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Synchronization of Kinematic Chains of Human's Muscosceletal System and the Exosceleton During Movement

A.V. Borisov

The Smolensk Branch of National Research University "MEI" (Technical University), Energeticheskiy proezd1, 214013 Smolensk, Russia

borisowandrej@yandex.ru

***Abstract*-The phenomenon of synchronization in core mechanical systems is considered in the article. Synchronization is the most important phenomenon while steady human motion and while motion in exoskeleton, which actually makes this article urgent. The aim of this article is to study different models: two - and four-with one-dimensional, two-dimensional translational and rotational movement of the suspension point. The differential equations of motion are used for dynamic models, and their numerical solution is carried out. The result is graphs of solutions, presented in the article, which demonstrate the existence of the phenomenon of synchronization in various modes of movement and control. In the issue, the study of the phenomenon of synchronization is a creation of the exoskeleton, most comfortable for human use, performing synchronous movements.**

Keywords- Synchronization; Exoskeleton; Musculoskeletal System of a Human; Core Mechanical System; Control

I. INTRODUCTION

The purpose of this article is to study the timing mechanisms of the core links of the mechanical system of the type endo - and exoskeleton.

Obtained in [1] a dynamic model is subscribed by essentially nonlinear differential equations, which can cause nonlinear effects in the behavior of the exoskeleton. In this regard, there is the need for a thorough study of these phenomena. A problem of synchronization of legs while walking appears. It is important for controlling the movement of the exoskeleton.

When solving problems of motion, control of the exoskeleton and the synthesis of its stable periodic gaits question about the possible study synchronization of the movement of the lower limbs during walking occurs. It is necessary to simplify the movement control system during an established gait of the person in the exoskeleton, and, therefore, reduce the energy consumption of a computer system of the exoskeleton to control.

The following definition of synchronization is "the property of tangible objects of various natures to develop a common rhythm of co-existence despite different individual rhythms and sometimes very weak mutual connection". Mathematically, the synchronization phenomenon follows from the properties of nonlinear differential equations of a certain kind to allow stable periodic solutions.

Questions of adaptive synchronization in the output of network of interconnected nonlinear dynamical systems with bounded perturbations are considered in [2], the asymptotic synchronization in [3], decentralized and adaptive synchronization of a network of interconnected dynamical subsystems with a leading subsystem in [4-6].

Many works devoted to problems of creation of the exoskeleton and its individual parts [7]. The work [8] and an extensive review of the work are devoted to the modeling of joints to reflect the changes in its geometry. Not a lot of works devoted to synchronization in the exoskeleton and its co-functioning with the musculoskeletal system of man. Mostly, HAL and the robot in several works [9-11], the phenomenon of synchronization have been studied.

This article is based on a detailed study of the dynamics of the lower extremities exoskeleton, with the simulated rods with concentrated masses, applied to such a relatively unknown phenomenon as synchronization links of the exoskeleton and the locomotor apparatus of man in their joint functioning. The clause is equivalent to the dynamic model, which is based on the differential Lagrange equations of the second kind to describe the phenomenon of synchronization and assumptions about the form of control actions and relationships providing the effect of the synchronization is the main contribution of this paper. This work can be used as a practical approach for creating an ergonomic exoskeleton, providing comfortable movement of a person in it. The remainder of the paper is organized as follows: Section 2 presents a simple dynamic model of the two links of the exoskeleton and studied many different variants of its functioning. Section 3 presents a close to the real musculoskeletal system of the person and a four-step model of the exoskeleton. Section 4 represents the model with two additional degrees of freedom for the point of connection of the limbs (hip joint). Section 5 contains a matrix form of differential equations of motion used in this work. Finally, section 6 presents the important conclusions and suggestions for future work.

II. A MODEL RESEARCH TASK OF SYNCHRONIZATION OF THE KINEMATIC CHAIN DURING CYCLIC MOVEMENTS

To study the possible synchronization of the legs when walking, consider a model consisting of the lower limbs of the person and the body. In this case, there is a weak link between the lower limbs, making a periodic oscillatory motion and their suspension point associated with the body on which they act and which implements a certain transfer of impacts from one leg to the other and back. The legs themselves are not connected.

To a first approximation, we consider a simple synchronization of the lower extremities. In this formulation, the problem is similar to the problem of synchronization of pendulums suspended on a common base.

The objective in this section of the model is modified. Let two of the pendulum with concentrated masses m_1 and m_2 suspended from a common point – hip joint mass m_0 (Fig. 1).

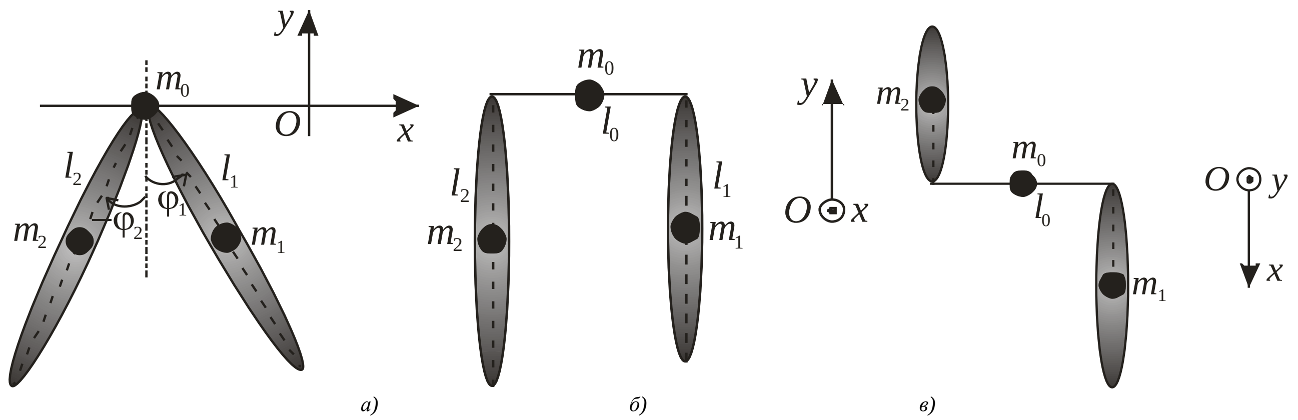


Fig. 1 Synchronization of two kinematic links of similar parameters which oscillates in antiphase

(a) view in profile; b) view of full face; c) view from above)

In the model, the pendulums oscillate in different planes, parallel to each other, but they are linked with a rod. If we consider motion in the plane was passing through the center of mass, this relationship does not affect the motion in the plane, and only synchronizes.

In Fig. 1, the angles φ_1 and φ_2 are measured from the vertical counterclockwise, the distance between the centers of mass of links l_1 and l_2. Each link has one degree of freedom. The angles φ_1 and φ_2, is taken as the generalized coordinates. The hip joint has one degree of freedom for translational motion in the horizontal direction is the x coordinate, which is also a generalized coordinate (Fig. 1). Assume that all generalized coordinates are functions of time: $x = x(t)$, $\varphi_1 = \varphi_1(t)$, $\varphi_2 = \varphi_2(t)$.

The coordinates of the lumped masses in the selected coordinate system are written as follows:

$$C_0 = (-x, 0),\ C_1 = (-x + l_1\sin\varphi_1, -l_1\cos\varphi_1),\ C_2 = (-x + l_2\sin\varphi_2, -l_2\cos\varphi_2). \quad (1)$$

Then the kinetic energy of this system of bodies is:

$$T = \frac{1}{2}\left((m_1 + m_2 + m_0)\dot{x}^2 + l_1^2 m_1\dot{\varphi}_1^2 + l_2^2 m_2\dot{\varphi}_2^2\right) - \dot{x}\left(l_1 m_1\dot{\varphi}_1\cos\varphi_1 + l_2 m_2\dot{\varphi}_2\cos\varphi_2\right) \quad (2)$$

Potential energy is the energy of a gravity force and elastic energy of foundation:

$$\Pi = -g\left(l_1 m_1\cos\varphi_1 + l_2 m_2\cos\varphi_2\right) + \frac{1}{2}c_x x^2 \quad (3)$$

where: g is the acceleration of gravity, c_x – stiffness of the elastic system.

The last addend in the equation (3) is a potential energy of the elastic pull of muscles, and can be used for its calculation.

The system applies a control - M_1 and M_2 at the points of suspension links will be given in the form:

$$M_1 = E_1\mathrm{sign}\dot{\varphi}_1,\ M_2 = E_2\mathrm{sign}\dot{\varphi}_2. \quad (4)$$

where: E_1, E_2 – constant components of control points.

The resistance force K_0, K_1, K_2 acting on the system, we approximate:

$$K_0 = -k_0\dot{x},\ K_1 = -k_1\dot{\varphi}_1,\ K_2 = -k_2\dot{\varphi}_2. \quad (5)$$

where: k_0, k_1, k_2 – the coefficients of viscous resistance fluctuations of the base and links accordingly.

Using the Lagrange formalism, we obtain the equations of motion for the considered model.

$$(m_1+m_2+m_0)\ddot{x} - \ddot{\varphi}_1 l_1 m_1 \cos\varphi_1 - \ddot{\varphi}_2 l_2 m_2 \cos\varphi_2 + \dot{\varphi}_1^2 l_1 m_1 \sin\varphi_1 + \dot{\varphi}_2^2 l_2 m_2 \sin\varphi_2 + c_x x = -k_0 \dot{x}, \tag{6}$$

$$m_1 l_1^2 \ddot{\varphi}_1 - \ddot{x} l_1 m_1 \cos\varphi_1 + l_1 m_1 g \sin\varphi_1 = E_1 \mathrm{sign}\dot{\varphi}_1 - k_1 \dot{\varphi}_1, \tag{7}$$

$$m_2 l_2^2 \ddot{\varphi}_2 - \ddot{x} l_2 m_2 \cos\varphi_2 + l_2 m_2 g \sin\varphi_2 = E_2 \mathrm{sign}\dot{\varphi}_2 - k_2 \dot{\varphi}_2. \tag{8}$$

Even in this simplest formulation, the resulting system of differential equations is a substantially non-linear and to obtain its analytical solution is not possible. Practically it is very difficult to research it on sustainability. Therefore, we carry out a numerical solution in Mathematica SCM.

For the numerical solution, we use the values of the relevant links to the person defined in the previous work [10]. The mass of the link is assumed to equal to the mass of the entire leg, i.e. the sum of the weight of the foot, shank, and thigh, the length of the sum of the lengths of these links. The weight of the attachment point of the legs is the weight of the body and hands.

Synchronization occurs when the joint oscillations in antiphase, that is implemented with the human walking (Fig. 2 a, b). When this was taken in agreement with the theory of synchronization, slightly different initial conditions for links.

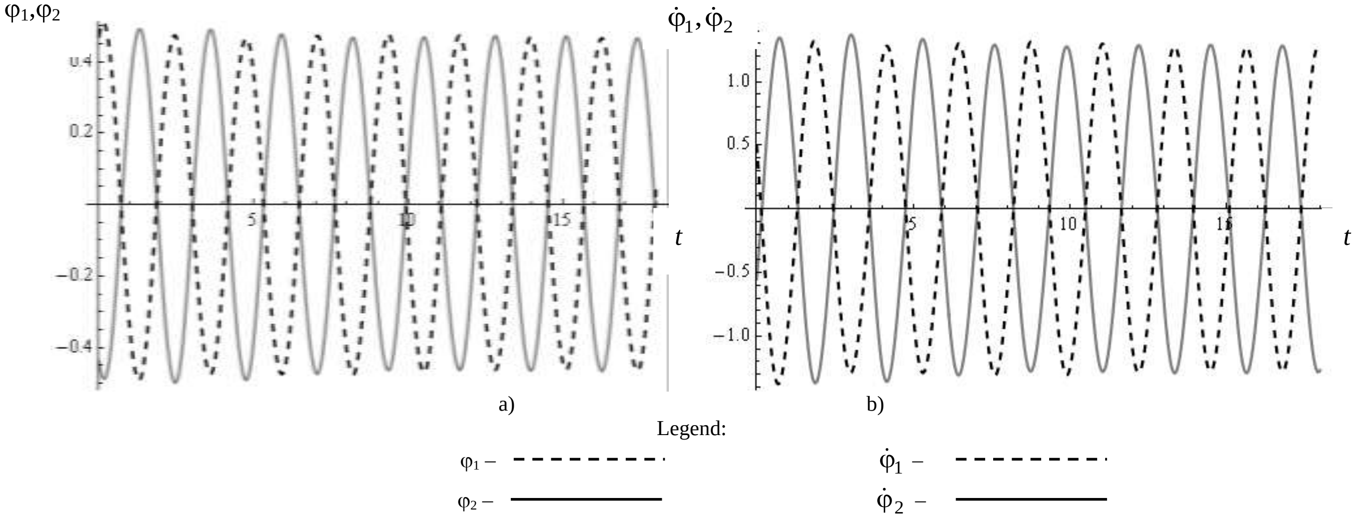


Fig. 2 The dependence of the degree of rotation of link (rad) a) and angular velocity (rad/sec) b) from time with oscillation in opposite phase

The dotted line designated according to the first link

As we can see from the graph, the oscillations are synchronized almost immediately and then happen in a coordinated manner.

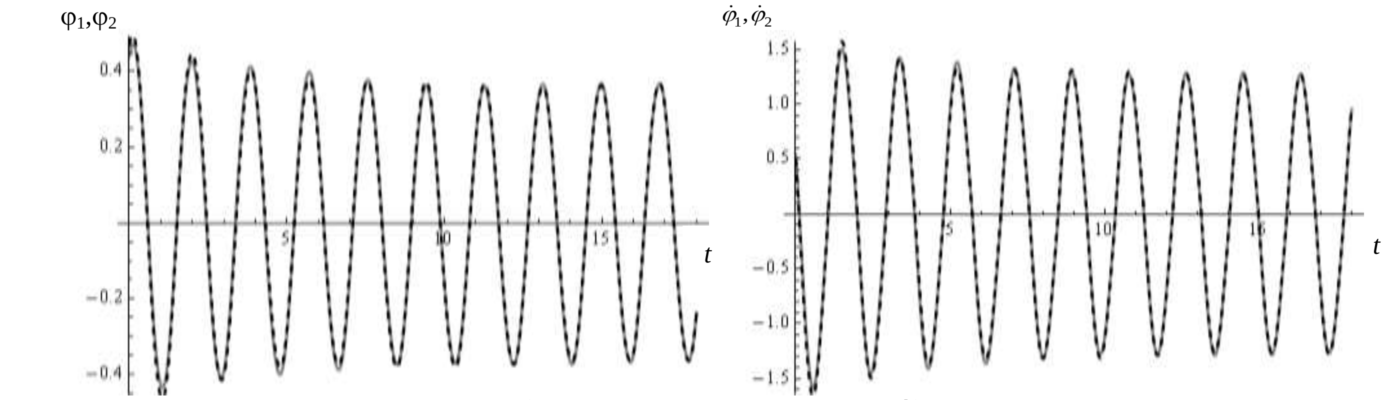
In phase of synchronization it is visually easier to evaluate (Fig. 3). Such movement may be performed by the human walking in the exoskeleton, assuming that one limb belongs to the person, and the second is the exoskeleton, dressed per person. Thus, it is possible to synchronize the operation of the exoskeleton and endoskeleton. The movement of the exoskeleton must minimally keep up with endoskeleton, otherwise, the person in the exoskeleton move will be uncomfortable.

The figures show that after the start of motion of the system there are small differences in the angular coordinate and angular velocity of links 1 and 2 related to task of different initial conditions. Then over time occurs almost full synchronization, which can last indefinitely.

The case where there are no control points is considered. In this case, relaxation oscillations both units occur, but there is a synchronization effect (Fig. 4).

Synchronization of oscillations during the decay time of the movements of the feet also takes place.

Consider the case where a control moment acts only on one link (Fig. 5), i.e. the second link is a passive element. Such model has no place in practice and is of theoretical interest.



a) b)

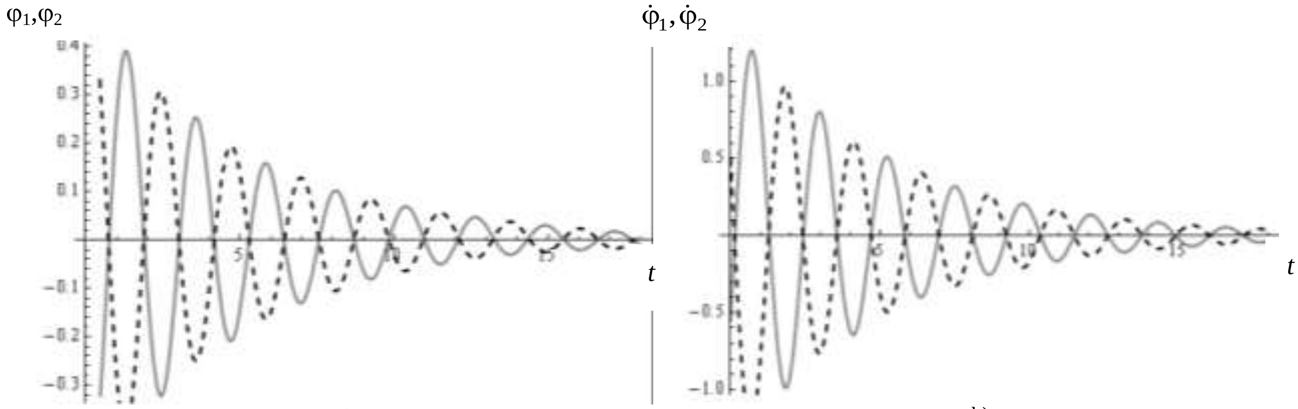
Legend:

φ_1 – - - - - - - - $\dot{\varphi}_1$ – - - - - - - -

φ_2 – ——— $\dot{\varphi}_2$ – ———

Fig. 3 The dependence of the angle of rotation of link (rad) a) and angular velocity (rad/s) b) from time with fluctuations in one phase

The dotted line designated according to the first link



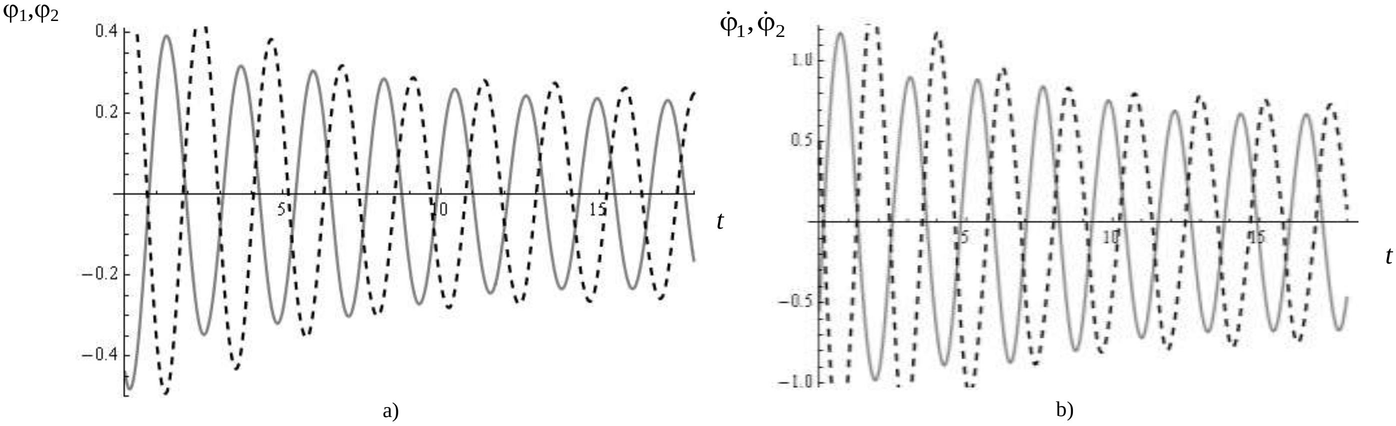
a) b)

Legend:

φ_1 – - - - - - - - $\dot{\varphi}_1$ – - - - - - - -

φ_2 – ——— $\dot{\varphi}_2$ – ———

Fig. 4 The dependence of the angle of rotation of link (rad) a) and angular velocity (rad/s) b) from time for the damped oscillations: oscillations in opposite a), b). The dotted line designated according to the first link



a) b)

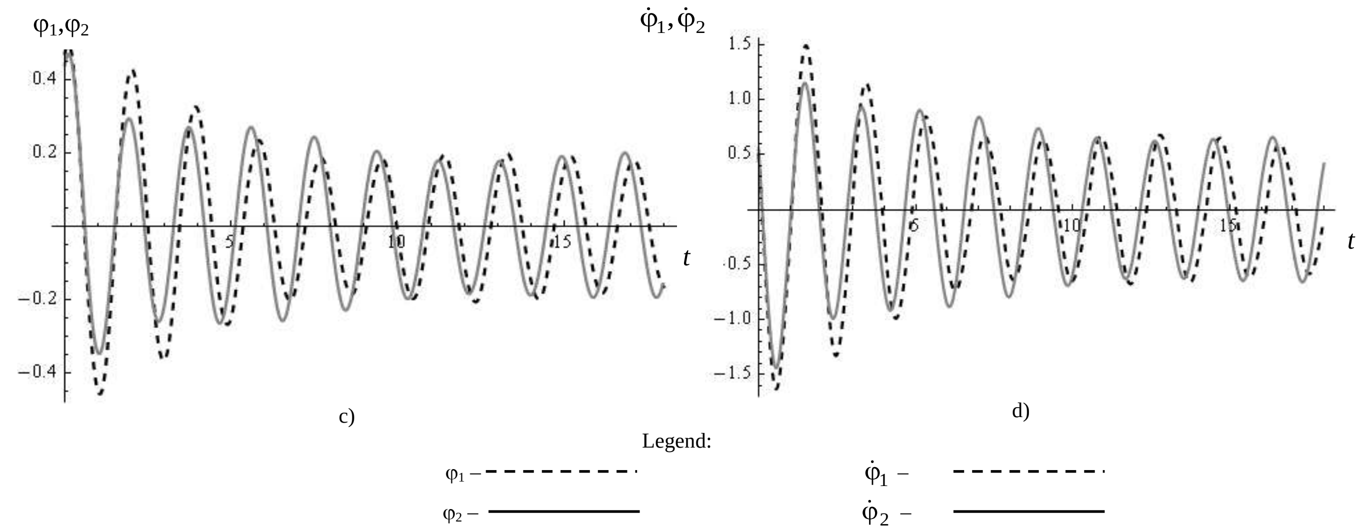


Fig. 5 The dependence of the angle of rotation of link (rad) a), c) and angular velocity (rad/s) b), d) from time with fluctuations with one driving moment applied to the first link for oscillation in opposite phase a), b), and in the same phase c), d). The dotted line designated according to the first link

There is an effect of the maintenance of oscillations and the second link while oscillation in opposite phase and in phase, which is not supplied with external energy, and the dissipation of energy is present. However, in this case, to maintain a stable sustained oscillation (Fig. 5) should be attached to the first pendulum ten-fold torque compared to the one that was attached to two pendulums (Fig. 2). In the case of application, fewer effort fluctuations are damped, though not as fast as in the absence of exposure in the previous case. This partially collapses completely synchronized movement of the links. This is very similar to impulse control of human walking, when, after push the portable foot moves by inertia. It can be assumed that the phenomenon of synchronization of the movements of the feet while walking also takes place here.

If the second link in the initial moment is at rest and no forcing has applied the effect, then it will still appear oscillatory motions, due to vibrations of the first link (Fig. 6).

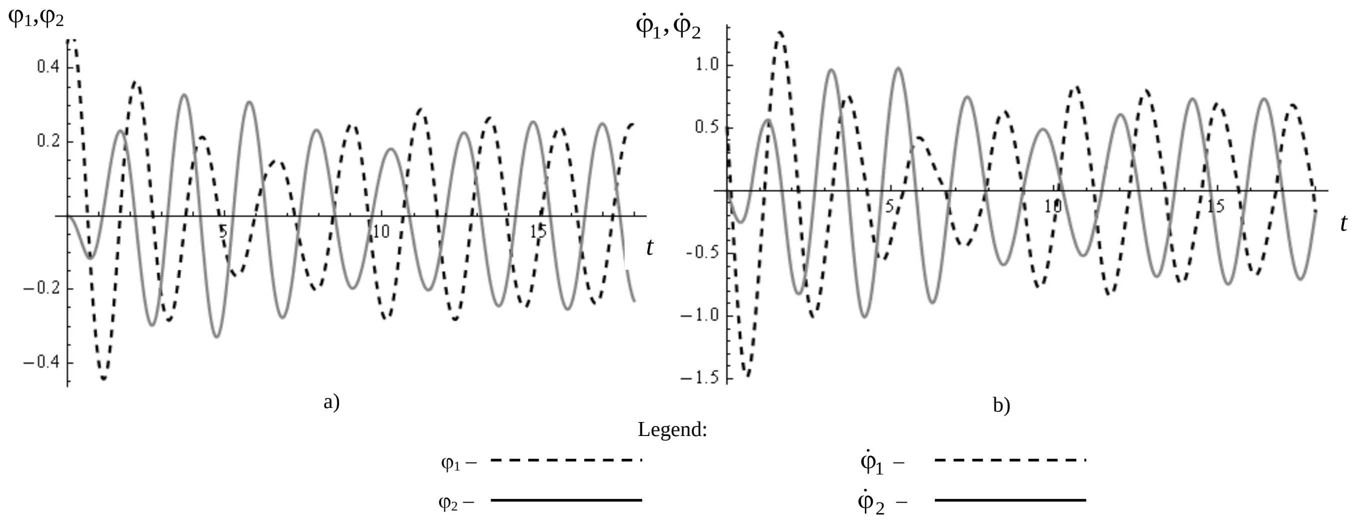


Fig. 6 The dependence of the angle of rotation of link (rad) a), c) and angular velocity (rad/s) b), d) from time with fluctuations with one driving moment applied to the first link for oscillation with the second stationary link. The dotted line designated according to the first link

It appears that vibrational motion occurring in the second link is mostly in opposite phase to each other, in this case, the synchronization phenomenon is poorly expressed.

Thus, the synchronization phenomenon for the model of two-link mechanical systems with the one-dimensional movement of the point of suspension of the rods is investigated, it is shown that the phenomenon of relationship occurs when different modes of oscillations in the system.

III. SYNCHRONIZATION IN LADDER CIRCUIT KINEMATIC CHAINS UNDER CYCLIC MOVEMENTS

For consideration of human walking in the exoskeleton it is necessary to explore the model with two-tier lower limb consisting of the femur and tibia each. Consider the model corresponding to two two-link foot (Fig. 7).

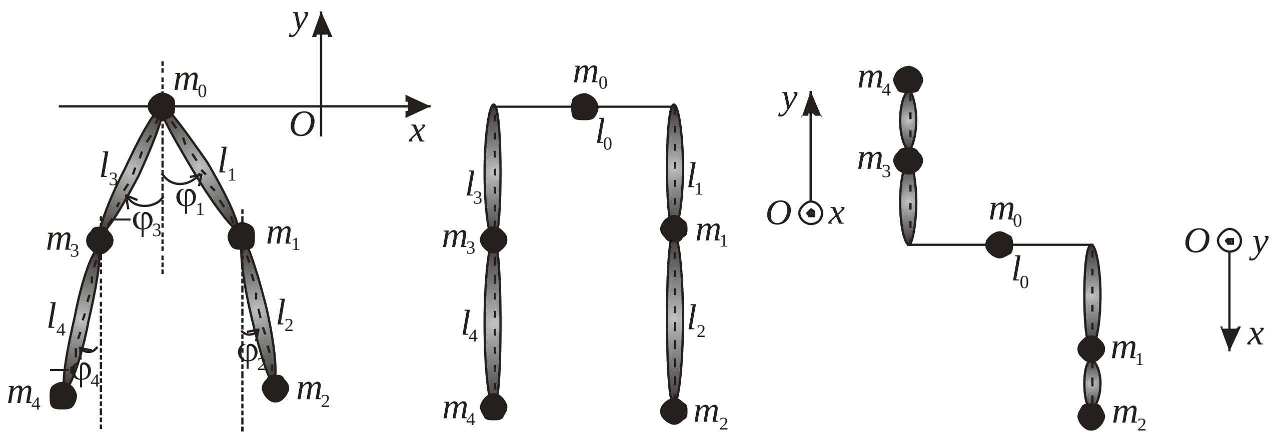


Fig. 7 Synchronization of the model with four movable links, oscillates in antiphase (a) view in profile; b) view of full face; c) view from above)

Averaging the equations of motion as described above and following the notation (Fig. 7), the following system of differential equations in the form of Lagrange equations is obtained, describing the motion in the system of bodies.

$$\begin{gathered}(m_0+2(m_1+m_2))\ddot{x}-\ddot{\varphi}_1 l_1(m_1+m_2)\cos\varphi_1-\ddot{\varphi}_2 l_2 m_2\cos\varphi_2-\ddot{\varphi}_3 l_1(m_1+m_2)\cos\varphi_3-\ddot{\varphi}_4 l_2 m_2\cos\varphi_4+\\+\dot{\varphi}_1^2 l_1(m_1+m_2)\sin\varphi_1+\dot{\varphi}_2^2 l_2 m_2\sin\varphi_2+\dot{\varphi}_3^2 l_1(m_1+m_2)\sin\varphi_3+\dot{\varphi}_4^2 l_2 m_2\sin\varphi_4+c_x x=-k_0\dot{x},\end{gathered} \tag{9}$$

$$\begin{gathered}(m_1+m_2)l_1^2\ddot{\varphi}_1-\ddot{x}l_1(m_1+m_2)\cos\varphi_1+l_2 m_2\cos(\varphi_1-\varphi_2)\ddot{\varphi}_2+\\+l_2 m_2\sin(\varphi_1-\varphi_2)\dot{\varphi}_2^2+l_1(m_1+m_2)g\sin\varphi_1=E_1\mathrm{sign}\dot{\varphi}_1-k_1\dot{\varphi}_1,\end{gathered} \tag{10}$$

$$m_2 l_2^2\ddot{\varphi}_2-\ddot{x}l_2 m_2\cos\varphi_2+l_1 l_2 m_2\cos(\varphi_1-\varphi_2)\ddot{\varphi}_1-l_1 l_2 m_2\sin(\varphi_1-\varphi_2)\dot{\varphi}_1^2+l_2 m_2 g\sin\varphi_2=E_2\mathrm{sign}\dot{\varphi}_2-k_2\dot{\varphi}_2, \tag{11}$$

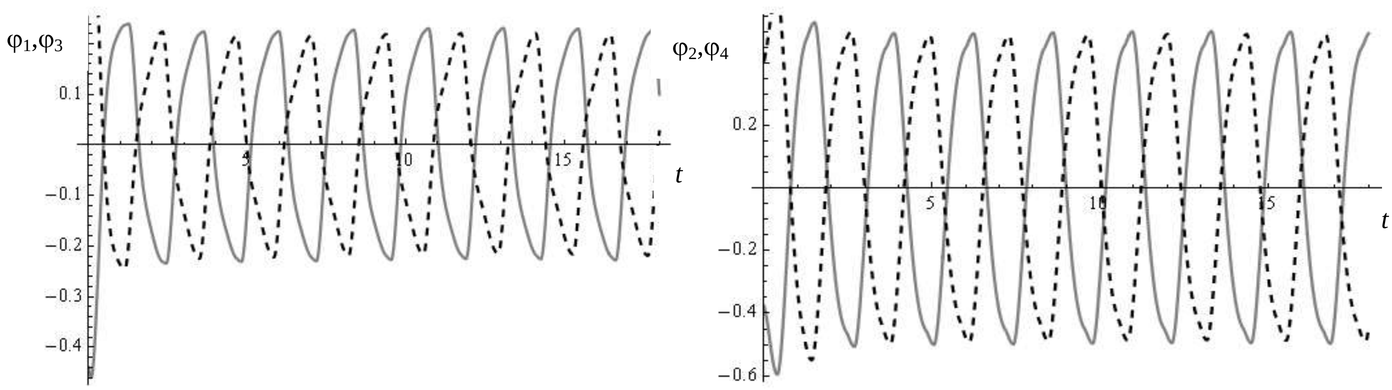
$$\begin{gathered}(m_1+m_2)l_1^2\ddot{\varphi}_3-\ddot{x}l_1(m_1+m_2)\cos\varphi_3+l_2 m_2\cos(\varphi_3-\varphi_4)\ddot{\varphi}_4+\\+l_2 m_2\sin(\varphi_3-\varphi_4)\dot{\varphi}_4^2+l_1(m_1+m_2)g\sin\varphi_3=E_1\mathrm{sign}\dot{\varphi}_3-k_1\dot{\varphi}_3,\end{gathered} \tag{12}$$

$$m_2 l_2^2\ddot{\varphi}_4-\ddot{x}l_2 m_2\cos\varphi_4+l_1 l_2 m_2\cos(\varphi_3-\varphi_4)\ddot{\varphi}_3-l_1 l_2 m_2\sin(\varphi_3-\varphi_4)\dot{\varphi}_3^2+l_2 m_2 g\sin\varphi_4=E_2\mathrm{sign}\dot{\varphi}_4-k_2\dot{\varphi}_4. \tag{13}$$

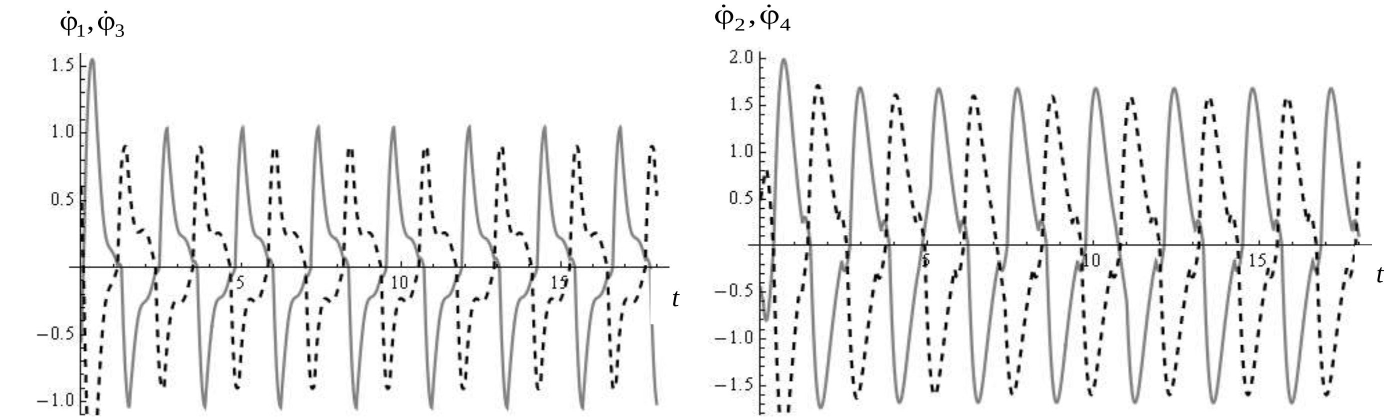
The resulting system of differential equations is highly nonlinear and its analytical solution is not possible to get. Therefore, we solve it numerically in Mathematica SCM.

For the numerical solution, we use the values of the respective links to the test person as defined earlier. The mass of the link is assumed to equal to the mass of the respective links of the legs. The mass of the suspension point is the weight of the body and hands.

Multilink synchronization of the limb occurs while the joint oscillations in antiphase, that is implemented with the human walking (Fig. 8 a, b). When it is taken in agreement with the theory of synchronization slightly different initial conditions appear.



a) b)



c) d)

Legend:

φ_1, φ_2 – - - - - - - - $\dot{\varphi}_1, \dot{\varphi}_2$ – - - - - - - -

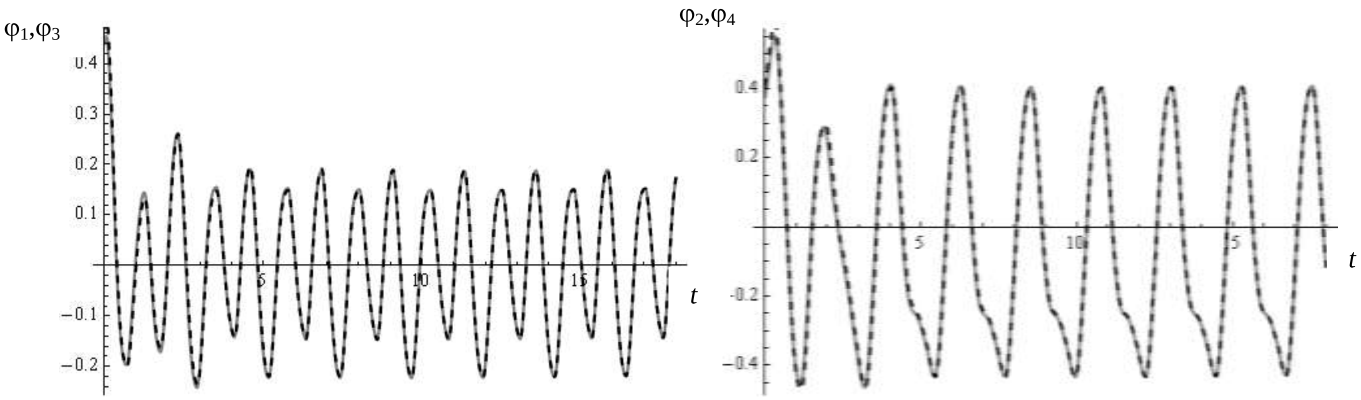
φ_3, φ_4 – ——— $\dot{\varphi}_3, \dot{\varphi}_4$ – ———

Fig. 8 The dependence of the angle of rotation of link (rad) a) and angular velocity (rad/s) b) from time with fluctuations in opposite phase

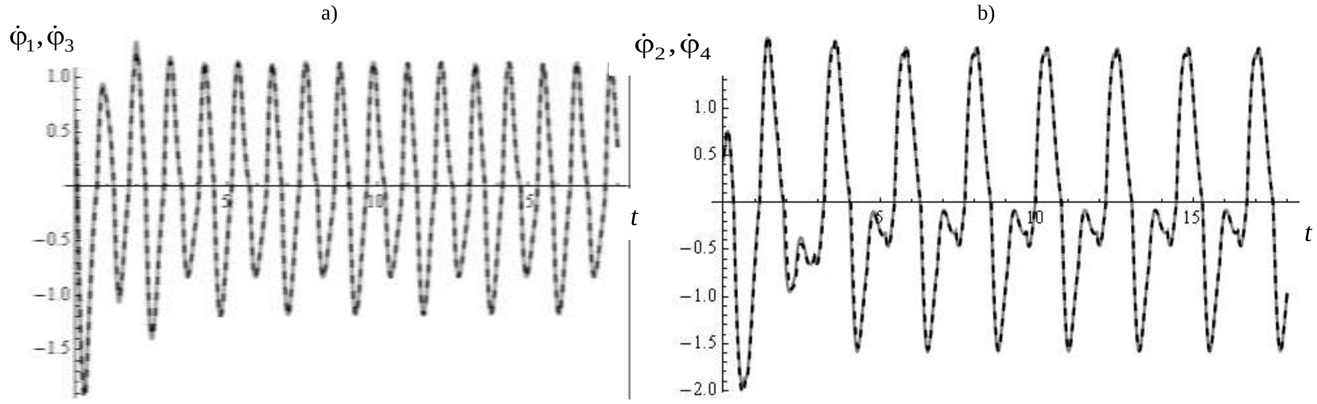
The dotted line designated according to the first link

According to the charts, the oscillatory motion of the links of sync almost immediately, and then happen in a coordinated manner. However, the kind of oscillations is changed in comparison with the single-link model (Fig. 2). The differences are particularly apparent for the angular velocities of links of a mechanical system.

Synchronization is easier to assess visually in the same phase (Fig. 9), but such motion cannot be realized when walking.



a) b)



c) d)

Legend:

φ_1, φ_2 – - - - - - - - $\dot{\varphi}_1, \dot{\varphi}_2$ – - - - - - - -

φ_3, φ_4 – ——— $\dot{\varphi}_3, \dot{\varphi}_4$ – ———

Fig. 9 The dependence of the angle of rotation of link (rad) a) and angular velocity (rad/s) b) from time with fluctuations in one phase

The dotted line designated according to the first link

The figure shows that almost complete synchronization of oscillations occurs over time.

Thus, in this work the synchronization phenomenon in the four-bar mechanical system was first investigated, it is shown that synchronization takes place.

The results partly explain the stability of the steady gait of a person. They can be applied to the creation of exoskeletons and anthropomorphic robots with reduced power consumption and easier system management in the case of the steady motion.

IV. MODEL OF SYNCHRONIZATION OF LINKS OF THE KINEMATIC CHAIN FOR AN ARBITRARY MOTION OF SUSPENSION POINT

This task is modified in the case of model synchronization links of the kinematic chain with the arbitrary motion of suspension point. Let two of the pendulum with concentrated masses m_1 and m_2 suspended from a common point based on the mass m_0 (Fig. 1). Unlike (Fig. 1) the base can move not only along the horizontal x-axis, but also along the vertical y-axis and make a rotation around its own axis. This is the difference between the model considered here from the model presented on (Fig. 1).

In the model, the pendulums oscillate in different planes, parallel to each other, but they are linked with a rod. If we consider motion in the plane is passing through the center of mass, this relationship does not affect the motion in the plane, and only synchronizes.

In Fig. 1, the angles are measured from the vertical counterclockwise. The edge lengths will be denoted respectively by l_1 and l_2. Each link has one degree of freedom. Generalized coordinates we denote $\varphi_1 = \varphi_1(t)$ and $\varphi_2 = \varphi_2(t)$. The base has three degrees of freedom. For generalized coordinates we will take: $x = x(t)$, $y = y(t)$, $\varphi = \varphi(t)$.

The coordinates of the lumped masses in the selected coordinate system are written this way:

$$C_0 = (-x, -y),\ C_1 = (-x + l_1\sin\varphi_1, -y - l_1\cos\varphi_1),\ C_2 = (-x + l_2\sin\varphi_2, -y - l_2\cos\varphi_2). \tag{14}$$

Then the kinetic energy of this system of bodies in generalized coordinates, after transformation, has the form:

$$T = (m_0(\dot{x}^2 + \dot{y}^2) + J\dot{\varphi}^2 + m_1((\dot{x} - \dot{\varphi}_1 l_1\cos\varphi_1)^2 + (\dot{y} - \dot{\varphi}_1 l_1\sin\varphi_1)^2) + \\ + m_2((\dot{x} - \dot{\varphi}_2 l_2\cos\varphi_2)^2 + (\dot{y} - \dot{\varphi}_2 l_2\sin\varphi_2)^2))/2. \tag{15}$$

Potential energy is the energy of a gravity force and elastic energy of Foundation:

$$\Pi = -g(l_1m_1\cos\varphi_1 + l_2m_2\cos\varphi_2) + (c_x x^2 + c_y y^2 + c_\varphi \varphi^2)/2, \tag{16}$$

where g is the acceleration of gravity, c_x – stiffness of the elastic system.

The suspension points of the links are control points M_1 and M_2, we will set in the form:

$$M_1 = E_1\operatorname{sign}\dot{\varphi}_1,\ M_2 = E_2\operatorname{sign}\dot{\varphi}_2. \tag{17}$$

where: E_1, E_2 – constant components of control points.

The resistance force Kx, Ky, $K\varphi$, K_1, K_2 we will approximate:

$$K_x = -k_x\dot{x},\ K_y = -k_y\dot{y},\ K_\varphi = -k_\varphi\dot{\varphi},\ K_1 = -k_1\dot{\varphi}_1,\ K_2 = -k_2\dot{\varphi}_2, \tag{18}$$

where k_x, k_y, k_φ, k_1, k_2 – coefficients of viscous resistance to fluctuations of the base and links, respectively.

Using the Lagrange formalism, we obtain the equations of motion for the considered model:

$$(m_1 + m_2 + m_0)\ddot{x} - \ddot{\varphi}_1 l_1m_1\cos\varphi_1 - \ddot{\varphi}_2 l_2m_2\cos\varphi_2 + \dot{\varphi}_1^2 l_1m_1\sin\varphi_1 + \dot{\varphi}_2^2 l_2m_2\sin\varphi_2 + c_x x = -k_x\dot{x}, \tag{19}$$

$$(m_1 + m_2 + m_0)\ddot{y} - \ddot{\varphi}_1 l_1m_1\sin\varphi_1 - \ddot{\varphi}_2 l_2m_2\sin\varphi_2 + \\ + \dot{\varphi}_1^2 l_1m_1\cos\varphi_1 + \dot{\varphi}_2^2 l_2m_2\cos\varphi_2 + c_y y - (m_1 + m_2 + m_0)g = -k_y\dot{y}, \tag{20}$$

$$J\ddot{\varphi} + c_\varphi\varphi = -k_\varphi\dot{\varphi}, \tag{21}$$

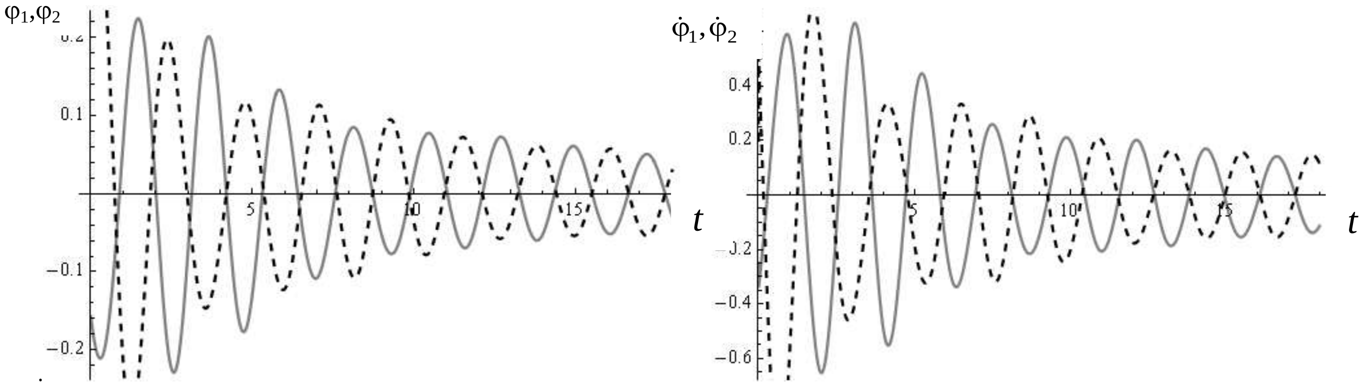
$$m_1 l_1^2\ddot{\varphi}_1 - \ddot{x}\, l_1m_1\cos\varphi_1 - \ddot{y}\, l_1m_1\sin\varphi_1 + l_1m_1 g\sin\varphi_1 = E_1\operatorname{sign}\dot{\varphi}_1 - k_1\dot{\varphi}_1, \tag{22}$$

$$m_2 l_2^2\ddot{\varphi}_2 - \ddot{x}\, l_2m_2\cos\varphi_2 - \ddot{y}\, l_2m_2\sin\varphi_2 + l_2m_2 g\sin\varphi_2 = E_2\operatorname{sign}\dot{\varphi}_2 - k_2\dot{\varphi}_2. \tag{23}$$

Even in this simplest setting is obtained the system of differential equations is highly nonlinear and its analytical solution to obtain the not possible. Practically, it is very difficult to research sustainability. Therefore, a numerical solution in Mathematica SCM is carried out.

For the numerical solution, we use the values of the relevant links to the person defined in our previous work [12]. The mass of the link is assumed to equal to the mass of the entire leg, i.e. the sum of the weight of the foot, shank, and thigh, the length of the sum of the lengths of these links. The weight of the attachment point of the legs is the weight of the body and hands.

Synchronization occurs when the joint oscillations in antiphase, that is implemented with the human walking (Fig. 10 a, b). When this is taken in agreement with the theory of synchronization slightly different initial conditions for links.



a) *b)*

Legend:

φ_1 – - - - - - - - - $\dot{\varphi}_1$ – - - - - - - - -

φ_2 – ——— $\dot{\varphi}_2$ – ———

Fig. 10 The dependence of the angle of rotation of link (rad) a) and angular velocity (rad/s) b) from time with fluctuations in opposite phase

The dotted line designated according to the first link

It follows from the figure that the oscillations are synchronized over time and continue to happen consistently Attenuation at the beginning of the oscillations are because the efforts of the impulse, causing vibrations, is chosen not so high as to support oscillations with sufficiently large amplitude. This follows from the fact that the synchronization phenomenon is better seen at low amplitudes of oscillatory motion.

Thus, it is shown that synchronization takes place and if the housing, i.e. the suspension of the legs has three degrees of freedom. A similar synchronization model is most suitable for use in the exoskeleton.

V. MATRIX NOTATION OF DIFFERENTIAL EQUATION OF MOTION

The differential equation of motion of the exoskeleton, regardless of the specific model (structure) can be represented in a compact matrix form of record.

$$A(q,l)\ddot{q} + B(q,l)\dot{q}^2 + gC(q)l = F(\dot{q},k,E), \tag{24}$$

where: q – generalized coordinates $q = (\varphi_1, \ldots, \varphi_n)^T$; l – the lengths of the links, $l = (l_1, \ldots, l_n)^T$; $A(q,l)$, $B(q,l)$ – matrixes, considering inertial qualities; $C(q)$ – matrix, determined by the moments of gravity; $F(\dot{q},k,E)$ – matrix-column of generalized forces, i.e., the control moments and forces of resistance; $\ddot{q}$ – matrix of generalized accelerations; $\dot{q}$ – the matrix of generalized speeds, then $\dot{q}^2 = (\dot{\varphi}_1^2, \ldots, \dot{\varphi}_n^2)^T$.

This matrix form describes all the equations (6)-(8), (9)-(13) and (19)-(23). For example, the vector of generalized coordinates for the three different models will be of the form:

$q = (x, \varphi_1, \varphi_2)^T$ – for equations (6)-(8);

$q = (x, \varphi_1, \varphi_2, \varphi_3, \varphi_4)^T$ – for equations (9)-(13);

$q = (x, y, \varphi, \varphi_1, \varphi_2)^T$ – for equations (19)-(23);

Similarly, it is possible to imagine the rest of the matrix included in these equations. They will not be written here because of the evidence. In a matrix form of a record, it is convenient to carry out the analysis of the structure of the mechanical system and the differential equations describing it.

VI. CONCLUSIONS

1. The phenomenon of synchronization in core mechanical systems is studied. A two-tier and four-tier system with the one-dimensional motion of suspension point is considered. Model of a two-link mechanical system with two-dimensional translational and rotational movement of the suspension point was studied. The possibility of the existence of the phenomenon of synchronization in various modes of movement and control has been shown.

2. The question of synchronization of movements while fluctuations of links while the bipedal walk is studied. It is shown that such phenomenon can occur and give new nonlinear effects, including easy management of the established movement and stabilizing bipedal walking. Practical reaching of movements close to human movement and its resilience in the dynamics of the exoskeleton and anthropomorphic robot can be due to the phenomenon of synchronization of oscillations of all elements of the exoskeleton.

3. The obtained results allow to conclude about the possibility of creation of the exoskeleton, most comfortable for the human. Synchronization of the work of the exoskeleton and the musculoskeletal system of a man can lead to the wide adoption and diffusion of exoskeletons, and accounting of the phenomenon of synchronization at a steady walk will help to simplify the control system of the exoskeleton to reduce energy consumption when driving.

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