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50. Internationales Wissenschaftliches Kolloquium
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Nenad T. Pavlović, Nenad D. Pavlović

Improving of Mechanical Efficiency of Compliant Mechanisms

ABSTRAKT

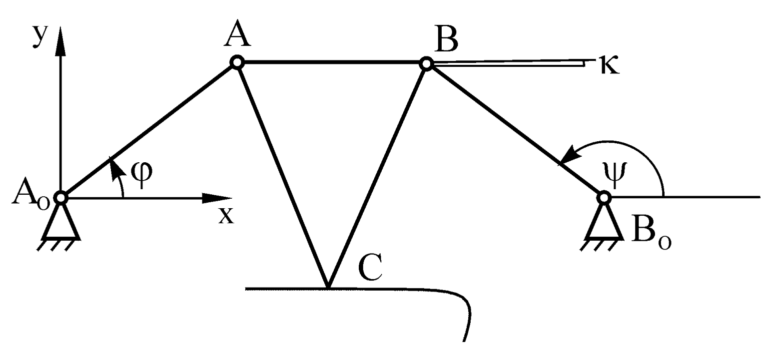
Compliant mechanisms gain some or all of their mobility from the relative flexibility of their joints rather than from rigid-body joints only. The paper deals with the mechanical efficiency of a compliant mechanism. The influence of the selection of the input force acting point, as well as selection of the input force direction, will be researched in order to improve the mechanical efficiency of the compliant mechanisms with plastic and silicone joints.

1. INTRODUCTION

Compliant mechanisms gain their mobility due to relative flexibility of their joints [1]. There are many advantages of using compliant mechanisms: a mechanism can be built in one piece, the weight can be reduced and wear, clearance, friction, noise and need for lubrication can be eliminated. In this paper we analyze the ways of improving of the mechanical efficiency of the compliant four-bar linkages for rectilinear guiding.

2. ROBERTS-ЧЕБЫШЕВ FOUR-BAR LINKAGE FOR RECTILINEAR GUIDING

The coupler point C of the Roberts-Чебышев four-bar linkage (Fig.1) can be guided on an approximately rectilinear path within range of the input crank rotation angle $\boldsymbol{\varphi = -5^o \div 43^o}$. For $\boldsymbol{\varphi_0 = 37.345^o}$ coupler link $\overline{\mathbf{AB}}$ will be in horizontal position, that is $\boldsymbol{\kappa = 0^o}$. The link length ratio of the Roberts-Чебышев four-bar linkage is [2]:



$$\mathbf{a} = \overline{\mathbf{A_0A}}$$
$$\mathbf{b} = \overline{\mathbf{B_0B}} = \mathbf{a}$$
$$\mathbf{c} = \overline{\mathbf{AB}} = \mathbf{0.85a}$$
$$\mathbf{d} = \overline{\mathbf{A_0B_0}} = \mathbf{2.44a}$$
$$\overline{\mathbf{AC}} = \overline{\mathbf{BC}} = \mathbf{1.105a}$$

Fig.1 Roberts-Чебышев four-bar linkage for rectilinear guiding of the coupler point C

2. DESIGN OF ROBERTS-ЧЕБЫШЕВ COMPLIANT MECHANISM

We have developed the compliant counterpart of the Roberts-Чебышев rigid-body four-bar linkage. Fig.2 shows the Roberts-Чебышев compliant mechanism with the notch joints [4]. The entire compliant mechanism has been built in one piece of material. The width of the elastic segments and the width of relatively rigid segments have been denoted with $\mathbf{w_E}$ and $\mathbf{w_R}$ respectively (Fig.3).

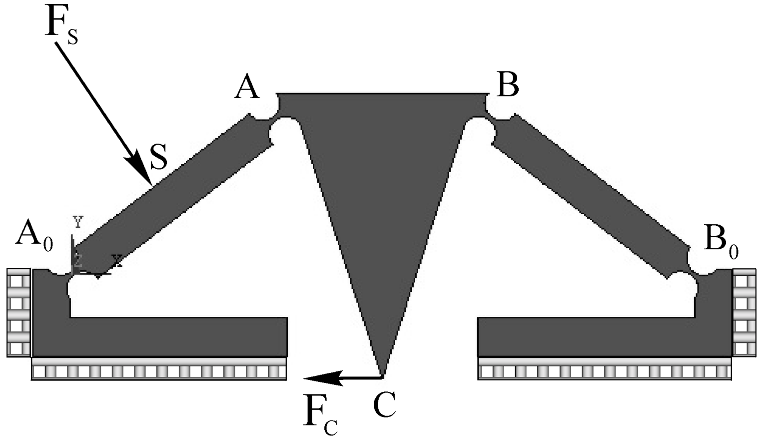


Fig.2 Roberts-Чебышев compliant mechanism with notch joints

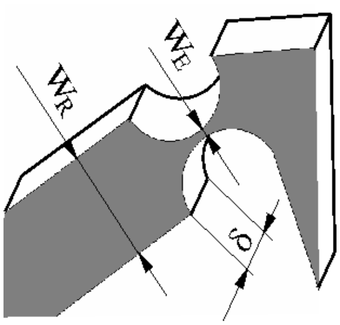


Fig.3 Compliant notch joint

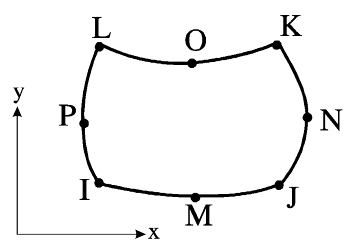


Fig.4 Two-dimensional-eight-node Structural Solid

The displacement and stress analysis have been performed for material piacryl (modulus of elasticity $\mathbf{E = 3700\ N/mm^2}$, bending strength $\boldsymbol{\sigma_{bs} = 90\ N/mm^2}$) and for material thickness of $\boldsymbol{\delta = 4mm}$. The calculation has been performed using ANSYS Software for the elements with rectangular cross-section using Two-dimensional-eight-node Structural Solid (Fig.4) as a characteristic ANSYS element type. The element is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x- and y-directions.

For great rigidity ratio $\mathbf{w_R/w_E} = 10$, this compliant mechanism can provide good guiding accuracy; the difference between realized and exact rectilinear path on horizontal displacement of $\boldsymbol{\Delta x_C = 5mm}$ would be $\boldsymbol{\Delta y_C = 1.3\mu m}$ [4].

3. MECHANICAL EFFICIENCY OF THE ROBERTS-ЧЕБЫШЕВ COMPLIANT MECHANISM

The work performed at the input can be determined by the input force (force acting on input link) and the displacement of the point acted by the input force. The work performed at the output can be determined by output force (force resisting the motion) and the displacement of coupler point C acted by the output force. The mechanical efficiency can be defined as the ratio of the work performed at the output and the work performed at the input [8]:

$$\eta = \frac{\mathbf{F_C s_C}}{\mathbf{F_S s_S \cos\angle(\overrightarrow{F_S}, \overrightarrow{s_S})}} \tag{1}$$

where (Fig.2):

η - mechanical efficiency,

$\mathbf{F_S}$ - input force (force acting on input link),

$\mathbf{s_S}$ - displacement of the input force acting point (S),

$\mathbf{F_C}$ - output force (force acting on the point C and resisting the motion),

$\mathbf{s_C}$ - displacement of the output force acting point C.

However, crank $\overline{\mathbf{A_0A}}$ does not have to be an input crank of a compliant mechanism and the input force can act at any links point in any direction. Figure 5 shows several different variants **(V1 ... V6)** of the input force acting point and input force direction.

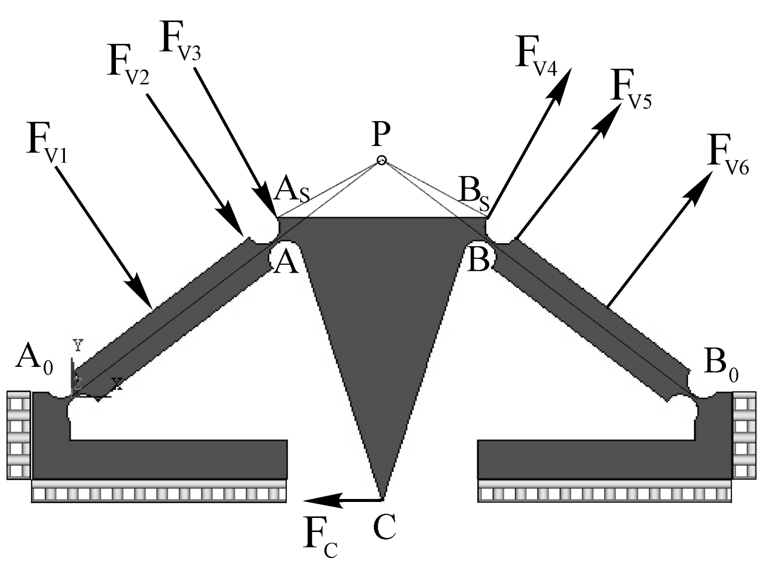


Fig.5 Different variants of the input force on
the Roberts-Чебышев compliant mechanism with notch joints

The input forces $\mathbf{F_{V1}}$ and $\mathbf{F_{V2}}$ (Fig.5) act on the crank, at the middle and at the end point respectively, and their directions are perpendicular to the crank. The input forces $\mathbf{F_{V3}}$ and $\mathbf{F_{V4}}$ act on the coupler, at the coupler points $\mathbf{A_S}$ and $\mathbf{B_S}$ respectively, and their directions are perpendicular to the lines connected instantaneous pole **P** and coupler point $\mathbf{A_S}$ ($\mathbf{B_S}$). The input forces $\mathbf{F_{V5}}$ and $\mathbf{F_{V6}}$ act on the follower, at the end and at the middle point respectively, and their directions are perpendicular to the follower.

We have analyzed mechanical efficiency and the ratio of the input force and output force for parameters: $\mathbf{a = 66.585mm}$, $\boldsymbol{\varphi_0 = 37.345^o}$, $\mathbf{w_R = 10mm}$, $\mathbf{w_E = 1mm}$, $\mathbf{s_C = 5mm}$. The results have been shown in Table 1.

Variant	$\mathbf{F_C}$ **[N]**	**η [%]**	$\frac{\mathbf{F_S}}{\mathbf{F_C}}$
V1	1	38.2	11.45
	3	60.0	6.83
	5	68.3	5.91
V2	1	40.4	6.20
	3	66.6	3.69
	5	75.4	3.19
V3	1	41.4	6.37
	3	68.3	3.80
	5	78.0	3.28
V4	1	36.0	8.40
	3	59.0	5.02
	5	67.1	4.34
V5	1	35.8	7.74
	3	58.8	4.63
	5	66.4	4.01
V6	1	33.0	14.4
	3	50.9	8.59
	5	54.4	7.44

Table 1. Mechanical efficiency and the ratio of the input force and output force on the Roberts-Чебышев compliant mechanism with notch joints

Mechanical efficiency increases with increasing of the output force $\mathbf{F_C}$ regardless of applied variant (Fig.6). Optimal selection of the input force acting point regarding mechanical efficiency is variant **V3** (the input force $\mathbf{F_{V3}}$ acts at the coupler point $\mathbf{A_S}$).

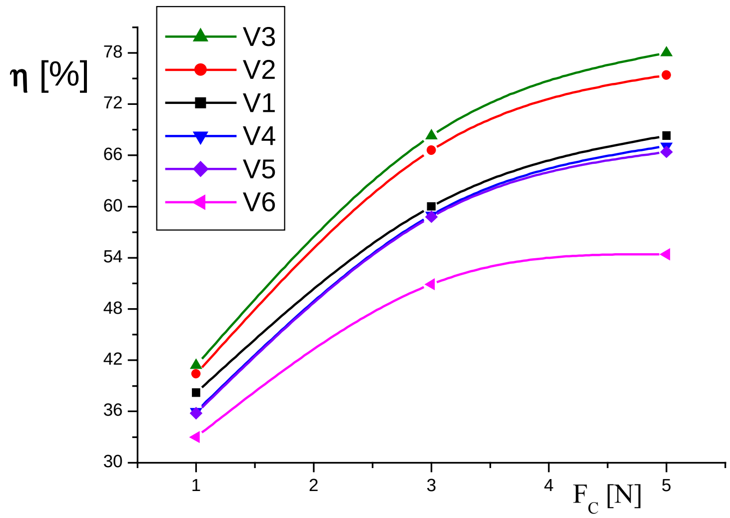


Fig. 6 Mechanical efficiency for different variants of the input force on the Roberts-Чебышев compliant mechanism with notch joints

The ratio of the input force and output force decreases with increasing of the output force $\mathbf{F_C}$ regardless of applied variant (Fig. 7) and it is approximately constant for the values of output force $\mathbf{F_C > 4N}$. Optimal selection of the input force acting point regarding the ratio of the input force and output force is variant **V2** (the input force $\mathbf{F_{V2}}$ acts at the end point of the crank), that is, for any value of the output force $\mathbf{F_C}$, necessary input force to realize a certain displacement of the coupler point would be the smallest for the variant **V2**.

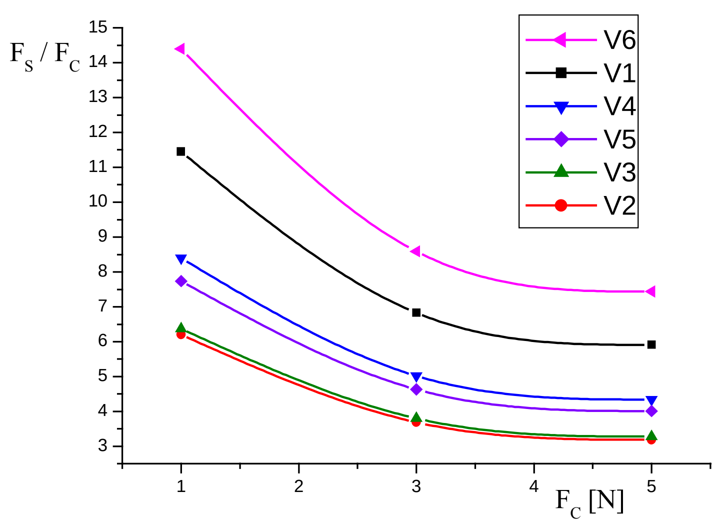


Fig. 7 Ratio of the input force and output force for different variants of the input force on the Roberts-Чебышев compliant mechanism with notch joints

The compliance of the joints and the mobility of the compliant mechanism can be increased by variations of geometry as well as material type of the joints (Fig. 8).

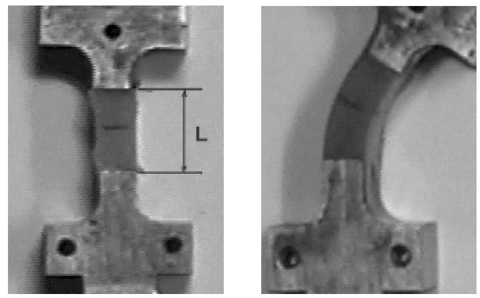


Fig. 8. Laboratory model of compliant silicone joint [6]

Fig. 9 shows the Roberts-Чебышев compliant mechanism with silicone joints. The compliant joints (Fig. 10) have been made of silicone (modulus of elasticity **E_2 = 1.3 N/mm^2**, bending strength **σ_{bs} = 7.9 N/mm^2** [10]), while the links have been made of some other material with greater rigidity (modulus of elasticity **E_1** on Fig.9 and Fig.10).

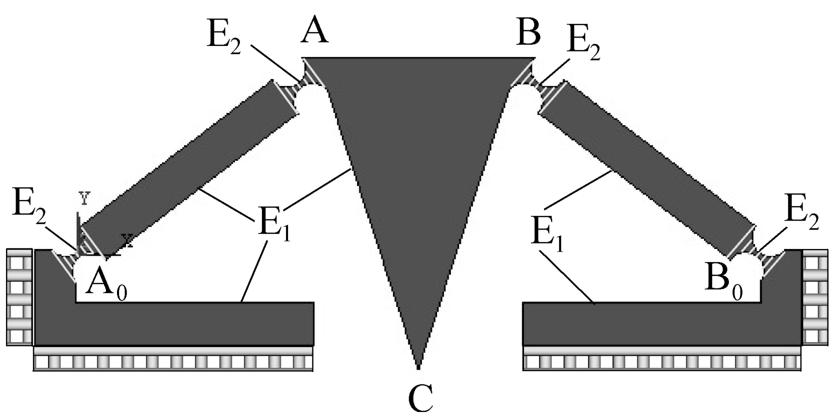


Fig. 9. Roberts-Чебышев compliant mechanism with silicone notch joints

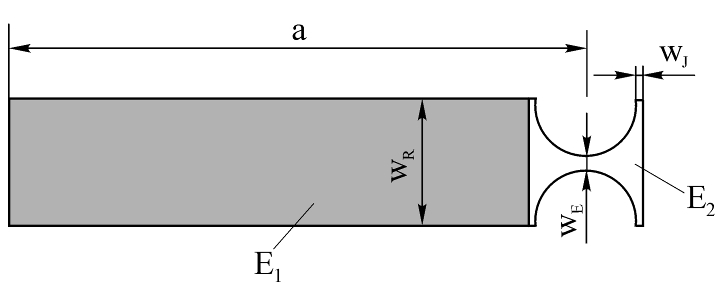


Figure 10. Compliant silicone notch joint

We have analyzed mechanical efficiency and the ratio of the input force and output force for parameters: **a = 66.585mm**, φ_0 **= 37.345°**, w_R **= 10mm**, w_E **= 1mm**, w_J **= 0.5mm**, s_C **= 5mm**, F_C **= 0.001N**, for different variants of the input force acting point and input force direction (**V1...V6** on Fig. 2). The results have been shown in Table 2.

Variant	**η [%]**	$\frac{F_S}{F_C}$
V1	62.9	6.85
V2	65.6	3.63
V3	67.6	3.83
V4	57.6	5.04
V5	57.8	4.66
V6	56.4	8.69

Table 2. Mechanical efficiency and the ratio of the input force and output force on the Roberts-Чебышев compliant mechanism with silicone notch joints

Optimal selection of the input force acting point regarding mechanical efficiency is variant **V3** (the input force F_{V3} acts at the coupler point A_S). The most convenient input force acting point regarding the ratio of the input force and output force is variant **V2** (the input force F_{V2} acts at the end point of the crank).

Both input force acting point variants **V2** and **V3** are more convenient than the other ones regarding the mechanical efficiency, as well as the ratio of the input force and output force, on the compliant mechanisms with plastic, as well as on the compliant mechanisms with silicone joints.

Necessary input forces on the compliant mechanism with silicone joints are considerably smaller than the ones on the compliant mechanism with plastic joints. Therefore we have performed calculation with the value of the output force being in the same range as the input force (F_C **= 0.001N**). Any greater value of the output force (for example F_C **= 0.01N**) would cause large deformation of compliant mechanism with silicone joints and appearing of maximal bending stresses greater than the bending strength.

If we want to compare the mechanical efficiency of the compliant mechanisms with plastic and silicone joints, it could be noticed that the output force F_C **= 0.001N** on the compliant mechanism with **plastic** joints provides extremely low mechanical efficiency ($\eta \approx 10^{-2}$) and extremely high ratio of the input force and output force ($F_S / F_C \approx 10^3$).

4. CONCLUSION

Introducing of compliant joints in the mechanism structure is desirable, because compliant mechanisms have less weight, wear, clearance, friction and noise than their rigid-body counterparts. On the other hand, the mobility of the compliant mechanisms is limited, that is, they can realize relatively small displacements.

In this paper we have analyzed the mechanical efficiency, as well as the ratio of the input force and output force, of the Roberts-Чебышев compliant mechanism for rectilinear guiding. We have analyzed several different variants of the input force acting point and input force direction on the Roberts-Чебышев compliant mechanisms with plastic and silicone notch joints.

The greatest mechanical efficiency of these mechanisms has been provided by the acting of the input force on the coupler at the coupler point $\mathbf{A_S}$, with force direction perpendicular to the line connected instantaneous pole **P** and coupler point $\mathbf{A_S}$.

If input force acts at the end point of the crank, whereas force direction is perpendicular to the crank, necessary input force to realize a certain (horizontal) displacement of the coupler point **C** would be the smallest.

The both conclusions are valid for compliant mechanism with plastic joints (made of one piece of material), as well as for compliant mechanism with silicone joints.

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