Pavlović, Nenad T. ; Pavlović, Nenad D.:

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URN: urn:nbn:de:gbv:ilm1-2012100142-025-4

URL: http://nbn-resolving.de/urn:nbn:de:gbv:ilm1-2012100142-025-4

Erschienen in:

Mechanismentechnik in Ilmenau, Budapest und Niš : Technische Universität Ilmenau, 29. - 31. August 2012. - Ilmenau : Univ.-Verl. Ilmenau, 2012. - S. 25-34.
(Berichte der Ilmenauer Mechanismentechnik ; 1)

ISSN: 2194-9476

ISBN: 978-3-86360-034-1 [Druckausgabe]

URN: urn:nbn:de:gbv:ilm1-2012100142

URL: http://nbn-resolving.de/urn:nbn:de:gbv:ilm1-2012100142

Universitätsverlag Ilmenau, 2012
http://www.tu-ilmenau.de/universitaetsverlag/

MODELLING OF A COMPLIANT SCOTT-RUSSEL MECHANISM WITH SMALL LENGTH FLEXURAL PIVOTS

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Abstract

This paper takes into consideration the Scott-Russel mechanism (the isosceles slider–crank mechanism) and its compliant counterpart mechanism, being developed on the basis of the rigid-body mechanism. Various types of this compliant Scott-Russel mechanism with small length flexural pivots and various geometry parameters of these joints, as well as various rigidity ratios of the relative rigid and relative elastic sections of the mechanism, are researched. The aim of the paper is to suggest optimal parameters, as well as the motion range of this compliant mechanism, in order to obtain the minimal deviation (the minimal difference between the realized path of the "coupler" point and the exact straight line). Finally, the mobility of the developed compliant mechanism, that is, the limit positions of the links determined by the maximal bending stress value, is examined.

Keywords: Scott-Russel mechanism, compliant mechanisms, small length flexural pivots, guiding accuracy, mobility

1. Introduction

Compliant mechanisms gain some or all of their mobility from the relative flexibility of their joints rather than from rigid-body joints only [1]. These mechanisms may be made, for example, from modern-day plastics by an injection moulding process that gives them the desired resiliency and strength. Compliant mechanisms can provide many benefits in the solution of design problems. They are desirable because they have less wear, weight, noise and backlash than their rigid-body counterparts. By reducing the number of required interconnections, the reliability of a design can be improved. The field of compliant mechanisms is expected to continue to grow as materials with superior properties are developed.

Although there are many advantages, the inclusion of compliance provides several challenges in mechanism analysis and design. Nonlinearities introduced by the large deflection of members further complicate the analysis of compliant mechanisms.

There are many papers dealing with the general compliant mechanisms, as well as considering the structure of the compliant slider-crank mechanisms.

The papers [2], [3], [4] deal with rectilinear guiding of a coupler point of the compliant four-bar linkages. The paper [5] introduces some new designs of compliant mechanisms being able to realize translating planar displacement of the link.

The paper [6] introduces a pseudo-rigid-body constant-force slider mechanism, as well as a compliant slider mechanism with three flexural pivots. The paper [7] introduces a general pseudo-rigid-body slider mechanism, as well as a compliant slider mechanism with flexible input crank and coupler. The paper [8] introduces a method of vibration control of a slider-crank mechanism with the flexible connecting-rod. The paper [9] introduces a design of compliant slider-crank mechanism with compliant joints designed as circular arc small length flexural pivots. The paper [10] introduces a new type of partially compliant spatial four-bar mechanism.

The paper [11] introduces a method for determining the limit positions of compliant mechanisms for which an appropriate pseudo-rigid-body model may be created. The paper [12] deals with the mobility of some compliant four-bar linkages.

This paper deals with the modelling, guiding accuracy and mobility of the compliant slider–crank mechanism with rectilinear small length flexural pivots, being developed on the basis of the rigid-body Scott-Russel mechanism (the isosceles slider–crank mechanism).

The aim of the paper is to suggest the optimal parameters, as well as the motion range of the Scott-Russel compliant mechanism, in order to obtain the minimal deviation, that is, the minimal difference between the realized path of the "coupler" point and the exact straight line.

2. Design of a compliant scott-russel mechanism with rectilinear small length flexural pivots

Fig. 4 shows a rigid-body Scott-Russel mechanism (the isosceles slider–crank mechanism: $a = \overline{A_0A} = \overline{AB} = \overline{AC}$). The coupler point C is guided along an exact rectilinear vertical path.

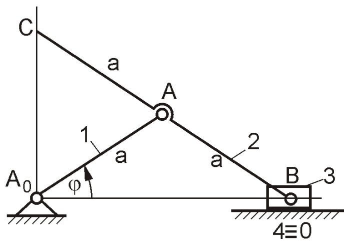


Fig. 4: A rigid-body Scott-Russel mechanism

On the basis of the rigid-body Scott-Russel mechanism, a compliant Scott-Russel mechanism with compliant joints designed as circular arc small length flexural pivots has already been developed [9]. Positions of the revolute joints of the rigid-body counterpart mechanism do not correspond to the positions of the compliant joints, that is, they are located out of the area of the compliant joints (Fig. 3a). It implies that the guiding accuracy (minimal difference between the realized path of the "coupler" point C and the exact straight line) of this compliant mechanism is not satisfying, therefore, there has been a need for designing a compliant Scott-Russel mechanism with different design of flexural pivots being able to produce better guiding accuracy.

Fig. 5 shows a rectilinear small length flexural pivot as a characteristic type of the compliant joint. This compliant joint is fully determined by three parameters: the width of relatively rigid segments w_R, the width of relatively elastic segments w_E and the "length" of the elastic segments l.

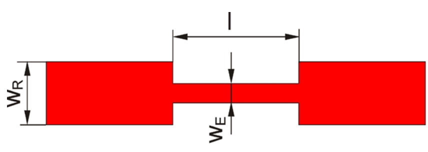
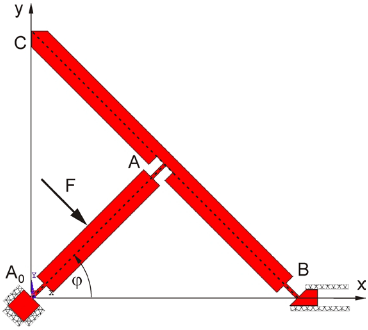


Fig. 5: A rectilinear small length flexural pivot

On the basis of the rigid-body Scott-Russel mechanism, a compliant Scott-Russel mechanism with rectilinear small length flexural pivots was developed (Fig. 6a). The input force F acts in the middle of the "input crank". The deformed and undeformed position of the compliant slider-crank mechanism with rectilinear small length flexural pivots are shown in Fig. 6b).



a)

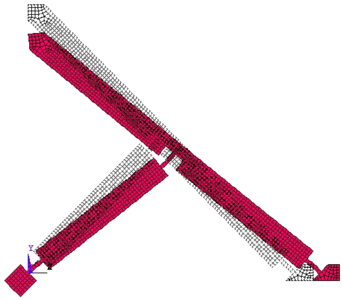

b)

Fig. 6: The compliant Scott-Russel mechanism with rectilinear small length flexural pivots

The characteristic key points of the compliant joint (rectilinear small length flexural pivot) A_0 (Fig. 7) can be calculated by using the set of equations:

$$\vec{r}_1 = \frac{w_E}{2} \cdot e^{i\left(\varphi+\frac{\pi}{2}\right)} \qquad \vec{r}_2 = \frac{w_E}{2} \cdot e^{i\left(\varphi-\frac{\pi}{2}\right)}$$
$$\vec{r}_3 = \frac{w_R}{2} \cdot e^{i\left(\varphi+\frac{\pi}{2}\right)} \qquad \vec{r}_4 = \frac{w_R}{2} \cdot e^{i\left(\varphi-\frac{\pi}{2}\right)}$$
$$\vec{r}_5 = l \cdot e^{i\varphi} + \frac{w_E}{2} \cdot e^{i\left(\varphi+\frac{\pi}{2}\right)} \qquad \vec{r}_6 = l \cdot e^{i\varphi} + \frac{w_E}{2} \cdot e^{i\left(\varphi-\frac{\pi}{2}\right)} \tag{3.1}$$
$$\vec{r}_7 = l \cdot e^{i\varphi} + \frac{w_R}{2} \cdot e^{i\left(\varphi+\frac{\pi}{2}\right)} \qquad \vec{r}_8 = l \cdot e^{i\varphi} + \frac{w_R}{2} \cdot e^{i\left(\varphi-\frac{\pi}{2}\right)}$$

where:

r_i – radius vector defining the position of the characteristic key point in the Cartesian coordinate system,

l – "length" of the compliant joint (rectilinear small length flexural pivot).

In a similar way the characteristic key points of the other compliant joints can be determined.

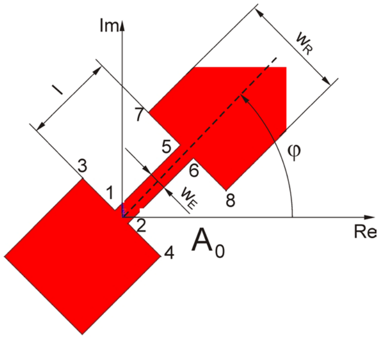


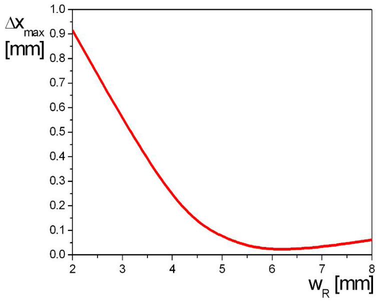
Fig. 7: Characteristic key points of a compliant joint (rectilinear small length flexural pivot)

3. Guiding accuracy of compliant Scott-Russel mechanism with rectilinear small length flexural pivots

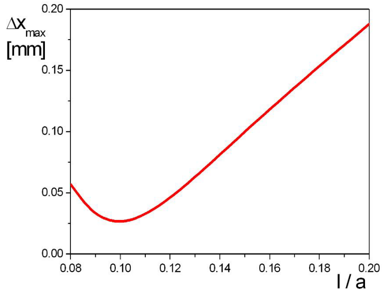
We analyzed a compliant Scott-Russel mechanism with rectilinear small length flexural pivots and determined its optimal dimensions in order to obtain the best guiding accuracy (minimal deviation between exact rectilinear and realized path) of the "coupler" point C on the path segment of $\Delta y_C = 5$ mm.

The position analysis of the mechanism was performed using the ANSYS Software for material piacryl (modulus of elasticity E = 3700 N/mm^2, bending strength σ_{bs} = 90 N/mm^2) and material thickness of δ = 4 mm. The calculation was performed for the elements with a rectangular cross-sectional area using Two-dimensional-eight-node Structural Solid as a characteristic ANSYS element type.

Firstly, we analyzed the influence of the rigidity ratio w_R/w_E, that is, the ratio between the width of relatively rigid segments w_R and the width of relatively elastic segments w_E, on the guiding accuracy. The results are shown in Fig. 8a. The best guiding accuracy (minimal deviation Δx_{max} = 0.0027 mm) was provided by the compliant Scott-Russel mechanism with the rigidity ratio w_R/w_E = 6 (w_R = 6 mm, w_E = 1 mm).



a)



b)

Fig. 8: Maximal horizontal deviation (Δx_{max}) of the "coupler" point C of the compliant Scott-Russel mechanism with rectilinear small length flexural pivots (a = 50 mm, φ = 45^o, w_E = 1 mm)

a) l/a = 0.10, b) w_R = 6 mm

Further, we analyzed the influence of the "length" of the rectilinear small length flexural pivot (l) on the guiding accuracy. The results are shown in Fig. 8b. The best guiding accuracy (minimal deviation Δx_{max} = 0.0027 mm) was provided by the compliant Scott-Russel mechanism with the "length" of the flexural pivot defined by ratio l/a = 0.10.

Finally, we analyzed the influence of the value of the angle of the "input crank" (φ), defining the initial (undeformed) position of the mechanism, on the guiding accuracy. The results are shown in Fig. 9.

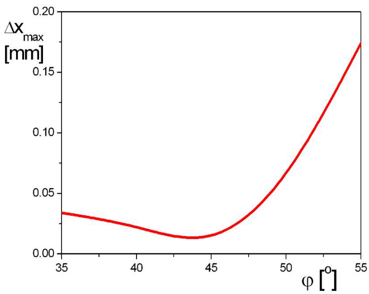


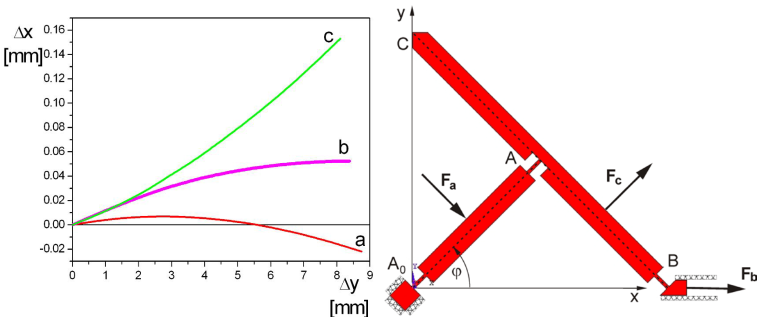
Fig. 9: Maximal horizontal deviation (Δx_{max}) of the "coupler" point C of the compliant Scott-Russel mechanism with rectilinear small length flexural pivots (a = 50 mm, l/a = 0.10, w_R = 6 mm, w_E = 1 mm)

The best guiding accuracy (minimal deviation Δx_{max} = 0.0027 mm) was provided by the compliant Scott-Russel mechanism with the angle of the "input crank" φ = 45^o defining the initial position of the mechanism.

4. Mobility of a compliant Scott-Russel mechanism with rectilinear small length flexural pivots

The compliant mechanisms are moveable due to the flexibility of their elastic segments. However, their mobility is limited. We researched the mobility of a compliant Scott-Russel mechanism using the ANSYS Software. The links were assumed to be made of piacryl with the link lengths and parameters providing the best guiding accuracy ($a = 50$ mm, $\varphi = 45^{o}$, $l / a = 0.10$, $w_R = 6$ mm, $w_E = 1$ mm). The maximal permissible bending stress $\boldsymbol{\sigma_{max} < \sigma_{bs}}$ determines the constraint positions of the links, that is, the limits of their displacement (mobility) and the maximal permissible acting force.

However, the acting point of the input force does not have to be located on the "input crank" of the compliant mechanism. Therefore, the mobilities and guiding accuracies were compared for three different cases of location of input force acting points: in the middle of the "input crank" (a), on the slider (b), in the middle of the coupler without the extension part (c). The results are shown in Fig. 10a. The best guiding accuracy and the great mobility were provided by the input force acting point located in the middle of the "input crank" (graph a). In this case, the maximal realizable displacement of the "coupler" point C was $\Delta y_{max} = 8.75$ mm with the maximal guiding inaccuracy of $\Delta x_{max} = 0.022$ mm. The maximal acting force causing the appearance of the maximal permissible bending stress was $F_{max} = 8.867$ N.



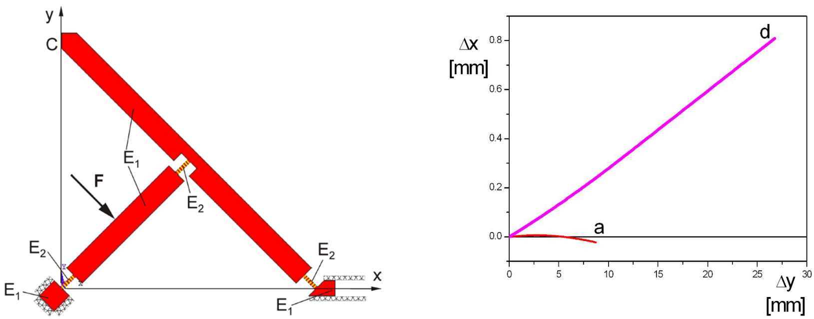
a) b)

Fig. 10: Mobility and guiding accuracy of the compliant Scott-Russel mechanism with rectilinear small length flexural pivots ($a = 50$ mm, $l/a = 0.10$, $w_R = 6$ mm, $w_E = 1$ mm) for three different cases of location of input force acting points

In comparison with the compliant Scott-Russel mechanism with circular arc small length pivots [9], the compliant Scott-Russel mechanism with rectilinear small length flexural pivots can produce better guiding accuracy with smaller mobility.

The compliance of the joints and the mobility of the compliant mechanism can also be increased by alteration of the material type of the joints. If the compliant joints are made of silicone (modulus of elasticity E_2 = 1.3 N/mm^2, bending strength σ_{bs} = 7.9 N/mm^2), while the links of the mechanism are made of some other material with greater rigidity (modulus of elasticity E_1 in the Fig. 11a), maximal permissible bending stresses will be considerably decreased and at the same time the mobility of the entire compliant mechanism will be considerably increased.

The mobility and guiding accuracy graph of the compliant Scott-Russel mechanism with silicone small length flexural pivots is denoted with d in Fig. 11b. In comparison with graph a (the mobility and guiding accuracy graph of the monolithic compliant Scott-Russel mechanism with rectilinear small length flexural pivots), it can be noticed that the mobility is considerably greater, but the guiding accuracy is considerably smaller.



a) b)

Fig. 11: Mobility and guiding accuracy of the compliant Scott-Russel mechanism with silicone small length flexural pivots (a = 50 mm, l/a = 0.10, w_R = 6 mm, w_E = 1 mm)

5. Conclusions

The introduction 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. Another limitation to their use is the fatigue failure at the elastic joints. This paper presents a new design of the compliant Scott-Russel mechanism with rectilinear small length flexural pivots. This compliant mechanism was developed as a counterpart of the rigid-body isosceles slider–crank mechanism.

The influence of the "length" of the rectilinear small length flexural pivots (l), the influence of the rigidity ratio w_R/w_E (the ratio between the width of relatively rigid segments w_R and the width of relatively elastic segments w_E), the influence of initial (undeformed) position of the mechanism (defined by the angle of the "input crank" φ), as well as the influence of the input force acting point location on the guiding accuracy, were analyzed. The optimal dimensions and parameters of the compliant Scott-Russel mechanism with rectilinear small length flexural pivots were determined in order to obtain the best guiding accuracy (minimal deviation between the exact rectilinear and realized path) of the "coupler" point C on the path segment of $\Delta y_C = 5$ mm for the dimension of the mechanism defined by the "input crank" length a = 50 mm. The best guiding accuracy (minimal horizontal deviation $\Delta x_{max} = 0.0027$ mm) was provided by the compliant Scott-Russel mechanism with the angle of the "input crank" $\varphi = 45^o$ defining the initial (undeformed) position of the mechanism, with the rigidity ratio $w_R / w_E = 6$ ($w_R = 6$mm, $w_E = 1$mm), with the "length" of the flexural pivots defined by ratio l / a = 0.1, as well as with the input force acting in the middle of the "input crank".

Furthermore, we analyzed the mobility of the compliant Scott-Russel mechanism for the dimensions and parameters of mechanism providing the best guiding accuracy. The limit positions of the guided "coupler" point, determined by the permissible maximal bending stress, enabled the maximal realizable displacement of the "coupler" point C of $\Delta y_{max} = 8.75$ mm with the guiding inaccuracy of $\Delta x_{max} = 0.022$ mm. The respective maximal acting force causing the appearance of the maximal permissible bending stress was $F_{max} = 8.867$ N. The compliance of the joints and the mobility of the compliant mechanism can also be increased by alteration of the material type of the joints. The mobility of the compliant Scott-Russel mechanism with silicone small length flexural pivots was considerably greater in comparison with the monolithic compliant Scott-Russel mechanism (compliant mechanism being made of one piece of piacryl). However, the guiding accuracy of the compliant Scott-Russel mechanism with silicone small length flexural pivots was considerably smaller in comparison with the monolithic compliant Scott-Russel mechanism.

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