensen, these stable stages achieved by storage and release energy, without friction force and locking structure [9]. Chen and Chang combined three parallel bistable mechanisms to generated a tristable mechanism [10]. Statically-balanced compliant mechanisms are employed in study nonlinear characteristics of these mechanisms. Wang et al designed an in-plane tristable compliant mechanism based on two series bistable mechanisms, they created a mechanism by connecting flexible curve beams without joints [11]. Another in-plane tristable mechanism developed by Chen et al., the macroscale device move in two directions which the second stable stage in the horizontal direction and third stable state in a vertical direction [12]. Micromechanism is fabricated and tested to verify the predict nonlinear behavior by the finite element method. Dai et al constructed a tristable structure that includes several laminars. Four rectangle plates were assembled to perform three different stable stages in three-dimension space [13]. Few energy harvester devices employ three stable equilibrium to increase the power based on the vibration of the cantilever beam and magnetic [14,15]. Additionally, a tristable mechanism was applied in order to design an accelerometer, operate when the device achieves a threshold value. Nontheless, these methods are very compliacted and take a long time for calculating the properties of the mechanism [16, 17].

Furthermore, multistable mechanisms have more than three equilibrium positions that have been investigated. For example, Oh and Kota proposed four stable rotational devices, formed on two bistable rotational mechanisms [18]. King et al. illustrated the rotational multistable mechanism with a flexible compliant beam [19]. A mechanism with four stable equilibrium position in a direction movement was presented by Pham and Wang [20], they combined two cosine curve profile to design this mechanism. Chen et al. synthesis a bistable mechanism and slider mechanisms into compliant multistable devices [21]. However, these designs are complex and unpredict the nonlinear behavior of the tristable mechanism easily. This paper describes a new approach to design a tristable compliant mechanism that combines the configuration of two bistable mechanisms. Two bistable mechanisms connect through a frame mass to maintain their behavior and place on the tristable mechanism. By the combound these mechanisms, the force of the tristable mechanism is easily archived. Finite element methods are executed to achieve the nonlinear behavior of two bistable mechanisms and a tristable mechanism. Some investigation of frame mass to predict the feasible design.

DESIGN BISTABLE MECHANISM

Bistable mechanisms have two stable equilibrium positions. The design bistable mechanism is assisted by several methods [4,5]. The principle operation of the bistable mechanism is illustrated in figure 3. The mechanism includes four slanted beams that connect with shuttle mass at one end and fixed at the other end. A coordinate system is performed in the figure. The shuttle mass protects the twisting of the mechanism. Initially, the shuttle mass place on the S_0 position, the first equilibrium position. A force is applied to shuttle mass in the y-direction, the beams deformed and stored energy by compression force. When the force is large enough, the energy is release and the shuttle mass snap through to the second equilibrium position S_1. The dimension parameters of the bistable mechanism are shown in figure 4. The profile of the beam is the straight line and the slanted section has an inclination angle of θ. The length of the beam is L, the width of the beam is W and the thickness of the beam is t. Four beams have the same dimension. The dimensions of shuttle mass are L_s and W_s, have the same thickness as the beams.

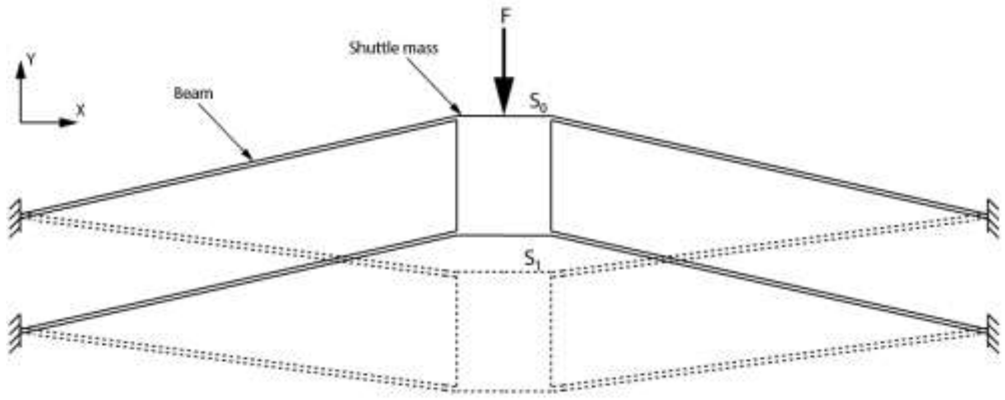


Figure 3. Operation of bistable mechanism

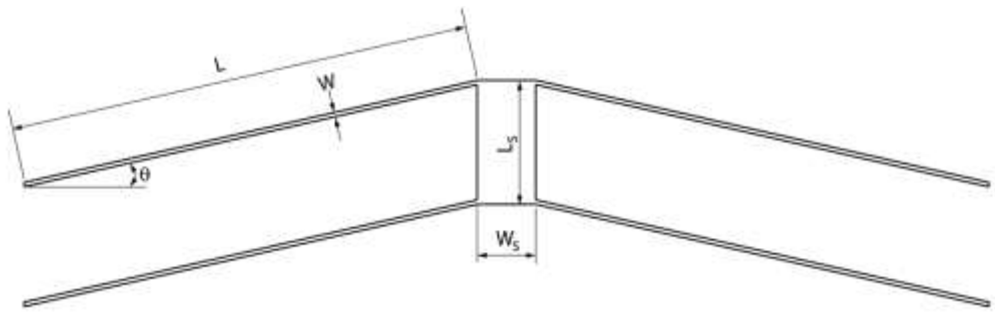
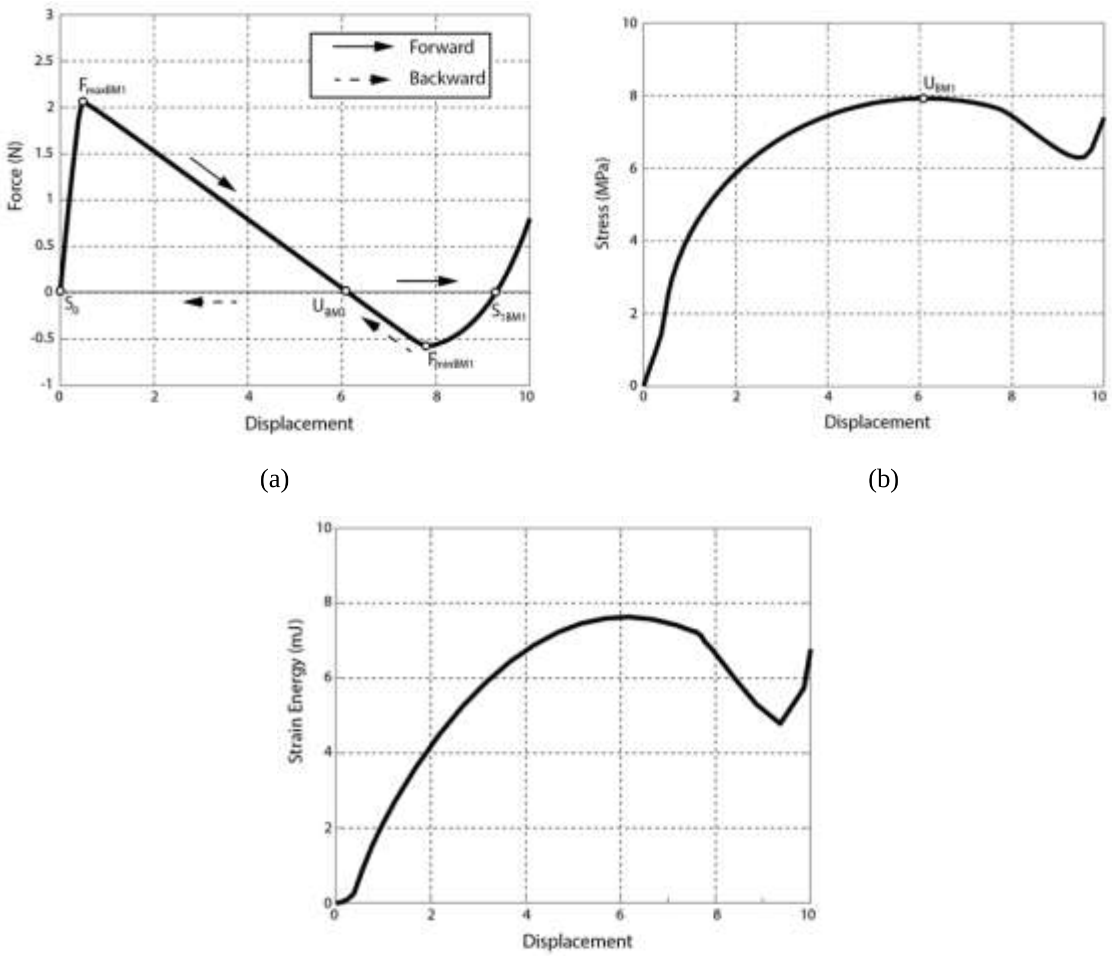


Figure 4. Dimension of bistable mechanism

Two bistable mechanisms were design based on the profile in figure 4. The design parameters shown in Table 1, two bistable mechanisms have the same thickness, width, dimensions of shuttle mass. Considering the nonlinear behavior of the bistable mechanism, the finite element method was applied to analyze the force-displacement characteristic of the mechanism. A commercial ABAQUS program is executed to solve the computation. Polyoxymethylene (POM) is the material to fabricate the model. The Young's modulus is gained as 2.15 Gpa, and the Poisson's ratio is 0.38. Figure 5 shows the force-displacement curve of bistable mechanism 1 (BM1). Because the external force applies in the y-direction, figure 5(a) only demonstrates the reaction force in the fixed end of the bistable mechanism in the y-direction. In the forward motion, the shuttle mass moves from the first stable equilibrium position S_{0BM1} to the second equilibrium position S_{1BM1}, the force archive the maximum force at F_{maxBM1}= 2.05 (N). At the unstable position U_{BM1}, the shuttle mass snap through to the second equilibrium position S_{1BM1}, also obtain the maximum stress in the mechanism. In the backward motion, S_{1BM1} is the first stable equilibrium position, S_0 is the second stable equilibrium position. The mechanism gets the F_{minBM1}= - 0.527 (N) and shuttle mass jump from U_{BM1} to S_{0BM1}. Figure 5(b) shows the maximum von Mises stress of the tristable mechanism based on the finite element model. The maximum value is the von Mises stress of all elements. From S_0 to S_{1BM1}, maximum Mises stress is 7.927 (Mpa) near the unstable position U_{BM1}, under a yield strength of POM material, 64 Mpa. The strain energy of the bistable mechanism is shown in figure 5(c). The energy is stored with maximum value is 15.26 (mJ) when the mechanism reaches the unstable position U_{BM1}. While the shuttle mass jumps to the second stable position, the energy drops down to the smallest value, 9.56 (mJ). The mechanism achives the stable form of equilibrium. Similarly, bistable mechanism 2 (BM2) designed with the parameters in Table 1, the characteristic of this mechanism is shown in Table 2.

Table 1. Design parameters of two bistable mechanisms.

Parameters	Bistable mechanism 1 (BM1)	Bistable mechanism 2 (BM2)
L (mm)	100	70
θ (degree)	5	5
W (mm)	1	1
t	5	5



(a) (b)

(c)

Figure 5. (a) Force - displacement curve, (b) Stress curve and (c) strain energy of bistable mechanism 1.

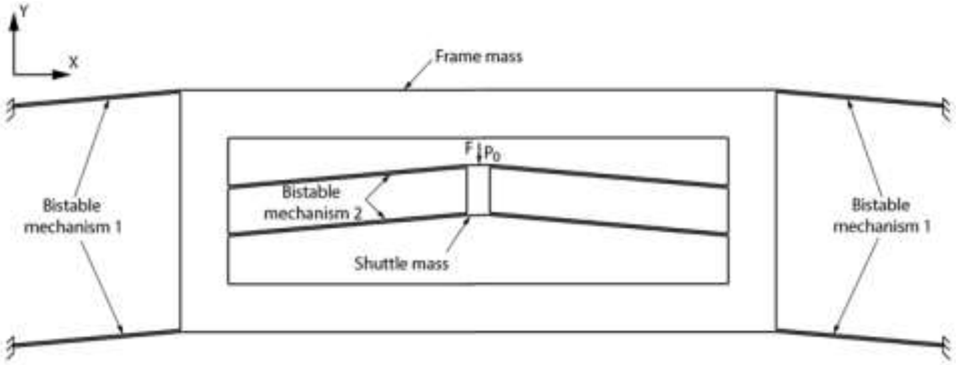
Table 2. Results of BM1 and BM2

	Bistable mechanism 1 (BM1)	Bistable mechanism 2 (BM2)
F_{maxBMi} (N)	2.05	1.058
F_{minBMi} (N)	-0.527	-0.327
S_{1BMi} (mm)	9.3	13.4
U_{BMi} (Mpa)	7.927	5.484

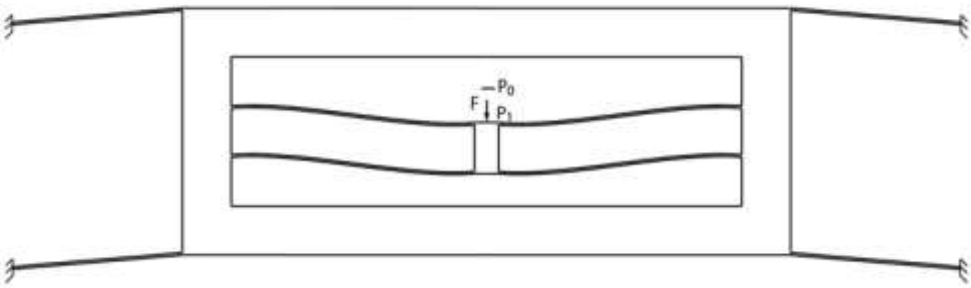
* i: number of bistable mechanisms

DESIGN TRISTABLE MECHANISM

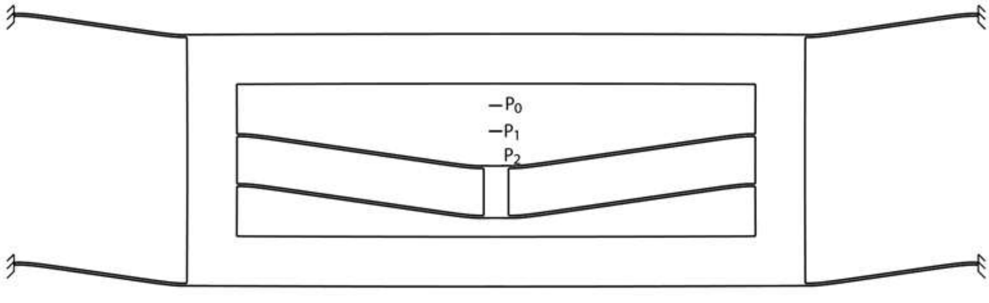
Two bistable mechanisms are employed to synthesize a tristable mechanism which combines characteristic of each bistable mechanism through a frame mass. Figure 6a introduces the design model of the tristable mechanism. The mechanism includes two bistable mechanisms connect through a frame mass. One end of BM1 is fixed at the anchor, the other end clamped at the frame mass. BM2 also clamped at the frame mass at one end, the other end connects to the shuttle mass. In the forward motion, an external force F place on the shuttle mass in the y-direction, the shuttle mass move from the first stable position P_0 to the second stable position P_1, follow figure 6b. Frame mass approaches constant, only BM2 deforms. Continually, external force F is applied to shuttle mass, BM1 is bent, and shuttle mass snaps through the third stable position, frame mass closely move with the shuttle mass, shown in figure 6(c). Two bistable have the same dimension in Table 1. The dimension of frame mass is illustrated in figure 7. G is the distance between the end of BM1 and the inside edge of frame mass. L_f is the distance between one end of BM2 and the inside edge of frame mass. L_f should be large enough to shuttle mass move from S_0 to S_1. W_f and W_m are the width of frame mass with x and y-direction, respectively. The thickness of frame mass is **t = 5 (mm)**, the same thickness of BM1, BM2, and shuttle mass. The design parameters of frame mass are given in Table 3.



(a)



(b)



(c)

Figure 6. Principle operation of tristable mechanism

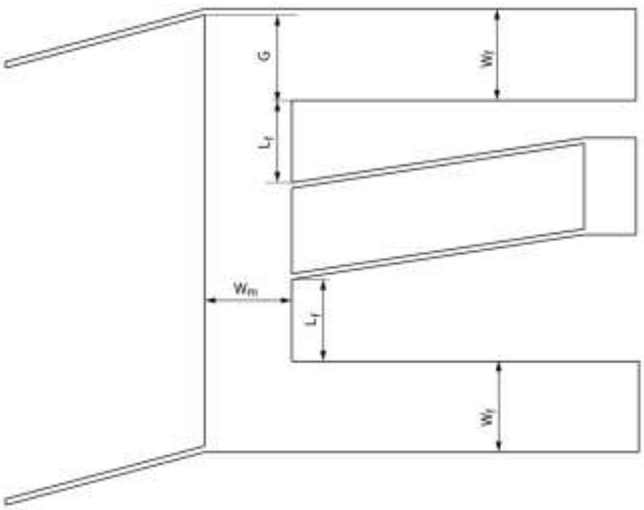


Figure 7. Dimension of the half model of the tristable mechanism

Table 3. Dimension of frame mass

Parameters	Value
G (mm)	19.9
L_f (mm)	20
W_f (mm)	20
W_m (mm)	20

The ABAQUS program is carried out to investigate the nonlinear behavior or the tristable mechanism. Due to the symmetric of the tristable, half model is used to mesh and analysis. Figure 8 shows a mesh of half model of the tristable mechanism and boundary conditions. One end of BM1 is fixed follow the figure. The shuttle mass and the frame mass are constrained in the y-direction and A displacement is placed on the shuttle mass in the y-direction. The tristable mechanism also uses POM material to analyze. The reaction force of fixed end of BM1 is collected.

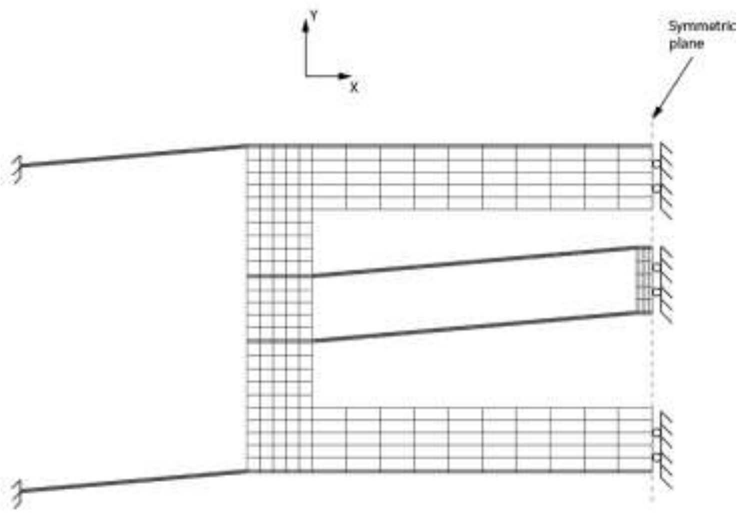


Figure 8. Meshing of half model of tristable mechanism

RESULT AND DICUSSION

The force-displacement relationship of the tristable mechanism in forwarding motion achieved by the finite element method is plotted in figure 9. The tristable mechanism is stable in the first position P_0, the external force is applied to the shuttle mass. When the force reaches local maximum force Fmax1, the force decreases until zero at U1 point which is the first unstable position of the tristable mechanism. The shuttle mass jumps to P_1, the second stable position. The external force still applies to shuttle mass and achieves the local maximum force F_{max2}, the force decrease quicky and reaches U_2 point, the second unstable position. The shuttle mass snaps through to the third stable position P_2.

Comparison with the characteristic of two bistable mechanisms, the maximum force of BM2, F_{maxBM2}=1.058 (N), is closed in local maximum force F_{max1} of tristable mechanism, F_{max1}= 1.021 (N), which error is 3%. Likewise, the local maximum force F_{max2}= 1.983 (N), approaches to the maximum force of BM1, F_{maxBM1}= 2.05 (N), the error is 3%. The second stable position, P_1= 13.61 (mm) is nearly reached to the second position of BM2, S_{1BM2}=13.6 (mm). The third stable position, P_2 = 22.73 (mm) is equal the sum of second stable position of BM1 and BM2, S_{1BM1}+S_{1BM2} = 22.7 (mm). Two unstable positions of the tristable mechanism are closed in the unstable position of BM1 and BM2, respectively. However, negative force have a feature of numerical artififact of finite element method. That means it is not the real value in backward motion. A buckling phenomenon effect to the force-displacement curve of the tristable when it reach the second unstable position.

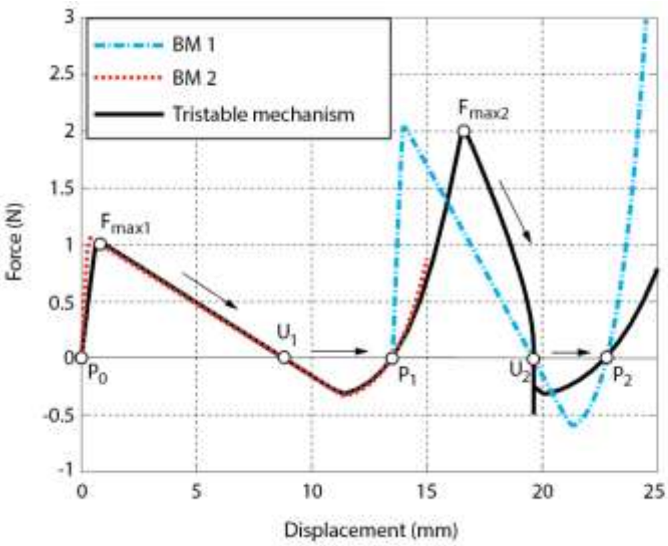


Figure 9. F-d curve of forward motion of tristable mechanism and two bistable mechanisms.

Indeed, a real backward motion is shown in figure 10. A simulation is executed wit theh initial condition is shuttle mass placed on the third stable position. A displacement applied to the shuttle mass which makes it move from moves from the third stable position P_3 to the first stable position P_0. The BM2 moves first, reaches the minimum local force of tristable mechanism F_{min1} = - 0.311 (N), still closes in the minimum force of BM1, F_{minBM1} = - 0.327 (N). The second minimum local force of tristable mechanism F_{min2} = - 0.54 (N) is near the minimum force of BM2, F_{minBM2} = - 0.527 (N). Due to the displacement of BM1 and BM2 is different, the second stable position in backward motion is dissimilar to forward motion. Based on the configuration of this tristable mechanism, characteristic of the tristable mechanism could be formed on two bistable mechanisms.

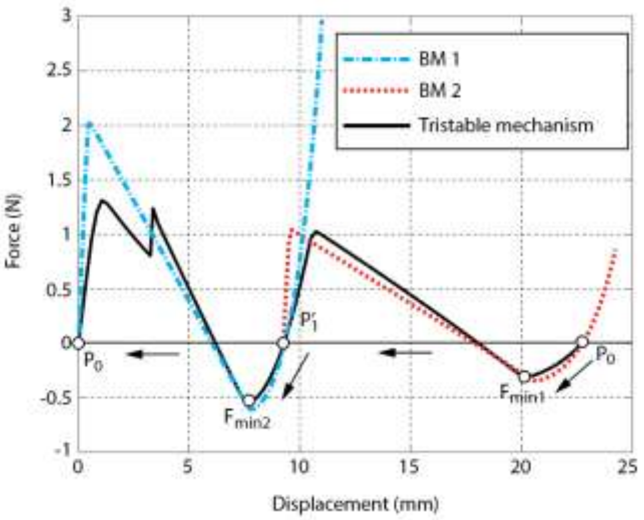
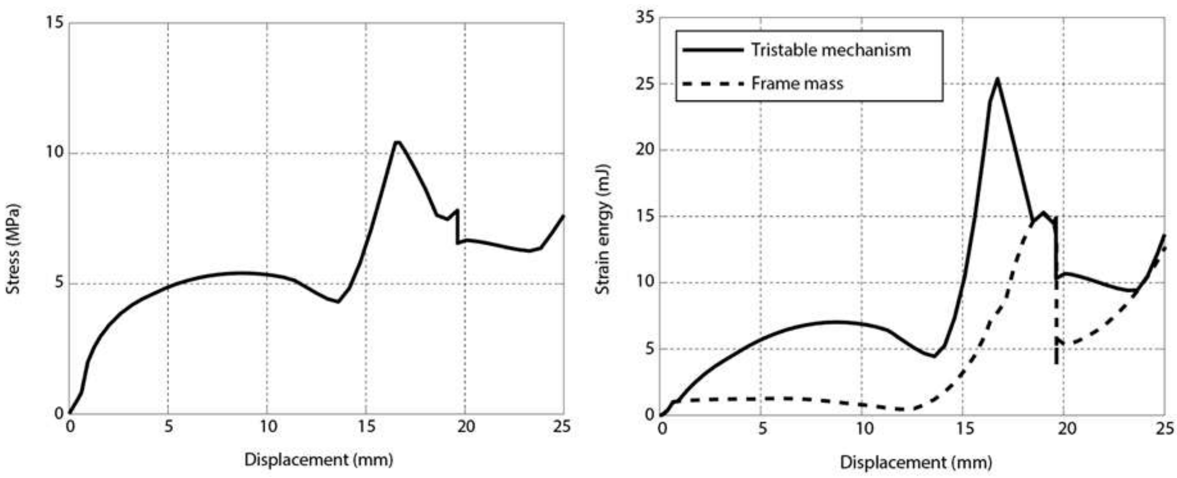


Figure 10. F-d curve of backward of tristable mechanism and two bistable mechanisms.

In order to prevent damage and fracture of the mechanism, an investigation of Mises stress influence on the tristable mechanism is considered. As seen in figure 11(a), the maximum stress of the mechanism, value is 10.92 Mpa, satisfied the yield strength of its material. Figure 11(b) performs the strain energy in the tristable mechanism and the frame mass. Maximum strain energy reaches 25.8 mJ at the position which has maximum local force F_{max2}. It explains the discrepancy of force-displacement between the bistable mechanism and the tristable mechanism. Because of the energy stores in the frame mass, when its release, the abrupt change occurs and makes the shuttle mass move quickly to the third stable position.



(a) (b)

Figure 11. (a) Stress curve and (b) strain curve of tristable mechanism

The influence of geometric parameters of frame mass is investigated to assist in the design tristable mechanism. Figure 12 shows how the value of G affects the value of the first and second local maximum force of the tristable mechanism. All other parameters of the tristable mechanism are kept unchanged. In this investigation, the magnitudes of F_{max1} and F_{max2} are increase when G decreases. In order to satisfy the maximum force of BM1 and BM2 approach the local maximum force of the tristable mechanism, the value of G should be closed to W_f. It means the position of BM1 place on the outside edge of the frame mass.

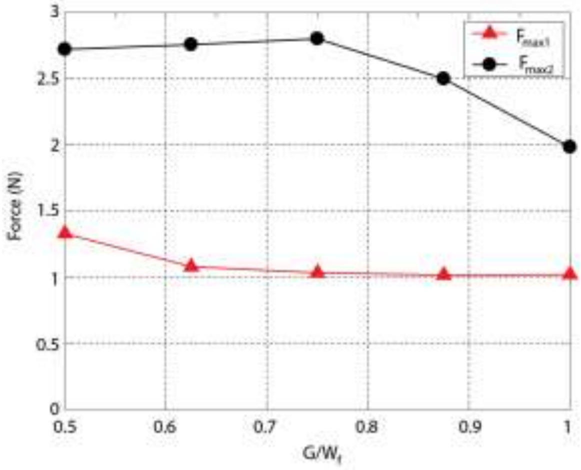


Figure 12. Relation between the parameters of frame mass

Table 4 verified the nonlinear behavior of the tristable mechanism involves the two bistable mechanisms. Two bistable mechanisms with different parameters are designed. The parameters of frame mass are listed in Table 3. The thickness of two bistable mechanisms, frame mass, and shuttle mass is 5mm. The finite element method is employed to achieve the f-d solutions. POM material is applied in analysis. The difference between characteristic of two bistable mechanism and the tristable mechanism is 3% to 5%.

Table 4. Synthesis of tristable mechanisms with BM1 and BM2

Case	BM1		BM2		Tristable mechanism			
	F_{maxBM1} (N)	S_{BM1} (mm)	F_{maxBM2} (N)	S_{BM2} (mm)	F_{max1} (N)	P_1 (mm)	F_{max2} (N)	P_2 (mm)
1	2.54	7.9	1.02	9.9	0.8	9.8	2.34	17.8
2	2.75	8.4	1.25	10.4	1.13	10.36	2.5	18.5
3	3.2	5.5	1.52	6.4	1.4	6.3	3.02	12.0
4	3.5	5.0	1.78	9.01	1.5	9.0	3.42	14.1
5	4.01	6.1	2.15	7.14	2.01	7.13	3.94	13.1
6	4.51	6.55	3.75	8.11	3.55	8.10	4.4	14.5
7	5.01	7.2	3.8	8.4	3.6	8.4	4.7	15.6
8	5.3	7.7	4.05	8.91	3.98	8.9	5.1	16.5

CONCLUSION

A new method for design compliant tristable mechanism has been presented in this paper, which connects the characteristics of two bistable mechanisms and places on the nonlinear behavior of the tristable mechanism. Based on employing a frame mass, maximum forces, and minimum forces of bistable mechanisms close to the local maximum forces and local minimum forces of tristable mechanism. The stable positions of the tristable mechanism are also determined by the stable position of bistable mechanisms. The potential of the design can be applied with many shapes of the bistable beam. The position of the clamped end of the bistable mechanism needs to reach the outer edge of frame mass. Future work of this topic will be verified the result by experiment with the prototype and the applications.

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