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# ADAPTIVE MECHANICAL DRIVE FOR SELF-ADAPTIVE SYSTEMS

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**Abstract**

Recently, self-adaptive systems have been widely used in robotics, in autonomous transport technology and in the aerospace industry. Weyns presented a set of basic principles, engineering fundamentals, and self-adaptation applications in software-intensive systems. Self-adaptation will be a crucial function in solving the problems of new and future systems. Bollinger presented an overview of automated drives and controls in the context of a wide variety of industrial and laboratory applications. It is stated that a multi-axis robotic device is a highly sophisticated machine that can have insurmountable theoretical control problems. Self-adaptation capabilities can be significantly improved by using adaptive mechanical drives that independently adapt to external loads and do not require power parameter control. The control of adaptive drives consists only in the coordination of their actions. A compact self-regulating adaptive drive containing a motor and an adaptive mechanical converter (without a control system) is the object of research. The author has developed an adaptive mechanical converter for continuously regulating the power and kinematic parameters of the drive in a wide range using a two-moving gear mechanism containing an additional constraint. The article presents the theoretical basis for creating a compact stepless drive with an adaptive mechanical converter that provides the ability to move in a wide range of control without a control system.

**Keywords:** Adaptive Drive, Adaptive Mechanical Converter, Two Degrees of Freedom, Additional Constraint, Steady Motion, Determinability of Motion

## I. INTRODUCTION

Recently, self-adaptive systems have been widely used in robotics, in autonomous transport technology, and in the aerospace industry. The topic of self-adaptation has become significant, although little attention is paid to this topic in the academic and technical literature. Weyns presented a set of basic principles, engineering fundamentals, and self-adaptation applications in software-intensive systems [1]. Self-adaptation will be a crucial contributing function in solving the problems of new and future systems.

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Bollinger presented an overview of automated drives and controls in the context of a wide variety of industrial and laboratory applications. It is stated that a multi-axis robotic device is a highly sophisticated machine that can have insurmountable theoretical control problems.

Self-adaptation capabilities can be significantly improved by using adaptive mechanical drives that independently adapt to external loads and do not require power parameter control. The control of adaptive drives consists only in the coordination of their actions. A compact self-regulating adaptive drive containing a motor and an adaptive mechanical converter (without a control system) is the object of research.

To create an adaptive drive for self-adaptive systems, a simple, compact and reliable mechanical converter is required.

Currently, the automotive controlled automatic transmission (CVT) is widely used in car drives as an adaptive converter. The CVT contains a torque converter, a step gear box and a control system. The action of the transmission is based on the laws of hydrodynamics and the theory of mechanisms and machines [3].

CVT is able to provide smooth control of power and kinematic parameters in a given range. The torque converter at each stage (within limited limits) changes the angular velocity depending on the moment of resistance, and the automatic control system switches the transmission stages in a wide range of control. However, a in the form of a CVT cannot be used in the space industry or in robotics due to the complexity and bulkiness of the design.

Many inventors Crockett [4], Harris [5], Vedeneev [6] tried to create an adaptive mechanical converter with a wide range of regulation without using a step gearbox and a torque converter based on a gear differential mechanism with two degrees of freedom, having one input and one output. However, the analytical apparatus used did not allow them to obtain reliable results of the interaction of the parameters and to achieve the converter motion definiteness.

The author has developed and patented a method and device for stepless regulation of force and kinematic parameters using a gear mechanism in a wide range [7, 8]. In these patents, the principle of virtual works with virtual displacements replaced by valid displacements was used to analyze the mechanism. This allowed us to formulate the necessary condition for force adaptation - the presence of a mobile closed contour [9].

Further research allowed us to find a regularity that leads to a sufficient condition for force adaptation. – In a closed loop, there must be an additional constraint [10]. This constraint should replace the unbalanced force in the instantaneous center of velocities

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in the closed loop. The method of replacing an unbalanced force with an internal force, for example, the friction force, was patented by the author [11].

This method allows you to use the constraint between force and speed, similar to the constraint created by the torque converter in the CVT. However, an additional constraint in a closed loop, in contrast to the constraint in a torque converter, can be created at a low relative speed of the links, which significantly reduces power losses.

The research method used in this paper corresponds to the conditions of existence of the observed object. An adaptive mechanical system is considered in the mode of steady motion, when the work of the driving forces is equal to the work of the resistance forces. The presence of an additional force constraint puts the system in a state with one degree of freedom while maintaining the ability to change the output power parameters. The input and output links move evenly. The interaction of forces in this case corresponds to the principle of virtual work (using real displacements instead of virtual ones). Then it is possible to use the conditions of static equilibrium, that is, the classical method of force analysis of the mechanism. The article presents the theoretical basis for creating an efficient stepless drive with an adaptive mechanical converter that provides the ability to move in a wide control range without a control system.

## II. ADAPTIVE MECHANICAL CONVERTER

An adaptive gear variator can be used as a mechanical converter [10]. The adaptive gear variator is a two-moving gear mechanism with constant gear engagement, in which the variable moment of resistance on the output shaft independently changes the gear ratio in a given range.

The kinematic chain of the gear variator (Fig. 1 a) contains a rack 0, an input carrier $H_1$, a movable closed circuit (contour or loop) with gears 1-2-3-6-5-4 and an output carrier $H_2$. A closed loop having zero mobility contains a satellite 2, a solar wheel block 1-4, a ring wheel block 3-6, and a satellite 5. The carriers $H_1$ and $H_2$ are the initial links of the mechanism. The initial links have given angular velocities $\omega_{H1}$ and $\omega_{H2}$ and given moments of forces $M_{H1}$ and $M_{H2}$. $M_{H1} = const$. $M_{H2}$ Can take different values within a given range.

Linear force and kinematic parameters take place:

$$F_{H1} = M_{H1} / r_{H1}, \quad F_{H2} = M_{H2} / r_{H2}, \quad V_B = \omega_{H1} r_{H1}, \quad V_K = \omega_{H2} r_{H2}$$

Here $r_{H1}$, $r_{H2}$ are the radii of the points of application $B$, $K$ of forces.

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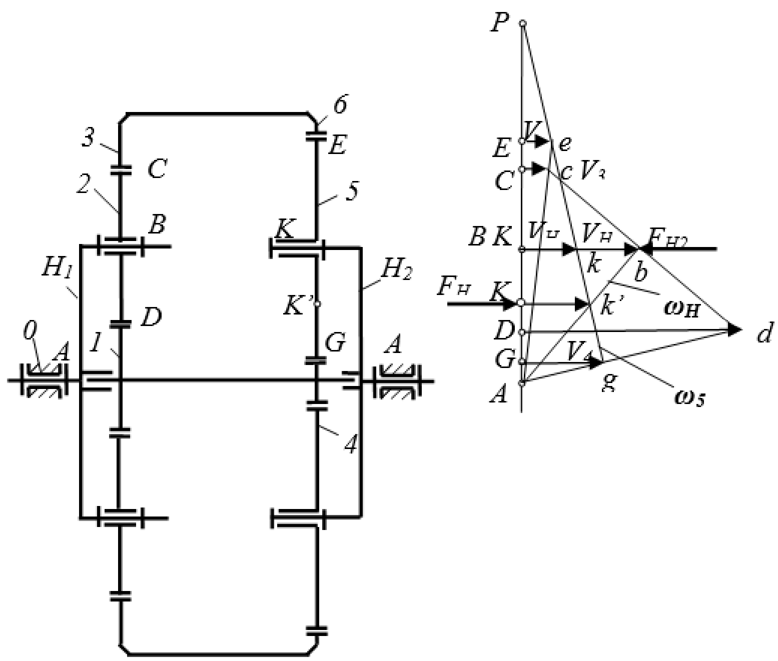
The steady-state mode of movement, in which the mechanism moves evenly, takes place. The work of the driving forces is equal to the work of the resistance forces during each cycle of steady motion. The transition mode of movement takes place when the moment of resistance changes. The presented two-moving scheme of the mechanism with a movable closed loop allows you to build a plan of linear velocities according to the specified velocities of the two initial links and obtain equilibrium conditions. (In a mechanism without a closed loop, equilibrium is not possible under the specified conditions). To the right of the mechanism is a plan of linear velocities (Fig. 1b).Let us present the theoretical regularities of the relationship between the parameters.

**Fig. 1: The mechanism with two degrees of freedom and the plan of its linear velocities**




a) b)

## III. FORCE ADAPTATION. A NECESSARY CONDITION

The theoretical possibility of force adaptation is proved by the author using the closed-loop theorem [9] based on the analysis of the interaction of the parameters of the

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mechanical system. To study the interaction of the parameters of a mechanical system with two degrees of freedom, the principle of virtual work [3] with the use of differential equations of motion is usually used. However, with a given scheme of the mechanism in a steady-state mode of movement, this method of research is not applicable.

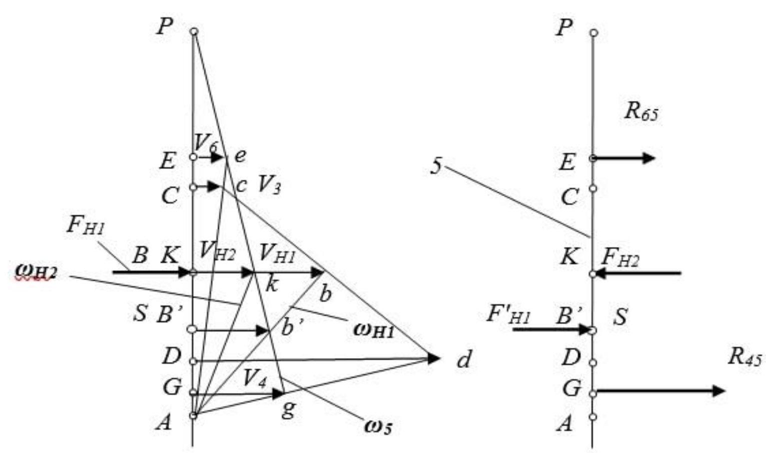
In this case, the research method should be based on the use of equilibrium equations. Force analysis of a mechanical system with two degrees of freedom in the steady-state motion mode is a solution to the direct problem of dynamics – to determine the acting forces from a given motion. We assume that with the steady motion of the system in the form of a gear mechanism, all the links move uniformly, and there are no inertia forces.

A refined formulation of the force adaptation theorem:

A two-moving kinematic chain with specified kinematic and power parameters is given (Fig. 1). It should be proved that a movable closed circuit in a two-moving kinematic circuit with one input and one output creates the possibility of force adaptation.

Let's assume that the system has two initial links, which are the input links. There are only real displacements (velocities) corresponding to the velocities of the initial links, according to which the plan of linear velocities is constructed (Fig. 1b). A movable closed loop allows you to transfer all the active forces to the satellite 5 (Fig. 2).

**Fig. 2: Plan of linear velocities and satellite 5 with applied forces**




The force $F_{H1} = M_{H1} / r_{H1}$ acting at the point $B$ is transmitted to the link 5 from the driver $H_1$ to the satellite 2 through the wheel blocks 3-6 and 1-4 in the form of reactions

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$R_{65} = 0.5F_{H1}r_3 / r_6$ and $R_{45} = 0.5F_{H1}r_1 / r_4$. The input force reduced to link 5 is equal to the sum of these reactions $F'_{H1} = 0.5F_{H1}(r_3 r_4 + r_1 r_6) / r_4 r_6$.

Here $r_i$ is the radius of the wheel i.

The position of the point of application $B'$ of the reduced force $F'_{H1}$ is determined by the formula $KB' = r_5(r_1 - r_4) / r_4$. Bringing the force to a link 5 corresponds to the condition of equality of power of the source power and the power of these forces $F_{H1}V_{H1} = F'_{H1}V'_{H1}$.

The force $F_{H2}$ is applied at the point $K$.

Consider the equilibrium of link 5. The sum of the moments relative to the instantaneous velocity center of the link is zero

$$\sum M_P = 0. \quad (1)$$

Or

$$F_1 \cdot (PK + KS) - R_6 \cdot PK = 0. \quad (2)$$

Here $KS = e$. From here, the position of the instantaneous velocity center $P$ (distance $PK$) can be determined from the given forces

$$PK = F_1 e / (R_6 - F_1). \quad (3)$$

Taking into account the movement of link 5 around a point $P$ with an angular velocity $\omega_5$, you can use the substitutions in equation (2)

$PK + KB' = V'_B / \omega_5 \quad PK = V_K / \omega_5$. Then equation (2) will take the form

$$F'_{H1} \cdot V'_B - F_{H2} \cdot V_K = 0.$$

Or

$$F_{H1} \cdot V_B - F_{H2} \cdot V_K = 0.$$

Taking this into account $V_B = \omega_{H1} r_{H1}, \quad V_K = \omega_{H2} r_{H2}$ we obtain the equilibrium equation of the entire mechanism according to the principle of possible operations (capacities) – the sum of the input and output capacities is zero

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$$M_{H1} \cdot \omega_{H1} - M_{H2} \cdot \omega_{H2} = 0. \quad (4)$$

It is generally assumed that the initial links have positive cardinalities. But according to the formula (4), one of the powers must be negative, that is, the output. Then formula (4 ) will express the law of conservation of energy for a mechanism with one input ($H_1$) and one output ($H_2$). At the same time, formula (4) corresponds to the principle of virtual work (capacity), but with a significant difference – using real displacements instead of virtual ones.

From equation (4) follows the expression of force adaptation

$$\omega_{H2} = M_{H1} \cdot \omega_{H1} / M_{H2}. \quad (5)$$

At a given constant input power, the output angular velocity $\omega_{H2}$ adapts to the variable output drag torque . $M_{H2}$

Thus, a movable closed circuit in a two-moving kinematic circuit with one input and one output creates the possibility of force adaptation, which was required to be proved.

Formula (4) defines the necessary condition for force adaptation.

## IV. ANALYSIS OF THE MOVEMENT DEFINITENESS

The formula (4) of the equilibrium of link 5 and the entire system corresponds to the principle of virtual work (capacity), using real displacements. A valid move is one of the virtual ones. It can be assumed that the equilibrium formula (4) proves the determinability of the motion of the system according to the principle of virtual operations. However, for the equilibrium of link 5, it is not enough to use only the condition (1) that the sum of moments is equal to zero. In the general case when $F_{H2} > F_{H1}$, at the instantaneous center of the velocities $P$ a force $R_{05} = F_{H2} - F_{H1}$ will appear - a conditional (not really existing) reaction from the rack. This force does not participate in the equilibrium condition according to the virtual work principle (4), since the velocity of its point of application $P$ is zero. In the case under consideration, condition (4) is not a necessary and sufficient condition for equilibrium.

For the determinability of motion at a point $P$, it is necessary to create a real constraint, but this will contradict the possibility of creating an adaptation (the presence of two degrees of freedom). Definiteness of motion and balance can only take place when force $R_{05}$ is taken into account.

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The force is determined from the second equilibrium condition of link 5 – the sum of the forces is zero $\sum F = 0$. From this condition

$$R_{05} = F_{H2} - F_{H1}. \tag{6}$$

The determinability of the motion of a two-moving system can be achieved by replacing the moment $M_{05}$ of this unbalanced force $R_{05}$ relative to the point $K$ stationary at the start with the moment of friction $M_{fK}$ in the satellite joint $K$ [11].

The replacement (balancing) moment of friction. $M_{fK} = M_{05} = R_{05} \cdot PK$

However, this method is associated with high friction losses.

A more efficient replacement method is possible.

## V. ENSURING THE DEFINITENESS OF THE MOVEMENT OF A TWO-MOVING KINEMATIC CHAIN WITH ONE INPUT. SUFFICIENT CONDITION FOR FORCE ADAPTATION

A closed circuit provides the necessary condition for force adaptation. The necessary condition provides only the possibility of force adaptation, without imposing a real structural constraint. However, this condition alone is not enough for the implementation of force adaptation. The block diagram of a closed-loop mechanical system must remain two-way when there is only one input. Obviously, to provide a real constraint that preserves the number of degrees of freedom, the constraint of the moment with the angular velocity is necessary (mobile force-velocity constraint). Such a constraint in mechanics is called a differential constraint.

In the technique, the constraint of the moment with the angular velocity is known – this constraint takes place between the moving links of the torque converter and is determined by its characteristic.

A closed loop allows us to obtain a fundamentally new, highly efficient way to create a constraint between the moment and the angular velocity. The method is based on the use of redundant coupling, which was found in the study of the linear velocity plan of the system [9, 10].

On the plan of linear velocities (Fig. 3), a certain point was found at the intersection of the inclined lines of angular velocities $\omega_{H1}$ and $\omega_5$. At a constant angular velocity $\omega_{H1}$ and a variable angular velocity $\omega_5$, this point occupied a constant position. That is, the line $\omega_5$ rotated around a fixed point $s$. The point $s$ corresponds to a point $S$ on the vertical

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initial velocity line of the points of the mechanism. The linear velocity vector $Ss$ is the same for the link $H_1$ point $S$ and the link 5point $S$. The point $S$ was named the center of coincidence of the link speeds.

If a real constraint is placed at a point $S$, for example, in the form of a contact point of the teeth of the gears 8 and 7, rigidly connected to the links $H_1$ and 5, then this constraint will be redundant, it will transfer movement from the driver $H_1$ to the link 5 with the same gear ratio as occurs in a planetary mechanism without this constraint. If the contact point $S'$ of the teeth of this constraint does $S$ not coincide with the point $S$, then the constraint will be jammed, the system will jam with the loss of one degree of freedom.

**Fig. 3: Definable effective converter**

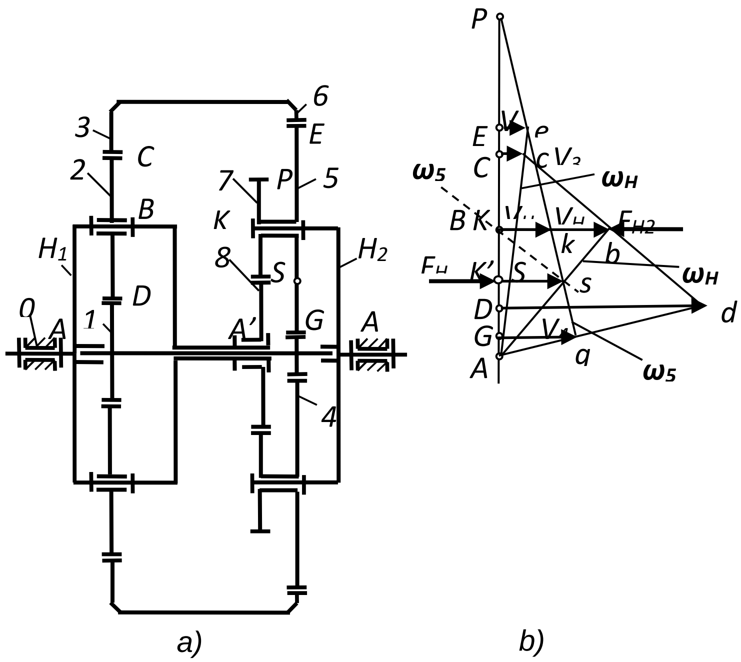


Fig. 3 shows a definable converter with a movable-jamming transmission. This transmission contains the input carrier $H_1 - 5$ and the jamming part 8-7-5, connected by a friction joint $A'$.

To create an effective real constraints of a new type is offered first to create a wedging relationship at a point close to the point in the form of wheels 8 and 7 and the wheel 8 to

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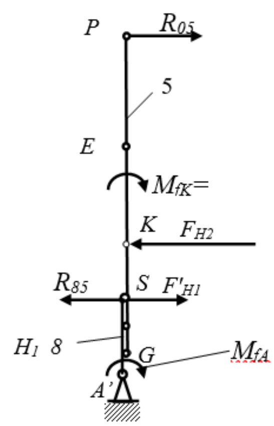
attach to the carriar *cage* $H_1$, a movable constraint, e.g. a frictional constraint in the hinge $A'$, allowing small relative motion of separated parts 8 and $H_1$. In this case, the links $H_1$ and 8 can interact more effectively. - The jamming force will be arbitrarily set, and the relative speed of the links will be small.

If we use the friction between the links $H_1$ and 8 of the jamming constraint, then at a low relative speed of the separated parts, the power loss for friction will be minimal

The interaction of forces is shown in Fig. 4.

**Fig. 4: The interaction of forces taking into account the mobile-jamming constraint**




As a substitute for the balancing frictional moment of resistance in the joint $A'$, the moment $M_{fA}$ that transmits the force $R_{85}$ to the link 5 will be used . As a result of replacing the force $R_{05}$ with the force $R_{85}$, we get the equilibrium condition of the link 5: $R_{85} = F'_{H1}$.

For link 8 or $H_1$, this condition will take the form $M_{fA} = M_{H1}$, that is, the balancing moment of friction in the joint $A'$ is equal to the input driving moment and is constant in magnitude (does not depend on the variable moment of resistance $M_{H2}$).

This unexpected result is explained as follows. By the equilibrium condition of link 5

$$F'_{H1} \cdot KS = R_{05} \cdot PK \text{ .} \qquad (7)$$

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Here, the left side of the equation is constant in magnitude. The right-hand side of the equation containing the variable drag force $F_{H2}$ (according to the formula $R_{05} = F'_{H1} - F_{H2}$) will also be constant in magnitude, since $F'_{H1} \cdot KS = const$ . This is explained by the fact that the parameter $PK$ that determines the position of the pole $P$ and depends on the resistance force according to formula (3) is also variable. This is an important feature of the converter. Therefore, the replacement moment at link 5 will also be a constant value $M_{05} = F'_{H1} \cdot KS$ .

Balance link 5 and the whole system will be ensured under the condition of replacement of the reaction $R_{05}$ on level 5 force $R_{85}$, creating a similar resistance with additional time on the input carrier $M'_{H1/} = R_{85} \cdot AS' = M_{H1}$.

As a result, it turns out that the input driver will transmit to the satellite 5 the driving moment $M_{H1}$ through the planetary chain and the moment $M'_{H1}$ overcoming the friction resistance through the direct transmission 8-7.

The use of a movable jamming constraint with a balancing moment of friction in the joint $A'$ (Fig. 3) will provide a wide range of control at a low relative speed of the links.

The angular velocity line $\omega_5$ can rotate under the action of the drag force $F_{H2}$ from the position providing $\omega_{H2} = 0$ (shown by the dotted line) until $\omega_{H2} = \omega_{H1}$, when the dotted line matches the line $\omega_{H1}$.

Thus, the range of transmission ratios of the converter $u_{H1-H2} = \omega_{H1} / \omega_{H2}$ will be within the limits $1 \le u_{H1-H2} \le \infty$ .

## VI. THE EFFICIENCY OF THE SYSTEM

The interaction of the system parameters can be determined using the law of conservation of energy (4), taking into account the friction losses

$$M_{H1} \cdot \omega_{H1} = M_{H2} \cdot \omega_{H2} + P_f \, . \qquad (9)$$

Here $M_{H1}$ is the input driving moment that overcomes the output moment of resistance $M_{H2}$ and the moment of friction $M_{fA}$ in the mobile - jamming constraint,

$P_f$ - the power of friction losses in the movable-jamming constraint (in the hinge $A'$).

$$P_f = M_{H1} \Delta \omega_f \, . \qquad (10)$$

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Here $\Delta\omega_f = \omega_{H1} - \omega_8$ is the difference between the angular velocities of the input driver and the wheel 8. The value $\Delta\omega_f$ can be set by the necessary appropriate placement of the engagement pole of the wheels 8 and 7 at a point $S'$ close to the center of the coincidence of speeds $S$ (Fig. 3).

You can set it . $\Delta\omega_f = k\omega_{H1}$ For example, $k = 0.1$. Then $P_f = kM_{H1}\omega_{H1}$.

The efficiency factor (KPI) is defined as follows

$\eta = (M_{H1}\omega_{H1} - P_f) / M_{H1}\omega_{H1}$. (11)

After substituting the values $P_f = kM_{H1}\omega_{H1}$, we get $\eta = 1 - k$ .

Here i $k$ s the loss coefficient.

For example, when $k = 0.1$ we receive $\eta = 0.9$ .

## VII. CONCLUSION

A self-regulating adaptive electric drive containing an electric motor and an adaptive mechanical converter (without a control system) is an efficient electromechanical system. The absence of a control system in the drive greatly simplifies the design and increases its reliability. The developed and patented methods (the presence of a closed loop, a movable-jamming constraint, the replacement of an unbalanced force with a calculated constant friction force), provide the possibility of optimal functioning of a fundamentally new electromechanical system.

The operation of the system is based on the static rather than dynamic interaction of parameters, which simplifies the analysis of the relationship of parameters.

A movable closed circuit in a two-moving kinematic circuit with one input and one output creates the possibility of force adaptation. The additional power-speed coupling brings the system to a state with one degree of freedom while maintaining the ability to change the output power parameters.

The interaction of forces in this case is subject to the principle of virtual work (using real movements instead of virtual ones). The range of transmission ratios of the converter is wide. An important feature of the converter is that the replacement friction moment on the link 5 is a constant value that does not depend on the variable load. The converter has a relatively high efficiency due to the low friction power loss at a low relative speed of the friction links.

The simplicity of the design, small dimensions and weight make it significantly more competitive and suitable for use in robotics, in the aerospace industry, as well as in mobile transport equipment.

### VIII. FINANCING OF THE WORK

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