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SIMULATION OF KINEMATIC PAIRS IN THE CALCULATION MANIPULATORS BY FINITE ELEMENT METHOD

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1 Introduction.

One of the methods for calculating manipulators of constructions lever mechanisms (LM) is the finite element method (FEM). Here is given the original approach, which allows the use of the finite element method for the analysis of stiffness and strength LM with kinematic pairs with arbitrary orientation in space. The idea of the proposed method is that the basic equilibrium equation solved by the method rigid of nodes in local coordinate systems. The basic algorithm FEM is not changed.

2 Types of rod constructions considered in FEM

Flat LM have kinematic pairs with mutually parallel axes, so their calculation on the stiffness and strength of FEM can be applied [1-6]. For spatial LM - orientation kinematic pairs is arbitrary. Let as consider the problem of accounting for such kinematic pairs in the calculation FEM - given the lack connections between some elements of kinematic pairs. As is well known in the rotational pair - the reaction torque is zero and of the slider - is zero reaction from its direction of motion. To account for the missing component, i.e. in order to equate it to zero, it is necessary to consider the equilibrium equation containing these components of the reaction. Obviously, such equations are the equations of equilibrium in the projections on the axis kinematic pairs. But in the FEM basic system of equations is composed of the equilibrium equations of nodes in projections on the axes of the global coordinate system (GCS). Hence, GCS should be chosen so that its axis is parallel to the kinematic axis. But, GCS can not simultaneously be all parallel to the axes of the kinematic pairs of a spatial mechanism.

Here we propose a method that allows to use the FEM for the analysis of any kinds of spatial LM with arbitrarily oriented kinematic pairs. The basic ideas and scheme of FEM realization in this case practically do not change. To make the missing components equate to zero it is necessary to consider the vectors of reactions to the balance equation of kinematic pairs in projections onto axis containing these components. To get these equations into each kinematic pair introduce local coordinate system (LCS) in such a way that the axis of kinematic pair and LCS axis coincide [7]. Then the equilibrium equation kinematic pair to the LCS this kinematic pair will include zero components of reactions. For example, if the hinge axis or the axis of the slide – is not parallel to the axis of the GCS, the equilibrium equation kinematic pairs in the projection on the axis GCS does not contain zero reaction components. Consequently, the possibility of accounting the absence of these reaction components is lost. Therefore, the FEM can always be used for flat LM since all kinematic pairs parallel to the some axis of GCS.

3 Simulation of kinematic pairs. Method of hard nodes

For the modeling of kinematic pairs it is used a method that was developed by the author [7]. It is called the method of hard nodes - by analogy with [8]. In general, if the kinematic pair are connected "n" the groups of rods ($n \geq 1$). Each group consists of $k_i \geq 1$, $i = 1,...,n$; rigidly connected rods. And for each degree of freedom, these groups have their own kinematic and force parameters. Then any kinematic pair is a combination of hard knots in one coordinate point and having "K" common degrees of freedom ("K"

- class kinematic pairs). In other words, the kinematic pair is modeled not as a whole, as it is usually modeled in the FEM for rod constructions, but as each element of the kinematic pair. Let as consider an arbitrary spatial kinematic pair. Total number of degrees of freedom of its constituent units is equal to the number of connections "K" imposed on it. That is the class of kinematic pair. Consider kinematic pairs for which $3 \le K \le 5$. Let us find degree of freedom W (in terms of FEM) kinematic pairs consisting of k hard nodes. Obviously, this is the sum of common degrees of freedom and the additional degrees of freedom of nodes: $W = K + k(6-K)$. Number **N** of degrees of freedom of the LM model are: $N = 6n_{Ж} + \sum_{i=1}^{n_{Ш}}(K_i + k_i(6-K_i)) - n_{Г}$, where $n_{Ж}$ - the number of hard nodes without kinematic pairs (single nodes); $n_{Ш}$ - the number of kinematic pairs; $n_{Г}$ - the number of degrees of freedom of the boundary conditions; $k_i \, (i = 1,...,n_{Ш})$ - number of hard nodes included in the $i-$th kinetic pair; $K_i \, (i = 1,...,n_{Ш})$ - $i-$the grade kinematic pair.

Thus, in compiling the finite element model LM any $i-$the kinematic pair represents a combination k_i hard knots. It is located in one coordinate point and has K_i common of degrees of freedom (class of kinematic pair). Method of hard nodes has the following advantages over the known method of accounting in the kinematic pairs FEM [10]:

) Possibility of accounting of complicated hinge connections, for which have can not be applied the traditional methods of modeling. For example, the hinge between two or more base triangles;

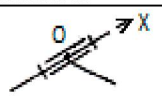
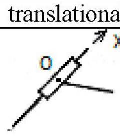
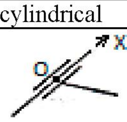
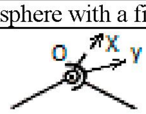
) No need to transform the stiffness matrices of elements kinematically connected elements before building a global SMS;

) Introduction to the number of unknowns of the problem is linearly dependent displacement components of the kinematic pair.

4 Simulation of kinematic pairs. Types of kinematic pairs

Consider the scheme LM in some position. Position of the axis kinematic pairs with respect to GSC OXYZ is known through corners α, β, γ between the kinematic axis and the axes OX, OY, OZ, respectively. Number of the kinematic axes depends on type of a kinematic pair. Translational, rotational and cylindrical couples have only one axis "S", which coincides with the direction of the translational motion or rotation axis. Spherical hinge with a finger has two axes "S_1" and "S_2". One coincides with the axis of the finger and the other - with the line extending perpendicularly the slit of a finger. For each kinematic pair LM is necessary to build LCS Oxyz. LSC single (non-paired) nodes and nodes spherical pair can be selected in parallel GSC OXYZ because of an arbitrary orientation of degrees of freedom of these nodes. For pairs class IV and V with one axis "S", the local axis Ox will direct along the axis "S". Axis Oy, Oz is obtained from the condition that the triple Oxyz was right. For a spherical pair with a finger we will direct the Ox-axis along the axis of the finger S_1, and the Oy-axis along the axis S_2 extending perpendicularly the slit of a finger. Then the direction the axis Oz is uniquely determined. Obviously, each pair is having a single common LSC. Information about the arrangement LSC of nodes relative to GSC is obtained by using matrix of direction cosines. For kinematic pair also we give degrees of freedom. That is for a pair you must specify the information - which are the degree of freedom nodes are common, and what - kinematic. Table 1 shows the types of kinematic pairs used in the LM. There are shown the orientation in space on their LCS, and also are shown the components of the reactions which are absent.

Table 1 - Types of kinematic pairs

pair	rotational	translational	cylindrical	sphere with a finger
unit designation zero efforts	 $M_x = 0$	 $N_x = 0$	 $N_x = 0$, $M_x = 0$	 $M_x = 0$, $M_y = 0$
LCS	ox – along the axis of rotation	ox – along the direction of the slide	ox – along the axis of rotation	ox – along the finger axis, oy – $\perp$ slits

There was a software developed on the basis of a computer program STAP [7]. In this program there was modified on input array ID, which is now formed as follows:

- If for j-th degree of freedom (j = 1, ..., 6) i-node imposed boundary condition, then ID(i,j)=-1
- If for the j-th degree of freedom of movement is possible, the ID (i, j) = 0.
- If the nodes $i_1, i_2, ..., i_k$ creates single kinematic pair, then:

is selected $l = \min\{i_1, i_2, ..., i_k\}$, (1)

$ID(l, j) = 0, \quad \forall j$, (2)

$ID(i_1, j) = ID(i_2, j) = ... = ID(i_k, j) = l$, if j - common degree of freedom of the pair,

$ID(i_1, j) = ID(i_2, j) = ... = ID(i_k, j) = 0$, if j – the kinematic degrees of freedom.

That is, total j-th degree of freedom of the nodes belonging to the same kinematic pair, is described in the ID array one zero in the j-th column and in a row, which corresponds to a node of the pair with the minimum number l. For the rest of nodes kinematic pair in the j-th column is stored number l. Number l shows that these nodes constitute a kinematic pair with the l-st node. Each row of the matrix ID is given in the LCS corresponding node. That is, the elements of the i-th row describe the degree of freedom of the l-st node in its LCS. Then when counting the number of global degrees of freedom and their the numbering:

- "0" in the ID array successively replaced by the global degrees of freedom;
- "-1" is replaced with "0";
- and each of an integer $l > 0$ in the j-th column is replaced by the ID(l,j), that is the global number of j-th degree of freedom of i-th node already previously determined from (1,2). This procedure is simple and can be written in the form:

1) Assign the N = 1.
2) In the cycle for i = 1, ... n, and j = 1, .. 6:
   1)) if ID (i, j) <O, then assign the ID (i, j) = O;
   2)) if ID (i, j) = O, then assign the ID (i, j) = N;
   3)) if ID (i, j)> O, then assign the ID (i, j) = ID (ID (i, j), j);
   4)) assigned to N = N + 1.

Thus, the type and class of a kinematic pair specified using ID. Suppose, for example, nodes i and j constitute any kinematic pair and i <j. Then the the i-th row of the array ID will be: $[\,0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0\,]$. Row “j” is dependent on the type and class of the kinematic pair. We show a string array ID, corresponding to the j-th node:

1. For the rotational pair (Class 5): $[\,i \;\; i \;\; i \;\; 0 \;\; i \;\; i\,]$, the 4th degree of freedom, ie, rotation around the axis Ox LCS pair is the kinematic; and the remaining five degrees of freedom - common to i-th node.

2. For translational pair (Class 5): $[\,0 \;\; i \;\; i \;\; i \;\; i \;\; i\,]$, 1st degree of freedom, ie, translational motion along Ox LCS pair is the kinematic; and the remaining five degrees of freedom - common to i-th node.

3. For a cylindrical pair (Grade 4): $[\,0 \;\; i \;\; i \;\; 0 \;\; i \;\; i\,]$, kinematic are 1st degree of freedom, ie, translational motion along Ox LCS pair and kinematic are 4th degree of freedom, ie, rotation around the axis Ox LCS pair; while the remaining four degrees of freedom - common to i-th node.

4. For a spherical pair with a finger (Grade 4): $[\,i \;\; i \;\; i \;\; 0 \;\; 0 \;\; i\,]$, kinematic are 4th and 5th degrees of freedom, ie, rotation around the axes Ox and Oy LCS pair; while the remaining four degrees of freedom - common to i-node.

5. For a spherical pair (Grade 3): $[\,i \;\; i \;\; i \;\; 0 \;\; 0 \;\; 0\,]$, the kinematic are 4th, 5th and 6th degree of freedom, ie, rotation around the axes Ox, Oy and Oz LCS pair; remaining 3 - common to i-th node.

5 Conclusion

The paper gives a simulation methodology that allows the use of finite element method to analyze the stiffness and strength of manipulators with kinematic pairs of an arbitrary orientation in space. The solution of the basic equation of equilibrium finite element method proposed to be considered in the local coordinate system nodes. It is shown the use of this simulation method with different spatial kinematic pairs.

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Моделирование кинематических пар в расчете манипуляторов по методу конечных элементов

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Ключевые слова: моделирование, манипулятор, механизм, кинематическая пара, метод конечных элементов

Аннотация. Объектом исследования являются манипуляторы на базе рычажных механизмов. Целью работы является изложение методики расчета на жесткость, сущность которой заключается в следующем. Как известно, один из самых распространенных методов расчета на прочность и жесткость манипуляторов является метод конечных элементов (МКЭ). В этой работе дается подход, который позволяет использовать МКЭ для анализа жесткости и прочности манипуляторов с кинематическими парами произвольной ориентации в пространстве. Решение основного уравнения равновесия метода конечных элементов при этом рассматривается в локальных системах координат узлов. Показано применение предлагаемого подхода для моделей с различными пространственными кинематическими парами: вращательными, поступательными, цилиндрическими, сферическими, сферическими с пальцем. При этом используется разработанный ранее авторами метод жестких узлов. Также для численной реализации разработана компьютерная программа. В отличие от прототипа, эта программа имеет некоторые изменения, в том числе входной массив ID, позволяющий в одной точке размещать несколько конечных элементов, имеющих общие связи.

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АЭӘ ПАЙДАЛАНЫП МАНИПУЛЯТОРЛАРДЫ ЕСЕПТЕУДЕ КИНЕМАТИКАЛЫҚ ПАРЛАРДЫ МОДЕЛЬДЕУ

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Зерттеу объектісі иінтіректі механизмдер базасында манипуляторларды зерттеу болып табылады. Жұмыс мақсаты қатаңдыққа есептеудің әдісін көрсету болып табылады. Белгілі жағдай бойынша манипуляторлардың қатаңдыққа және беріктікке есептеу әдісінің кең тараған түрі болып ақырлы элементтер әдісі (АЭӘ) алынады. Кеңістікте ерікті бағдарлы кинематикалық паралы манипуляторларды қатаңдыққа және беріктікке талдау үшін АЭӘ пайдаланады. Беріліп отырған әдістеменің идеясы, тепе-теңдік теңдеуінің негізі парларының жалпыланған координаталар жүйесінің қатаң түйіндерінің әдісімен шешіледі. Кеңістіктегі кинематикалық парлардың әр түрлі: айналмалы, ілгерілемелі, цилиндрлі, сфералы, саусақты сфералы үлгілері үшін қадамдар көрсетілген. Сонымен бірге автордың алдын-ала жасалған қатаң түйіндер әдісі қолданылған. Сандық пайдалану үшін компьютерлік бағдарлама жасалған. Бұл бағдарламаның прототиптен өзгешелігі, бір нүктеге бірнеше ақырлы элементтер сыйысатын ID кіру массивінде ортақ байланыстар бар.

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