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New Results of an Analytical Study of Self-Aligning Articulated Hinge-Lever Pendulum Mechanisms

R. Nauryzbaev [1], M. Nabiollina [2,*], M. Toilybayev [1], K. Sansyzbayev [1], Y. Zhaparkulova[2] and K. Kaliyeva[2]

[1]*Department of IT technologies, automation and mechanization of the agro-industrial complex, Kazakh National Agrarian University, Kazakhstan*
[2]*Department of water, land and forest resources and resources, Kazakh National Agrarian University, Kazakhstan*

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Abstract

The equation of motion of the mechanism with (n+n1) moving links, the equation of motion of the drive link is obtained. An exact analytical solution of a nonlinear differential equation is found. Based on the formula of the modern theory of mechanisms, a mathematical model of the structures of the self-aligning mechanism of the physical pendulum is determined. The parameters and the main operating modes of rational design, and the regular design of the pendulum-type mechanism are established. An innovative (unified) method of analytical research of the main object has been created. Based on this research method, structural geometric, kinematic general models of self-aligning flat two-link, three-link, four-link, five-link articulated lever mechanisms of the physical pendulum have been developed. The oscillations of the leading link of the physical pendulum mechanism are investigated based on their specific mathematical models. A flat, complex, closed kinematic chain of six (n+n1) = six moving links and two closed loops (A and B) is investigated separately. A structural, geometric, kinematic general model of a self-adjusting, flat, six-linked hinged-lever physical pendulum mechanism is developed and a non-linear differential equation of motion is derived. The parameters and basic modes of operation of rational design and regular design are established. A comprehensive, unified and consistent method of research of a self-aligned, six-linked flat articulated lever mechanism of the physical pendulum II second class, third family from structure to dynamic synthesis is established.

Keywords: Pendulum Mechanisms, Swing Mode, Physical Pendulum, Single-Mass Dynamic Model, Degrees of Freedom

1. Introduction

In future use in the drive construction of working elements of agricultural and other branches of production of self-aligning hinged-lever mechanisms of the physical pendulum are of great practical importance in improving the technical level and operational qualities of various branches of modern engineering. They have a sufficiently large load capacity, durability, high efficiency and lower requirements to accuracy of manufacture [1].

The idea of building self-aligning mechanisms has an age-long history. Initially, this idea was laid in the scientific works of the founders of machine mechanics and is associated with the names of Ch

ebyshev, Relo, Mora, Levi, Sylvestre, Burmester, Grubler, Somov, Gokhman, and others. The pioneering idea of building self-installing mechanisms was essentially turned into a coherent scientific structural theory in the works of the classics on the theory of mechanisms and machines [2]. The results of the fundamental classical studies in the field of the theory of the structure of mechanisms are associated with the names of Malyshev, Dobrovolskiy, Assur, Artobolevskiy, Baranov, Kozhevnikov, Kolchin, Ozol, Frolov, Dzholdasbekov, Dvornikov, Reshetov and others.

Various aspects of the fundamental classical theory of the structure of mechanisms continue to improve and develop in the scientific works of the greatest specialists in the theory of mechanisms and machines Kazykhanov, Dzhomartov and others, as well as their numerous students in our time, Nauryzbaev, Isakov, Kazykhanov and others [2, 3, 5]. The urgency of the problem of the development of an idea, the creation, implementation of self-aligning hinge-lever mechanisms is undoubtedly now, because their need for various branches of engineering is very high. The introduction of self-aligning hinged-lever mechanisms of the pendulum construction in the practice of engineering allows getting multiple winnings [5, 7, 25-27].

Objective is to develop a structural, geometric, kinematic general model of a self-aligning flat, two-link, three-link, four-link, five-link, six-link *articulation linkage of the physical pendulum*. Determine their dynamic model. Investigate the oscillations of the guide link of the mechanism driving based on their mathematical models.

2. Method

From the standpoint of the fundamental - the classic "Theoretical Mechanics":

- ***A mechanism*** is a mechanical system of solids designed to transform the movement of one or several solids into the required movement of other bodies [1, 2, 3].
- ***The pendulum*** is a solid, i.e., *a rod* that oscillates near a fixed point or axis under the action of applied forces [5-7, 12, 17].

*E-mail address: nabiollina_m@rambler.ru
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The self-mounting pendulum design mechanisms are statically determinable mechanisms, i.e., *mechanisms without redundant connections*. In general, the number of degrees of freedom of a self-aligning kinematic chain of a mechanism is determined by the formula [6, 7, 8, 9, 10, 11, 18]:

$$W = m\cdot (n + n_1 + n_2 - 1) - \sum_{k=1}^{k=m-1}(m-k)\cdot P_k \quad (1)$$

For the construction of the third family chains by systematization of academician Artobolevskiy in the formula (1) must be taken $\boldsymbol{m = 3}$.

The investigated mechanism of the simplest construction (Fig. 1), two-tier, self-installing, is devoid of redundant links, does not have excess degrees of freedom:

$$W = 3 \cdot n_1 - 2p_1 = 3 \cdot 1 - 2 \cdot 1 = 1 \quad (2)$$

The basis of the mechanism structure is a single-link, unlocked, simple kinematic chain with $\boldsymbol{W=1}$, it (n_1) joins rack 2 without changing the number of degrees of freedom.

In the scientific and theoretical courses of the theory of mechanisms and machine mechanics is known as the mechanism of the physical pendulum, the Froud pendulum, the swing mechanism, the mechanism of the first class, etc.

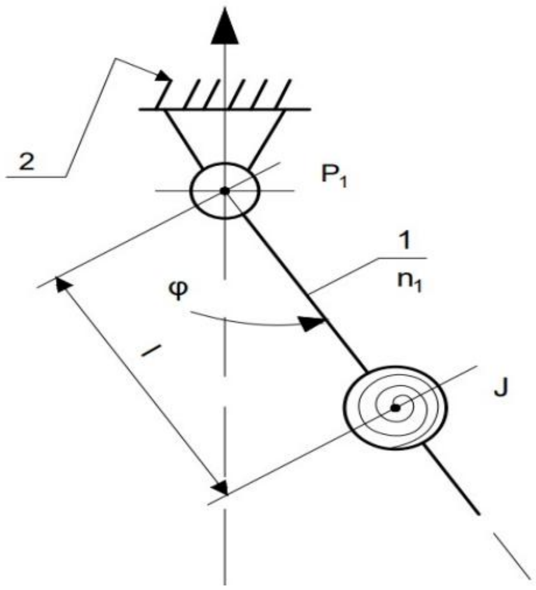

Fig. 1. The flat lever mechanism of the physical pendulum.

The equation of motion of the physical pendulum mechanism has the form of a record:

$$J \cdot \phi + m \cdot g \cdot l \cdot sin\,\phi = 0 \quad (3)$$

where J – moment of inertia of the mechanism of the physical pendulum relative to the axis of rotation (pin joint –P_1), [kg·м^2]; $\ddot{\varphi}$ – link acceleration (n_1) relative to link pin (P_1), [1/sec.^{2}].

Then the moment created by inertia forces is:

$$M_H = J \cdot \phi, [H \cdot M]. \quad (4)$$

m – rotating link mass (n_1) of physical pendulum mechanism, [kg];
g – intensity of gravity (g = 9,81 m/sec.^{2})

Then the gravity of the link of the mechanism of the physical pendulum is equal to the formula of the following form: Then the gravity of the link (n_1) of the mechanism of the physical pendulum is equal to the formula of the following form:

$$P = m \cdot g, [H]. \quad (5)$$

l – distance from the center of gravity to the axis of rotation of the link (n_1), [m];
φ– the generalized coordinate of the leading link of the physical pendulum mechanism. [rad.]

Round

$$\omega^2 = \frac{m\cdot g\cdot l}{J}, [1/sec^2]. \quad (6)$$

We obtain the equation of the form:

$$\ddot{\varphi} \cdot \omega^2 \cdot sin\varphi = 0 \quad (7)$$

Differential equation (7) has an exact analytical solution. [1, 2, 3, 19, 21, 22, 23, 24].

The oscillation period of the link (n_1) corresponding to the change in the angle φ by 2π is equal to the form:

$$\phi \cdot t = 4 \cdot \omega \cdot K_{(q)} \quad (8)$$

where $K(q) = F[\frac{\pi}{2}, q]$ – is called a complete elliptic integral of the first kind, and the quantity **q** is its module ($0<q<1$). The numerical value of the complete elliptic integral of the first kind is determined according to a given module by the tables of elliptic integrals.

With the values of the modulus of a complete elliptic integral of the first kind q^2= 1, the mechanism of the physical pendulum *has not yet been converted into rotational motion* (As shown in Fig. 2).

With the values of the modulus of a complete elliptic integral of the first kind q^2= 0, the link (n_1) the mechanism of the physical pendulum (As shown in Fig. 1) rotates uniformly (As shown in Fig. 2).

We write (8) taking into account the formula (6) and then we get an expression of the following form:

$$\phi_0 \rightleftarrows \cdot t = 4 \cdot \sqrt{\frac{m\cdot g\cdot l}{J}} \cdot F \rightleftarrows [\frac{\pi}{2} \cdot q] \quad (9)$$

The third mode of operation of the physical pendulum mechanism shows the uneven rotation of the leading link (n_1). In this formulation of the problem, the perturbation in the system is purely inertial (As shown in Figure 2).

The value of the critical angular velocity of the mechanism of the physical pendulum is determined by the formula of the form:

$$\omega_k = \frac{\sqrt{m\cdot g}}{J}, [1/sec.] \quad (10)$$

If the initial value of the angular velocity (ω_0) of the link (n_1) the mechanism of the physical pendulum (As shown in Fig. 1) is smaller $\omega_к$

$$\phi_0 < \omega_K \quad (11)$$

then the link (n_1) makes periodic oscillations. The mechanism of the physical pendulum operates in an oscillatory mode - *in the swing mode*. If the initial value of the angular velocity (ω_0) of the link (n_1) the mechanism of the physical pendulum is greater than (ω_K), i.e.

$$\phi_0 > \omega_K \quad (12)$$

then the free motion of the link (n_1) the mechanism of the physical pendulum is of a *rotational nature*, with a period of change in angular velocity according to the formula of the following form:

$$\mathrm{T} = \frac{4 \cdot \mathrm{K}_{(q)}}{\phi_0} \quad (13)$$

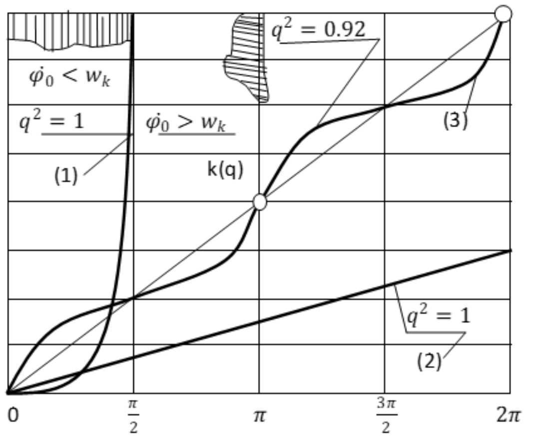

Fig. 2. Oscillations of the leading link of the mechanism of the physical pendulum with three values of the modulus ***q***.

The degree of uniformity of rotation of the leading link (n_1) the mechanism of the physical pendulum depends on the modulus (q) of the complete elliptic integral of the first kind F [$\frac{\pi}{2}$ q], the higher the larger the modulus value.

If the initial value of the angular velocity (φ_0) of the link (n_1) mechanism of the form: φ_0>> 2ω$_\text{k}$, then for small values of the modulus (q) of the complete elliptic integral of the first kind F [$\frac{\pi}{2}$ q] we have:

$$K = \frac{\pi}{2}\left(1 + \frac{1}{4}q^2 + \cdots.\right) = \frac{\pi}{2}\left(1 + \frac{\omega^2}{\phi_0^2} + \cdots..\right), \quad (14)$$

and the formula for the period of change in the angular velocity of the leading link (n_1) the mechanism of the physical pendulum will have the following form:

$$T_1 = \frac{2\pi}{\phi_0}\left(1 + \frac{\omega^2}{\phi_0^2}\right), [sec] \quad (15)$$

Taking into account the dependence (6) we have:

$$T_1 = \frac{2\pi}{\phi_0}\left(1 + \frac{m \cdot g \cdot l}{J \cdot \phi_0^2}\right), [sec] \quad (16)$$

Thus, the position or state of the oscillating link (n_1) the mechanism of the physical pendulum (Fig. 1) is determined by the generalized coordinate - (φ).

The inverse of the oscillation period (T) is called the oscillation frequency (f) and is equal to the number of oscillations per second:

$$f = \frac{1}{T}, \ [1/sec] = 1hz. \quad (17)$$

The circular frequency is the number of oscillations in 2π seconds:

$$\omega_c = 2\pi \cdot f = \frac{2\pi}{T}, \text{[1/sec]=[rad/sec]} \quad (18)$$

Taking into account (18), formulas (16), we write the circular frequency of oscillation of the leading link (n_1) the mechanism of the physical pendulum in the form of a record:

$$\omega_c = \phi_0^2 \cdot \left(1 + \frac{\phi_0^2 \cdot J}{m \cdot g \cdot l}\right), [rad/\,sec] \quad (19)$$

By the formula (19), the circular frequency of the natural (free) oscillations of the physical pendulum mechanism is calculated in the mode of non-uniform rotation of the leading link (n_1). The time during which one complete oscillation takes place is called the period (***T***), the parameters: ω_c and ***T*** - do not depend on the initial conditions and are constant characteristics of the oscillating system.

Equation (7) is *non-linear* if limited to small angles of deflection of the leading link (n_1) the mechanism of the physical pendulum φ << 1, then it can be simplified. In this case, equation (7) becomes linear:

$$\ddot{\varphi} + \omega^2 \cdot \varphi = 0 \quad (20)$$

Own oscillations are movements made by an oscillating system, which, after a brief external perturbation, is represented by itself. When this occurs, periodic transitions of one type of energy to another i.e., potential energy (determined by the position of the system) and vice versa.

If the sum of these energies in the process of oscillation is conserved, then the oscillations will be undamped (continuous) and the system in this case is called *conservative*.

If the energy of the system decreases (for example, due to the presence of friction), then damped (continuous) oscillations occur and the system is called *non-conservative*.

The circular frequency of natural oscillations of the driving link (n_1) the mechanism of the physical pendulum in the swing mode is equal to:

$$\omega_c = \omega = \sqrt{\frac{m \cdot g \cdot l}{\mathrm{J}}}, \ [rad/sec] \quad (21)$$

The free period of the leading link (n_1) the mechanism of the physical pendulum in the swing mode is equal to:

$$T = \frac{2\pi}{\omega_c} = 2\pi \cdot \sqrt{\frac{J}{m \cdot g \cdot l}} \ [sec], \quad (22)$$

With the parameter values: π = 3,14; g = 9.81 m/sec^2 it could be considered

$$J = m \cdot \frac{l^2}{3}, [kg \cdot M^2] \quad (22a)$$

Multiply the linear differential equation (20) by ($\dot{x}$) and integrate:

$$\ddot{x} \cdot x + \omega^2 x \cdot \dot{x} = \frac{d}{dt}\left(\frac{\dot{x}^2}{2}\right) + \omega^2 \frac{d}{dt}\left(\frac{x^2}{2}\right) = 0, \quad (23)$$

or

$$\dot{x}^2 + \omega^2 \cdot x^2 = const. \tag{24}$$

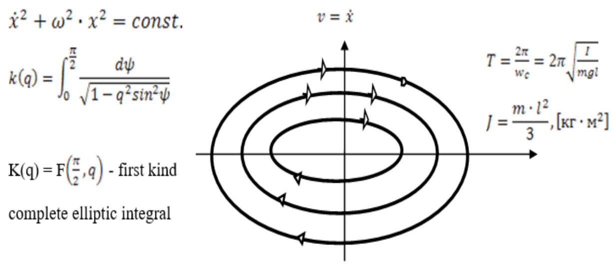

Fig. 3. Phase portrait of oscillations with a point of the center type of the leading link of the physical pendulum mechanism

3. Results and discussions

The resulting equation (24) is a phase trajectory equation, i.e., establishes a connection between
x and $\dot{x}$.

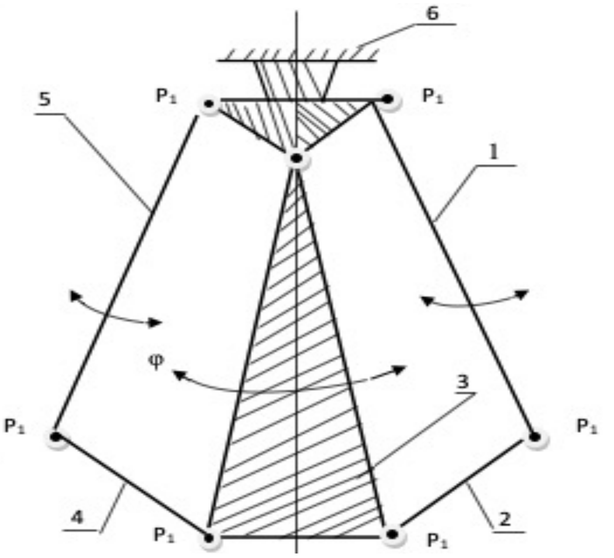

Fig. 4. Self-mounted flat, six-link articulated - lever mechanism of the physical pendulum. Structural, geometric, kinematic general model of the mechanism. ***1*** - The yoke - a rotating link mechanism, which can only make not a full rotation around a fixed axis.Two-shaft mechanism - a mechanism that consists of two rockers - ***1*** and ***5***. ***2*** and ***4*** - Rod - link lever mechanism, formed by kinematic pairs only with moving links. ***3*** - The pendulum is a link of the mechanism oscillating around a fixed point or axis. Lead link. ***6*** - Rack - link mechanism, taken as fixed. The link mechanism is a mechanism whose links form only rotational kinematic pairs - P1. A lever mechanism is a mechanism whose links form only rotational, translational, cylindrical, and spherical pairs.

The structural formulas of the mechanism construction are as follows:

$$\mathbf{II}(1,2) \rightarrow \mathbf{I}(3,6) \leftarrow \mathbf{II}(4,5) \tag{25}$$

II (1, 2) - two-link, the **II nd** class Assuric flat group, the **3rd genus**, **2nd** order (As shown in Fig. 5);
I (3, 6) - two-link mechanism of the **I nd class** Assuric;
II (4, 5) - two-link, the **II nd** class Assuric flat group, the **3rd genus**, 2nd order.

Thus, the six-link self-aligning, flat hinged-lever mechanism of the physical pendulum (Fig. 4) is the mechanism of the Assuric structure of the **II nd** class, the **3rd** genus.

Based on the formula (1) of Doctor of Technical Sciences, Professor of Science of Machine Science Nauryzbayev Rakhimzhan Kakzhevich (NRK), a structural, geometric, kinematic general model of a self-aligning flat, six-part hinged-lever mechanism of a physical pendulum (As shown in Fig. 4) was developed and its dynamic model was developed (As shown in Fig. 4). 1), the nonlinear differential equation of motion (3) is obtained. The parameters and main modes of operation of rational design and natural design (As shown in Fig. 2) are set. A phase portrait of oscillations with a point of the center type of the leading link of the mechanism of the physical pendulum is obtained (As shown in Fig. 3).

A comprehensive, unified and consistent method of researching a self-aligning, six-part flat hinged-lever mechanism of a physical pendulum of the **II nd** class, the **3rd** genus from the structure to the dynamic synthesis [1-7] was created.

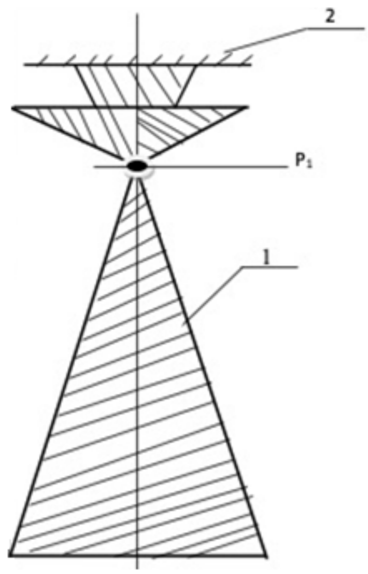

Fig. 5. Flat, self-aligning two-link pivot - lever mechanism of the physical pendulum. Structural, geometric, kinematic general model of the mechanism. General structural, geometric, kinematic model of the mechanism. **1** - The leading link of the mechanism of the **I st** on the basis of a single-link complex kinematic chain. $\mathbf{P_1}$ - Rotational kinematic pair of the V th class. **2** - Rack - link mechanism, taken as stationary.

A three-link mechanism in which the cylindrical pin on the rod 2 slides into the base slot when the lever is rotated [1, 9] (As shown in Fig. 6).

For the transfer of power in the machines and the transformation of motion, various flat and spatial self-installing pendulum-type pivotal lever mechanisms are used [1, 6-7, 9].

The structural formula of this mechanism:

$$I(1,4) \rightarrow II(2,3) \tag{26}$$

The self-aligning flat four-bar hinged-lever mechanism of the physical pendulum relates to the Assuric, the mechanism of the classical type [1-7, 10-13] (As shown in Fig. 7).

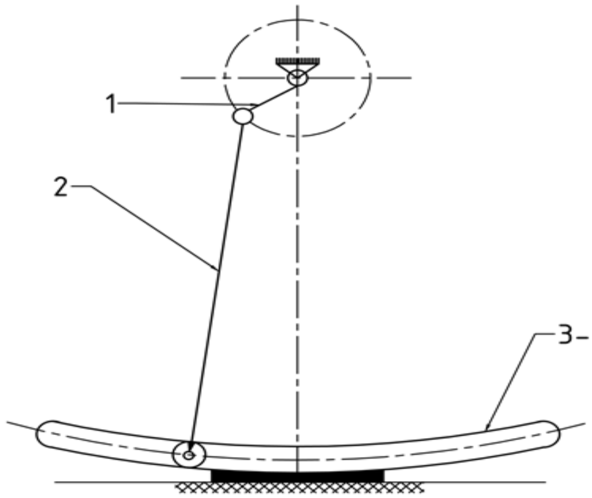

Fig. 6. Self-mounting three-link pendulum-type rod lever mechanism. **1** - Lever or crank is a rotating link of a mechanism that makes a complete revolution around a fixed axis. **2** - The rod is a link of the mechanism, one dimension of which (length) is much more than the other two. **3** - Stand - stand - a link of the mechanism, taken as fixed.

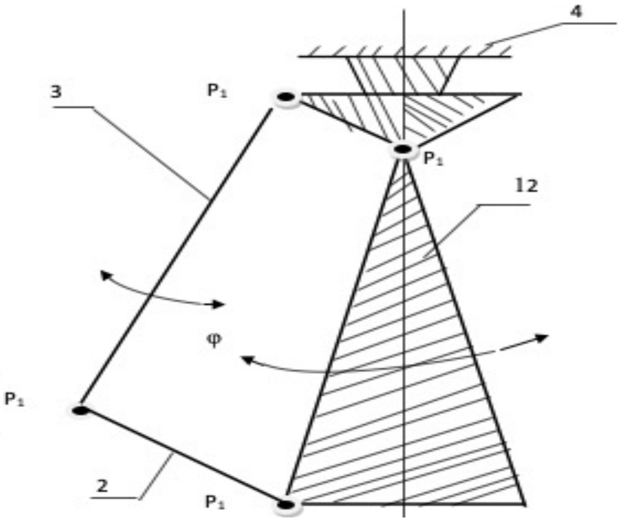

Fig. 7. Self-mounted flat four-bar hinged - lever mechanism of the physical pendulum. Structural, geometric, kinematic general model of the mechanism. ***1*** **-** lever, pendulum, leading link; ***2*** **-** connecting rod; ***3*** **-** rocker; ***4*** **-** stand; ***P_1*** **-** rotational pairs of the Vth class according to A.P. Malyshev.

The structural formula of this mechanism:

$$II(5) \rightarrow I(1,4) \leftarrow II(2,3) \quad (27)$$

I (1,4) - Self-aligning flat two-link mechanism of the Ist class.
II (2,3) - Structural group of the L.V. Assur IInd class, 1st type with three rotational kinematic pairs. The group of construction of the 3rd genus according to the classification of I.I. Artobolevskiy.
II (5) - structural group of the R.K. Nauryzbaeva (NRK) IInd class, 3rd genus, 2nd order. Single link kinematic chain of zero degree of mobility with kinematic pairs P_1 and P_5.

Thus, the self-aligning flat five-bar hinged - lever mechanism of the physical pendulum is formed by joining of the Assur first class and one group of the classical type - II (2,3) and one new group from one link of the form - II (5) (As shown in Fig. 8).

$(n + n_1) = 6$.

$P_1 = 7$.

$W_{к.с.}$ = 4. ($W_{kinematic\ chain.}$ = 4.)

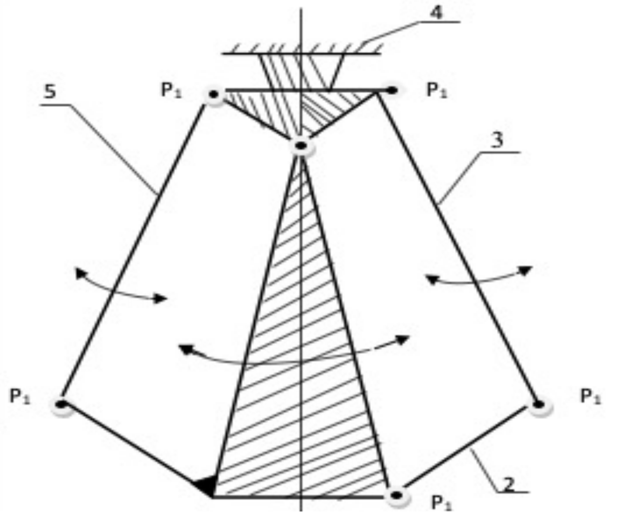

Fig. 8. Self-mounted flat five-bar hinged - lever mechanism of the physical pendulum. Structural, geometric, kinematic general model of the mechanism.

Every mechanism is based on a kinematic chain (as shown in Fig. 9). The mechanism is intended for the implementation of predetermined regular movements. Therefore, only that kinematic chain will be a mechanism whose links carry out expedient movements arising from engineering production tasks for which the mechanism is designed.

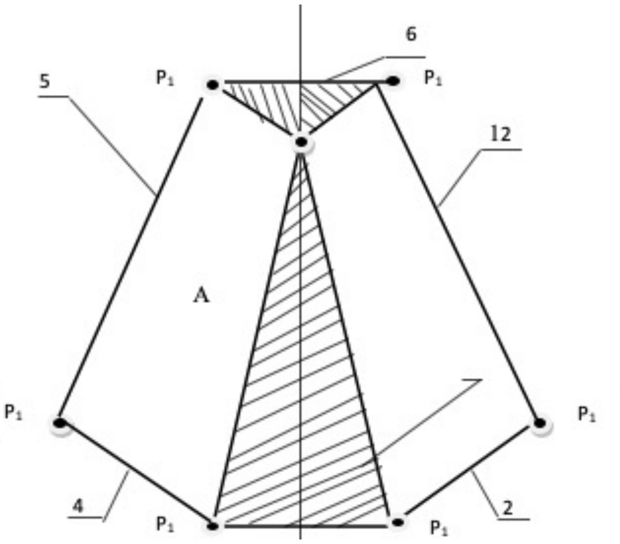

Fig. 9. A flat, complex closed kinematic chain of six moving links (1, 2, 3, 4, 5, 6) and two closed loops (A and B). ***A kinematic chain*** is called flat if the points of all links can move in parallel planes. ***A compound kinematic chain*** is a chain that has one link that is included in more than two kinematic pairs. A complex closed kinematic chain is called such a complex kinematic chain, each link of which is included in at least two kinematic pairs.

In our case, when the link 6 is selected as the rack (As shown in Fig. 9), the mechanism becomes a self-aligning flat six-arm articulated-lever mechanism of the physical pendulum (As shown in Fig. 4). Modernization of the studied mechanism, consisting of the same links and kinematic pairs, with preservation of the number of coupling conditions and degrees of freedom can be obtained by choosing its different links as a rack.

The degree of the mechanism freedom (As shown in Fig. 4) is determined on the basis of formula (1), taking into account m = 3, $(n + n_1) = 5$, $p_1 = 7$, using the formula:

$$W = 3 \cdot (n + n_1) - 2 \cdot P_1 = 3 \cdot 5 - 2 \cdot 7 = 1 \quad (28)$$

4. Conclusions

Self-installing, statically definable mechanisms for the construction of a pendulum at this stage of the study can be divided:

- Self-excited, statically definable two-link mechanisms of the pendulum design based on single-link simple unlocked kinematic chains (As shown in Fig. 1);
- Self-excited, statically definable two-link mechanisms of the pendulum design based on single-link complex open, two-contact kinematic chains (As shown in Fig. 5);
- Self-excited, statically definable three-link mechanisms of the pendulum design based on three-link kinematic chains (As shown in Fig. 6). The self- excited three-link pendulum rod lever mechanism refers to non-acanthus structures. There are no known, classical two-tier structural groups of Assur [1-7];
- Self- excited, statically definable four-link articulated lever mechanisms of the physical pendulum (As shown in Fig. 7) belong to Assur structures of the classical type;
- The self- excited, flat, statically definable five-link articulated-lever mechanisms of the physical pendulum (see Fig. 8) relate to mixed designs of actuators and machines;
- Self-installing, statically definable six-link mechanisms of the pendulum design based on six-link complex kinematic chains (As shown in Fig. 4). This lever mechanism of the pendulum refers to Assuranov structures [1-7].

The dynamic model of the mechanism is an idealized mapping of the studied structure of the self-establishing mechanism scheme used in its theoretical research and engineering calculations.

The main parameters of the single-mass dynamic model of the flat, two-link self-aligning mechanism of the pendulum (As shown in Fig. 1):

P_1 – single-motion, rotational kinematic pair of the V^{th} class;
φ– angle of rotation of the pendulum is taken as the generalized coordinate;
$J_П$ - the reduced moment of inertia of the mechanism of the pendulum relative to the axis of rotation of the link 1 (pendulum) [kg·m²].
$\dot{\varphi}$ – generalized velocity of a single mass dynamic model;
$M_П$- the reduced moment of inertia of forces relative to the axis of rotation of the leading link 1 (pendulum) [H·m].

Based on the formula (1) of Doctor of Technical Sciences, Professor of Science of Machine Science Nauryzbayev Rakhimzhan Kakzhevich (NRK), a structural, geometric, kinematic general model of a self-aligning flat, six-part hinged-lever mechanism of a physical pendulum was developed and its dynamic model was developed, the nonlinear differential equation of motion (3) is obtained. The parameters and main modes of operation of rational design and natural design are set. A phase portrait of oscillations with a point of the center type of the leading link of the mechanism of the physical pendulum is obtained (As shown in Fig. 3).

A comprehensive, unified and consistent method of researching a self-aligning, six-part flat hinged-lever mechanism of a physical pendulum of the II^nd class, the 3^rd genus from the structure to the dynamic synthesis was created.

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