UDC 621.01 DOI: 10.18372/0370-2197.3(84).13852

V. O. KHARZHEVSKYI, M. V. MARCHENKO

Khmelnytskyi National University, Ukraine

KINETOSTATIC ANALYSIS OF LINKAGE MECHANISMS TAKING INTO ACCOUNT THE FRICTION IN KINEMATIC PAIRS

The paper deals with a problem of designing of linkage mechanisms that can be used in various types of machines in different fields of machinery. One of the important parts of mechanisms' design process is carrying out their kinetostatic analysis in order to find forces in the kinematic pairs of mechanisms. But the kinetostatic analysis of linkages is usually performed without friction considerations, so the development of the numerical and analytical methods to carry out the kinetostatic analysis of linkage mechanisms taking into account the friction in the kinematic pairs is an important task that can be solved using a modular approach. In this paper we consider the second-class linkage mechanisms (at the classification of Assur-Artobolevsky), and it is known that there exist 5 types of structural groups of the II class. Since every mechanism of the second class can be divided into several structural groups of certain types, so for every type of the structural group the general analytical dependencies can be written. It can be used to calculate kinematic and kinetostatic characteristics of every links and points of mechanism. It is established that such calculations can be performed with the friction taken into account by means of consecutive approaching method. So, the algorithms of the kinetostatic analysis of the second-class linkage mechanisms with considering the friction in the kinematic pairs and the appropriate software on their basis have been developed. An optimization procedure using different parameters can be also carried out. Some results of carried calculations are given, in particular the kinetostatic analysis of the sample six-link linkage mechanism.

Keywords: *linkage mechanisms, kinetostatic analysis, friction in kinematic pairs, optimization, unified algorithms.*

Introduction. The usage of linkage mechanisms has a number of essential advantages over the other types of mechanisms: the absence of higher kinematic pairs, geometrical closure of the links, the possibility to transfer higher loads with high working velocities of machines etc. As a result, the linkage mechanisms are more reliable and have a number of essential advantages in many cases in comparison to other types of mechanisms, in particular cam mechanisms, gear or Geneva-type mechanisms.

State of the problem. As it is known, the process of creating new mechanisms consists of the following steps [4]: 1) structural synthesis, which defines the structural scheme of the mechanism; 2) kinematic synthesis, which includes the task of determining of the size of the mechanism's scheme to provide the necessary kinematic and dynamic characteristics of the output link; 3) kinematic analysis of the mechanism and its approximate force calculation, which is made taking into account only the load on the output link; 4) preliminary development of the structure, determination of masses, moments of inertia of the links and carrying out a full force calculation of the mechanism (kinetostatic analysis); 5) refined calculation of strength, rigidity, other requirements, followed by refinement of the mechanism design. So, to make the final decision about the dimensions and design of the mechanism, it is necessary to carry out the force calculations in the step 4 as precise as it is possible in order to make correct final decisions in step 5. But the kinetostatic analysis of linkage mechanisms is usually performed without friction considerations [1,3,5], so the development of the numerical and analytical methods to perform the kinetostatic analysis of linkage mechanisms taking into account the friction in the kinematic pairs is an important task. The analytical dependencies for the kinetostatic calculations with friction in kinematic pairs is considered in [2], but it can be used only for the mechanisms with the structural group of the 1st type (RRR Assur group). It is also known, that it is possible to carry out kinetostatic analysis of the mechanisms with the friction considered using CAD systems, but the usage of the proposed unified algorithms enables completing the multiparametric optimization procedures.

Purpose of the paper. The aim of the research that was carried out in the paper is to develop the methods and algorithms of the kinetostatic analysis of the second-class linkage mechanisms (including all possible types of structural groups) with taking into account friction in their kinematic pairs. The task is also to estimate the influence of the friction forces on the results of the kinetostatic analysis.

Main part. The process of analysis of linkage mechanisms (as described in step 3 above) can be divided into 2 parts:

1) Kinematic analysis, which includes calculation of velocities and accelerations of any point or link of mechanism. The appropriate graphs and trajectories of points can be calculated;

2) Kinetostatic analysis, which includes the following: the calculation of reaction forces in kinematic pairs with the inertia and friction forces taken into account; the determination of counterbalancing force or moment; the drawing of hodographs of reaction forces in kinematic pairs, graphs of moments of inertia forces; the drawing of plans of forces for the given position of mechanism.

As it is known, it is convenient to divide the whole process of analysis of linkage mechanisms using the modular principle [1,3-5]: the main idea is to make up the unified algorithms for every type of structural groups. For the mechanisms of the second class, there are 5 types of groups [4,5]. For example, such algorithms (and appropriate software) can be made up using Mathcad, as it is described in [5]. In this paper we shall use such algorithms, but with the friction forces in kinematic pairs taken into account.

The possible procedures of kinetostatic analysis with the friction considered is also described in [4]. The first proposed method is the following: the main equations that are used to calculate reaction forces can be modified in such way that friction forces and moments of friction forces will be taken into account. But in this case, even for the simple structural group of the 1st type (for example, 4-5 group in fig.1), there will be 6 equations of equilibrium that can be composed for both links of the group. But this method significantly complicates the reaction forces definition procedure, so we can consider another method that is also described in [4]. The main idea is to use the consecutive approaching in defining the reaction forces, which is convenient for the practical usage.

So, initially, at first approximation, we define the moments of friction forces as zero values: $M_f = 0.$ So, for example, for the group 4-5 (fig. 1) we should assume that $M_{24}^f = 0, M_{45}^f = 0, M_{50}^f = 0.$ In this case, the task can be solved as ordinary one without the friction forces taken into account and the necessary reaction forces R_{21}, R_{34}, R_{32} can be found. Then, during the second iteration, the values of moments of inertia can be calculated as follows:

$$M_{24}^f = R_{24} f_C r_C; M_{45}^f = M_{54}^f = R_{54} f_D r_D; M_{50}^f = R_{50} f_E r_E, \quad (1)$$

where R_{24}, R_{45}, R_{50} – reaction forces in kinematic pairs *C,D,E*; f_C, f_D, f_E – coefficients of friction in the mechanism's kinematic pairs; r_C, r_D, r_E – radiuses of appropriate pivots. Thus, the values of the reaction forces R_{24}, R_{45}, R_{50} in kinematic pairs can be defined more precisely. So, using (1), we can also define the moments of inertia forces *M* more precisely. During the further iteration, it is possible to refine the values of *R* and continue that process until the difference between the values of *R* in the current and previous iteration become insignificant.

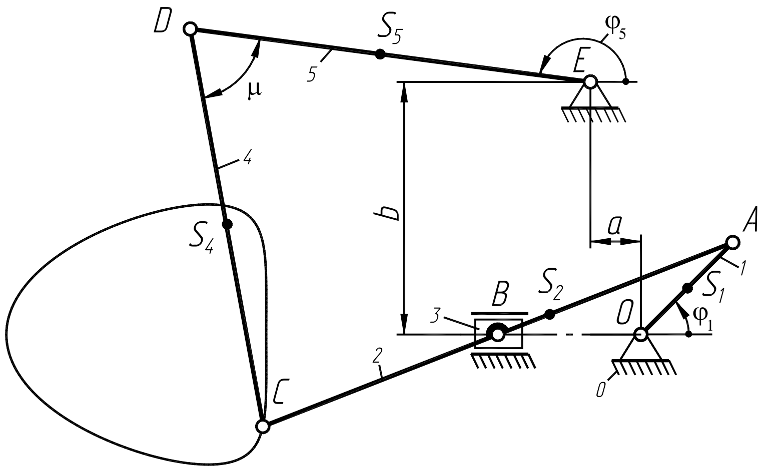

Fig. 1. The sample kinematic scheme of the six-link linkage mechanism

The same procedure can be applied for sliding kinematic pairs. Unlike the rotational ones, in this case it is necessary to consider not the moment of friction force *M*, but the friction force $F_f = fR$, where *R* is the reaction force in appropriate sliding kinematic pair (for example, *B* in the fig. 1).

It is also important to find the values of counterbalancing force F_{cb} with the friction forces in the kinematic pairs taken into account. So, for the defined sizes of mechanisms' links (for example, for the mechanism in the fig.1), it is possible to calculate the reaction forces in the kinematic pairs and counterbalancing force. The samples of received results are shown in the fig.2.

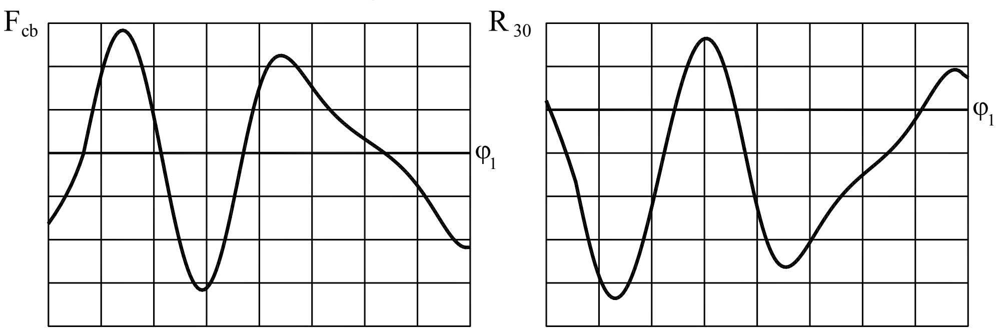

Fig. 2. The samples of the results of kinetostatic analysis of the linkage

For the visualization of the calculated results, it is convenient to build the hodographs of the reaction forces that show not just the value of the found forces, but also their directions (fig. 3).

The mentioned algorithm was extended for all types of structural groups of the second-class mechanisms and the appropriate software was also developed. Thus, the kinetostatic analysis was carried out for the different types of second-class mechanisms, and it was established that the values of reaction forces in rotational kinematic pairs in case of taking into account the friction forces differ insignificantly from ones that were obtained from the calculations without friction considerations. But the opposite situation is with the sliding kinematic pairs: if take into account the friction forces in sliding pairs, the results of calculated reaction force can differ up to 15-20%.

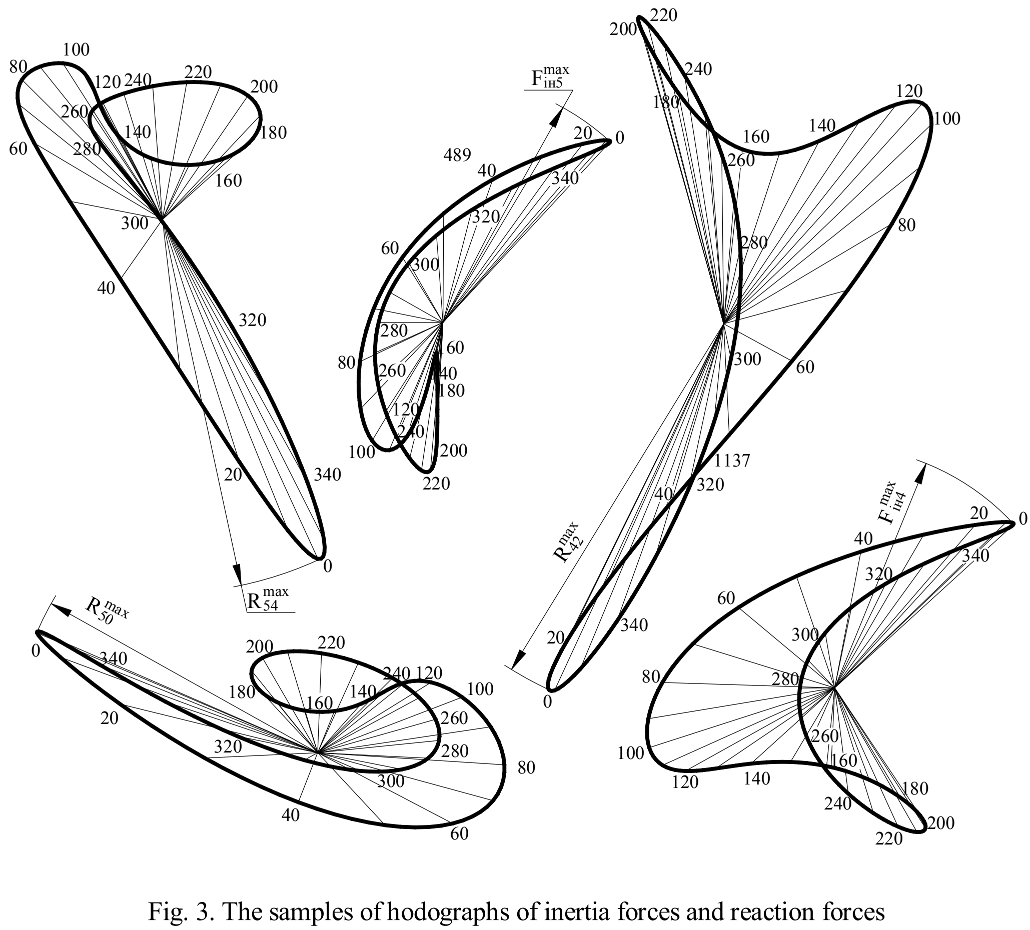

Fig. 3. The samples of hodographs of inertia forces and reaction forces in kinematic pairs with friction took into account

Conclusions. The kinetostatic analysis of the second-class linkage mechanisms is an important part of the mechanisms' design process. So, the developed refined methods of the definition of their kinetostatic characteristics with the friction forces in kinematic pairs are taken into account, can help to carry out their optimal synthesis. The developed software also allows performing optimization procedures using different criteria.

References

1. Belokonev I.M. Theory of Mechanisms and Machines. Methods of automatic designing. Kyiv.:Vyshcha shkola, 1990. – 208 p.

2. Durango S. Analytical method for the kinetostatic analysis of the second-class RRR Assur group allowing for friction in the kinematic pairs / S. Durango, G. Calle, O. Ruiz //Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol.32 no.3, 2010. - P.200-207.

3. Kharzhevskyi V. Unified algorithms of kinetostatic analysis of second-class linkage mechanisms using Mathcad // Study of problems in modern science: new technologies in engineering, advanced management, efficiency of social institutions [collective monograph], University of Technology and Life Sciences in Bydgoszcz, Poland. – 2015. P. 368-379.

4. Kinytskyi Ya.T. Theory of Mechanisms and Machines. – Kyiv.:Naukova Dumka, 2002. – 650 p.

5. Kinytskyi Ya.T., Kharzhevskyi V.O., Marchenko M.V. Theory of Mechanisms and Machines using Mathcad: Textbook. - Khmelnytskyi: RVC KhNU, 2014. – 296 p.

Стаття надійшла до редакції 09.09.2019.

В. О. ХАРЖЕВСЬКИЙ, М. В. МАРЧЕНКО

КІНЕТОСТАТИЧНИЙ АНАЛІЗ ВАЖІЛЬНИХ МЕХАНІЗМІВ З ВРАХУВАННЯМ ТЕРТЯ У КІНЕМАТИЧНИХ ПАРАХ

У наведеній роботі розглядається проблема оптимального проектування важільних механізмів, які можуть використовуватись в різних машинах у різноманітних галузях машинобудування. Використання таких механізмів має ряд суттєвих переваг перед іншими типами механізмів, зокрема: відсутність вищих кінематичних пар, геометричне замикання ланок, можливість передачі більших навантажень та більші роботі швидкості машин. Одним з важливих етапів проектування таких механізмів є проведення їх кінетостатичного аналізу, зокрема, з метою визначення реакцій у кінематичних парах. Проте кінетостатичний аналіз важільних механізмів зазвичай проводять без врахування тертя у кінематичних парах, отже розробка методів кінетостатичного аналізу важільних механізмів з врахуванням сил тертя є важливою задачею, яка може бути розв'язана з використанням погрупного методу дослідження. В даній роботі розглядаються важільні механізми II класу (за класифікацією Ассура-Артоболевського), до складу яких, як відомо, можуть входити структурні групи 5-ти видів. Оскільки для кожного виду структурних груп можна скласти аналітичні залежності, отже можна провести розрахунок як кінематичних, так і кінетостатичних характеристик, використовуючи уніфіковані підпрограми розрахунку. Причому, розроблені алгоритми дозволяють проводити відповідні розрахунки з врахуванням сил тертя у кінематичних парах, використовуючи метод послідовних наближень. На основі зазначених алгоритмів розроблено відповідне програмне забезпечення, яке дозволяє визначати кінетостатичні параметри проектованих механізмів, а також проводити оптимізацію з врахуванням різноманітних критеріїв. В роботі наведено деякі результати проведених розрахунків, зокрема приклади кінетостатичного аналізу шестиланкового механізму.

Ключові слова: важільні механізми, кінетостатичний аналіз, тертя в кінематичних парах, оптимізація, уніфіковані алгоритми.

Харжевський В'ячеслав Олександрович – д-р техн. наук, доцент, професор кафедри галузевого машинобудування та агроінженерії, Хмельницький національний університет, вул. Інститутська, 11, м. Хмельницький, Україна, 29106, тел.: +380673771249, E-mail: vk.solidworks@gmail.com

Марченко Максим Васильович – канд. техн. наук, доцент, доцент кафедри галузевого машинобудування та агроінженерії, Хмельницький національний університет, вул. Інститутська, 11, м. Хмельницький, Україна, 29106, тел.: +380987282277, E-mail: max@solidworks.net.ua.