Abstract—Motor-wheel of transport machine demands a using of step gear box. Necessity of the controlled coordination of forces on different wheels takes place. Recently the theory of adaptive continuously variable transmission (CVT) in the form of gear differential with mobile closed contour has been developed. The patents on the simplest adaptive transmission were created. Such transmission allows creating the small-size adaptive motor-wheel with ideal adjustable to conditions of joint movement of all wheels of the transport machine without any control system. The work is devoted to working out of self-adjusting motor-wheel on the basis of theory of mechanisms and machines.

Index Terms—Adaptive Transmission, Closed Contour, CVT, Self-Adjusting Motor-Wheel.

I. INTRODUCTION

The motor-wheel represents the complex assembly which is containing electric motor, power transmission, wheel and brake. Motors-wheels are used for the drive of the transport machine. The basic problems at creation of motors-wheels: 1) Necessity to use a step switching power transmission that complicates a design of a motor-wheel and increases its sizes, 2) Necessity to coordinate the forces of simultaneously working motors-wheels that demands complex control system.

The electric drive with the hydrodynamic gear box is very complex and has big sizes. The electric drive with the direct-current motor for regulating of rotational speed also is bulky.

Recently the Ivanov’s theory of adaptive continuously variable transmission (CVT) with two degrees of freedom [1]–[4] has been developed. Harries’s [5] and Ivanov’s [6]–[8] patents on CVT were created. Such transmission possesses property of force adaptation. It is capable to be independently adjustable for external loading without use of any control system and has small gabarits because does not demand the switching of transfers. Such transfer allows to create the simple and reliable small-size adaptive motor-wheel with ideal adaptation to conditions of simultaneously movement of all wheels without any control system.

The present work is devoted to design of a motor-wheel with CVT and to development of the basic analytical regularities for designing of self-adjusting motors-wheels on the basis of theory of mechanisms and machines.

II. DESIGN OF A SELF-ADJUSTING MOTOR-WHEEL

The basic parts of motor-wheel with the adaptive mechanical reductor (Fig. 1) are: 1. Frame. 2. Hub.

Fig. 1. Motor-Wheel with the Adaptive Mechanical Reductor

3. Alternating current induction motor 4. Adaptive small-size mechanical reductor. 5. Wheel rim. 6. Tyre The motor-wheel with the adaptive mechanical reductor has small sizes and provides adaptation of a wheel to variable technological loading without any control system.

III. ADAPTIVE WHEELWORK WITH TWO DEGREES OF FREEDOM

The self-regulating wheelwork in the form of differential mechanism with the closed contour consisting from toothed wheels is presented at Fig. 2. Picture of speeds of gear adaptive mechanism is presented on Fig. 3.

The mechanism contains a frame 0, input carrier $H_1$, input satellite 2, block of the central wheels 1-4, block of epicycle (ring) wheels 3-6, output satellite 5 and output carrier $H_2$. In an operating time the links are rotated around the central axis. Sizes of toothed wheels 1, 2, 3, 4, 5, 6 are determined through radiiuses $r_i \quad i = 1, 2, 3, 4, 5, 6$. Radiuses of carriers:

$$r_{H1} = r_1 + r_2, \quad r_{H2} = r_4 + r_5.$$  

The picture of speeds $v_i \quad i = 1, 2, 3, 4, 5, 6$ of mechanism links is presented on Fig. 3. Linear speeds $v_i$ are expressed through angular speeds $\omega_i$ by formula $v_i = \omega_i r_i$. Linear speeds of carriers are: $v_{H1} = \omega_{H1} r_{H1} \quad i = 1, 2$.  

Index Terms—Adaptive Transmission, Closed Contour, CVT, Self-Adjusting Motor-Wheel.
On the mechanism the external moments of forces are acting: \( M_{H1} \) – input driving moment, \( M_{H2} \) – output moment of resistance (torque).

Mechanism has two degrees of freedom.

Mechanism has following structural groups with zero mobility:

1) Group \( H2 = 5 \) containing two links \( H2 \) and 5, two lowest kinematics pairs \( A \) and \( K \) and two higher kinematics pairs \( E \) and \( G \);

2) Group 3-6 containing one link 3-6, one lowest kinematics pair \( A \) and one higher kinematics pair \( C \);

3) Group 1-4 containing one link 1-4, one lowest kinematics pair \( A \) and one higher kinematics pair \( D \).

Mechanism has input structural group with two degrees of freedom containing links \( H_1 \) and 2 and two lowest kinematics pairs \( A \) and \( B \).

Basic features of the mechanism:

1) Input structural group with two degrees of freedom contains consistently connected two links, \( H_1 \) and \( H_2 \) act at the one line because radiuses of carriers \( H_1 \) and \( H_2 \) are equal.

2) Superposed forces \( F_{H1} \) and \( R_{H6} \) on links \( H_1 \) and \( H_2 \) are equal.

3) Mechanism has the closed contour containing links 2, 3-6, 5, 4-1.

Let's do the power analysis of the mechanism when the output moment of resistance \( M_{H2} \) is set.

1) We determine reactions in kinematics pairs \( E \) and \( G \) of structural group \( H2 = 5 \):

\[
R_{65} = R_{H2} / 2, \quad R_{45} = R_{H2} / 2 .
\]

Here \( R_{H2} = M_{H2} / r_{H2} \).

2) We determine reactions in kinematics pairs \( C \) and \( D \) of structural groups 3-6 and 1-4:

\[
R_{23} = R_{65} \frac{r_6}{r_3}, \quad R_{21} = R_{45} \frac{r_4}{r_1} .
\]

Or

\[
R_{32} = -R_{65} \frac{r_6}{r_3} = -R_{H2} \frac{r_6}{2r_3} .
\]

\[
R_{12} = -R_{45} \frac{r_4}{r_1} = -R_{H2} \frac{r_4}{2r_1} .
\]

3) We determine the input moment on a link 2

\[
M_2 = -(R_{12} - R_{32}) r_2 . \quad \text{Or} \quad M_2 = R_{H2} \frac{r_3 r_4 - r_1 r_6}{2\eta r_3} .
\]

4) We determine the input impellent on a link \( H_1 \)

\[
F_{H1} = -(R_{12} + R_{32}) . \quad \text{Or} \quad F_{H1} = R_{H2} \frac{r_1 r_6 + r_3 r_4}{2\eta r_3} .
\]

Each link of mechanism is statically counterbalanced in the absence of an inertial force. Hence the mechanism will move in regular intervals.

So, for overcoming of output resistance force it is necessary to use in input structural group 1-2 the input force \( F_{H1} \) on input link \( H_1 \) and the input moment \( M_2 \) on input link 2. Then the number of input links (generalized co-ordinates) matches to number of degrees of freedom.

Let's present moment \( M_2 \) counterbalancing link 2 of input structural groups in an aspect the pairs of forces \( P_2 \) acting in points \( C \) and \( D \)

\[
P_2 = M_2 / 2 r_2 = R_{H2} \frac{r_3 r_4 - \eta_1 r_6}{4\eta r_3} .
\]
Then total forces $R_C$ and $R_D$ on a link 2 in points $C$ and $D$ will accept values:

$$R_C = R_{32} - P_2 = -R_{H2} \frac{r_6}{2r_3} - R_{H2} \frac{r_3 r_4 - r_1 r_6}{4r_1 r_3} =$$

$$= -R_{H2} \frac{r_1 r_6 + r_3 r_4}{4r_1 r_3}.$$

$$R_D = R_{12} + P_2 = -R_{H2} \frac{r_4}{2r_1} + R_{H2} \frac{r_3 r_4 - r_1 r_6}{4r_1 r_3} =$$

$$= -R_{H2} \frac{r_1 r_6 + r_3 r_4}{4r_1 r_3}.$$

Or considering the formula (1) we will gain $R_C = R_D = -F_{H1} / 2$. It means if on a link 2 of input structural group $H_1 - 2$ with two degrees of freedom to add reactions $R_{12}$ and $R_{32}$ transferred on it from the kinematic chain with the counterbalancing moment $M_2$ the link 2 will appear counterbalanced only one force $R_{H1-2} = R_{12} + R_{32} = F_{H1}$ applied in a point $B$.

But the same result will be gained on statics conditions if to consider that on input structural group $H_1 - 2$ one input driving moment $M_{H1} = F_{H1} r_{H1}$ and one set input force $F_{H1}$ matching to it counterbalancing reactions $R_C$ and $R_D$ transferred to this group act only. It means that the input structural group with two degrees of freedom is statically counterbalanced at presence only one generalized force $F_{H1}$ (or the counterbalancing moment $M_{H1} = F_{H1} r_{H1}$) on an input link $H_1$.

The gained conclusion defines paradox of mechanics - the input structural group with two degrees of freedom in the kinematic chain with the closed contour is statically definable (counterbalanced) at presence only one generalized force.

The paradox of mechanics provides static definability of the kinematic chain with two degrees of freedom at presence only one input. Thus the examined kinematic chain with two degrees of freedom but with one input is the mechanism.

Let’s prove it analytically.

With the input structural group having only one input impellent it is possible to examine the kinematic chain as the converted kinematic chain. The converted kinematic chain is equivalent on acting forces to initial kinematic chain with the input counterbalancing moment on a link 2.

Reactions are transferred to intermediate links 1-4 and 3-6: $R_{23} = R_{21} = F_{H1} / 2$ from the input satellite 2 and $R_{54} = R_{56} = R_{H2} / 2$ from the output satellite 5.

The balance of superposed forces in the kinematic chain takes place

$$M_{H1} + M_{H2} = 0. \quad (2)$$

At equality of magnitudes of the external moments $M_{H1} = M_{H2}$ we have $R_{H12} = F_{H1} r_{H1} / r_{H2}$.

As a result the link 1-4 will appear under the action of the unbalanced moment

$$M_{1-4} = R_{21} r_1 - R_{54} r_4 =$$

$$= \frac{F_{H1}}{2} \left( r_{H2} r_1 - r_{H1} r_4 \right). \quad (3)$$

The link 3-6 will appear under the action of the unbalanced moment

$$M_{3-6} = R_{23} r_3 - R_{56} r_6 =$$

$$= \frac{F_{H1}}{2} \left( r_{H2} r_3 - r_{H1} r_6 \right). \quad (4)$$

Let’s substitute in formulas (3), (4) values $r_{H1} = (r_1 + r_3) / 2$, $r_{H2} = (r_4 + r_6) / 2$ we will gain

$$M_{1-4} = \frac{F_{H1}}{2} \left( r_1 r_6 - r_3 r_4 \right). \quad (5)$$

$$M_{3-6} = \frac{F_{H1}}{2} \left( r_4 r_6 - r_3 r_4 \right). \quad (6)$$

From here the equation follows $M_{1-4} = -M_{3-6}$. That is

$$M_{1-4} + M_{3-6} = 0. \quad (7)$$

The formula (7) defines balance of internal forces. Thus for wheelwork internal forces on each intermediate link 1-4 and 3-6 are led to the moments $M_{1-4}$ and $M_{3-6}$ on each intermediate block of wheels which are unbalanced on conditions of statics. However for the mechanism as a whole according to the formula (7) balance of internal forces (moments) takes place. Balance of superposed forces (moments) by formula (2) simultaneously takes place. Hence all mechanism is in balance.

IV. THE ANALYSIS OF MOTION OF THE KINEMATIC CHAIN

Let’s examine regularities of interacting of parameters on the motion of the kinematic chain by means of a principle of virtual works. This condition of balance contains not only acting forces but also possible displacements (speeds). It is used for the kinematic chain moving under the action of forces.

According to a principle of possible works - the sum of works (powers) of all external and internal forces is equal to zero.

Let’s make for each satellite an equilibrium equation by a principle of possible works (powers). We will gain for the satellite 2

$$F_{H1} v_{H1} + R_{12} v_1 + R_{32} v_3 = 0.$$

Let’s express linear speeds of links through angular speeds. We will gain

$$F_{H1} \omega_{H1} r_{H1} + R_{12} \omega_1 r_1 + R_{52} \omega_3 r_3 = 0. \quad \text{Or} \quad M_{H1} \omega_{H1} + M_1 \omega_1 + M_3 \omega_3 = 0. \quad (8)$$
Analogously for the satellite 5 (with the account \( \omega_0 = \omega_4, \omega_3 = \omega_h \))

\[
M_{H_2\omega_2} + M_4\omega_1 + M_6\omega_3 = 0.
\]  
(9)

As satellites are a part of the mechanism we will add the made expressions for satellites. We will gain a condition of interacting of parameters of the mechanism as a whole

\[
M_1\omega_1 + M_3\omega_3 + M_4\omega_1 + M_6\omega_3 +
\]

\[
+ M_{H_1\omega_{H_1}} + M_{H_2\omega_{H_2}} = 0.
\]  
(10)

Or

\[
(M_1 - M_4)\omega_1 + (M_3 - M_6)\omega_3 +
\]

\[
+ M_{H_1\omega_{H_1}} + M_{H_2\omega_{H_2}} = 0.
\]  
(11)

In the presence of balance the sum of powers of superposed forces is equal to zero

\[
M_{H_1\omega_{H_1}} + M_{H_2\omega_{H_2}} = 0.
\]  
(12)

Then from (11) for internal forces

\[
M_{1-4}\omega_1 + M_{3-6}\omega_3 = 0.
\]  
(13)

For a particular case examined above at \( M_{H_1} = -M_{H_2} \) and \( M_{1-4} = -M_{3-6} \) the conditions (11) and (12) are carried out if \( \omega_{H_1} = \omega_{H_2} = \omega_3 = \omega_4 \) - the kinematic chain moves as a single whole without internal mobility of links.

Further let's examine the common case of balance in the movement at

\[
M_{H_1} \neq -M_{H_2}, \quad \omega_{H_1} \neq \omega_{H_2}.
\]

Let's express the internal moments on blocks of wheels 1-4 and 3-6 through superposed forces (moments)

\[
M_{1-4} = M_1 - M_4 = \]

\[
= R_{12}r_1 - R_{45}r_4 = \frac{F_{H_1}}{2} r_1 - \frac{R_{H_2}}{2} r_4. \quad \text{Or}
\]  
(14)

\[
M_{1-4} = \frac{M_{H_1}}{2r_{H_1}} r_1 - \frac{M_{H_2}}{2r_{H_2}} r_4.
\]

\[
M_{3-6} = M_3 - M_6 = \]

\[
= R_{32}r_3 - R_{65}r_6 = \frac{F_{H_1}}{2} r_3 - \frac{R_{H_2}}{2} r_6. \quad \text{Or}
\]  
(15)

\[
M_{3-6} = \frac{M_{H_1}}{2r_{H_1}} r_3 - \frac{M_{H_2}}{2r_{H_2}} r_6.
\]

From (12) taking into account signs of the moments

\[
M_{H_1} = M_{H_2}\omega_{H_2}/\omega_{H_1}.
\]

Let's mark out \( u_{12} = \omega_{H_2}/\omega_{H_1} \) - the transfer ratio of the mechanism. Then we have \( M_{H_1} = M_{H_2}u_{12} \). After substitution of value of the moment \( M_{H_1} \) in formulas (14) and (15) we will gain

\[
M_{1-4} = \frac{M_{H_2}}{2} \cdot \frac{u_{12}r_{H_2}r_1 - r_{H_1}r_4}{r_{H_1}r_{H_2}}.
\]  
(16)

\[
M_{3-6} = \frac{M_{H_2}}{2} \cdot \frac{u_{12}r_{H_2}r_3 - r_{H_1}r_6}{r_{H_1}r_{H_2}}.
\]  
(17)

Let's substitute in the formula (13) values of the moments \( M_{1-4} \) and \( M_{3-6} \). After abbreviation on \( M_{H_2}/2r_{H_1}r_{H_2} \) we will gain

\[
(u_{12}r_{H_2}r_1 - r_{H_1}r_4)\omega_1 +
\]

\[
+ (u_{12}r_{H_2}r_3 - r_{H_1}r_6)\omega_3 = 0.
\]  
(18)

Let's substitute in the formula (18) value \( u_{21} = \omega_{H_2}/\omega_{H_1} \).

With the account \( v_{H_2} = \omega_{H_2}r_{H_2}, v_{H_1} = \omega_{H_1}r_{H_1} \)

\[
v_1 = \omega_4 r_1, \quad v_4 = \omega_4 r_4, \quad v_3 = \omega_3 r_3, \quad v_6 = \omega_3 r_6 \]

we will gain

\[
v_{H_2}v_{H_2} - v_4v_{H_1} + v_3v_{H_2} - v_6v_{H_1} = 0. \quad \text{Or}
\]

\[
\omega_{H_1} \omega_{H_1},
\]

\[
v_{H_2}(v_1 + v_3) - v_{H_1}(v_4 + v_6) = 0.
\]  
(19)

From a picture of speeds of a wheelwork (Fig. 3) it is visible

\[
v_1 + v_3 = 2v_{H_1}, \quad v_4 + v_6 = 2v_{H_2}.
\]

After substitution these values in the formula (19) we will gain

\[
2v_{H_2}v_{H_1} - 2v_{H_2}v_{H_1} = 0. \quad \text{That is } 0 = 0.
\]

It means that the condition of balance of internal forces (13) by a principle of possible work is carried out if the condition of balance (12) for superposed forces is satisfied.

Thus for the kinematic chain balance of internal forces in the presence of unbalanced separately links 3 and 4 takes place. But this balance takes place only in the motion.

The executed researches of kinematics and the power analysis of the kinematic chain with two degrees of freedom allow making following conclusions:

1) Power analysis of a chain is carried out as the solution of a direct problem of dynamics – on the set motion to define forces. The set parameters are input angular speed \( \omega_{H_1} \) and output moment of resistance \( M_{H_2} \). However the formula (12) allows setting the input driving moment also \( M_{H_1} \). The setting of the external moments \( M_{H_1} \) and \( M_{H_2} \) (on which internal forces are defined) characterizes static definability of the kinematic chain. According to the formula (12) static (power) definability of the kinematic chain takes place on the motion.

2) Formula (12) characterizes the kinematic definability of the kinematic chain with two degrees of freedom. At the set input speed \( \omega_{H_1} \) and the set external moments \( M_{H_1} \) and \( M_{H_2} \) the formula (12) allows determining an output speed \( \omega_{H_2} \). Through the speeds \( \omega_{H_1} \) and \( \omega_{H_2} \) the speeds of intermediate links are determined.

3) Formula (12) connecting the kinematic and power parameters of the kinematic chain with two degrees of freedom represents additional constraint which imposes the
V. CONCLUSION

Use of the found regularities allows to create the motors-wheels possessing property of mechanical adaptation to variable technological loading. The adaptive mechanism provides possibility of motion of output link with a speed inversely proportional to external resistance moment. The effect of power adaptation characterizes the major property for machines with variable technological resistance – ability independently and continuously to adapt for variable technological loading.

The kinematic chain with two degrees of freedom having only one input is gear continuously variable transmission.

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AUTHOR BIOGRAPHY

Konstantin Ivanov - doctor of technical sciences, professor, author of more 150 publications on theory of gear CVT and 25 patents on gear CVT in Kazakhstan, Russia and Germany, member of ASME.


Mechanical and Machine science institute of National Academy of Sciences of Kazakhstan. Head of Laboratory “Adaptive Mechanisms”. Current address: 050026, Isaev street, 28, ap. 3, Almaty, Kazakhstan. E-mail: ivanovk@mail.ru. Phone: 8-727-379-79-30.

Experience of scientific and pedagogical activity:
- He has created the theory of a synthesis of lever mechanisms on the basis of the inverse of motion;
- He has developed the theory of adaptive mechanisms;
- He has developed 88 inventions and patents.

The basic scientific works: