

Structural Analysis and Study of Self-Adjusting Mechanisms [†]

Konstantin Ivanov 

Joldasbekov Institute of Mechanics and Engineering, Almaty 050000, Kazakhstan; ivanovgreek@mail.ru;
Tel.: +038-3582483052

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Abstract

The self-adjusting mechanism, as the study shows, independently (without a control system) adapts to changes in the working process, which significantly expands the possibilities of its use in automatic machines. The main idea of creating a self-adjusting mechanism is to use a structural chain instead of a kinematic chain. A structural chain is a system of links connected by kinematic and force pairs. Previous studies have shown that the new mechanism can self-adjust (or independently adapt to a variable external load) and is a self-regulating mechanism. The proposed article is a structural analysis and study of self-adjusting mechanisms.

Keywords: definability of motion; structural chain; force connection (constraint); structural pair; self-adjusting mechanism; force adaptation

1. Introduction Materials and Methods

Almost all the mechanisms used in engineering are built based on a kinematic chain with one degree of freedom—they are single-moving mechanisms. They are based on a kinematic chain with one degree of freedom with one input. A single-moving mechanism has the definability of movement—a one-to-one correspondence of input and output kinematic (or force) parameters. The capabilities of the mechanism will be significantly expanded if it has not only kinematic pairs but also force pairs. A force pair is first described in the article [1] as a structural element that provides the definability of motion of a two-movable kinematic chain with a single input. A force pair is created in a rotational kinematic pair (in a joint) by a tensioning screw that causes the friction moment of the interacting surfaces. The friction moment prevents the relative rotation of the links and creates a force coupling, $M_f = Nfd$. Here f is the coefficient of friction, and d is the diameter of the axle of the joint. In a similar way, a force pair can be created by a tensioning screw as a friction force, $F_f = Nf$, in a translational kinematic pair.

System of links, connected by kinematic and force pairs, form a structural chain. A definable two-movable structural chain with a single input will undoubtedly have fundamentally new properties. A definable two-movable structural chain with one input, containing additional force coupling (constraint), is the basis for the creation of self-adjusting mechanisms with new properties. An adaptive self-adjusting gear variator has been developed and patented [2], which independently changes the gear ratio under the action of a variable external load. A prototype of the gear variator was tested on a test bench and published in the MDPI journal *Machines* [3].

Many inventors have tried to use a two-moving kinematic chain to create a continuously variable transmission (CVT) [4–6]. However, these attempts were unsuccessful due



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to the lack of definability of motion. The practical use of a kinematic system with two degrees of freedom with one input is hindered by the following statement of mechanics and theory of mechanisms and machines [7,8]: the number of inputs of the system must be equal to the number of degrees of freedom.

A self-adjusting mechanism is a fundamentally new mechanism in the theory of machines and mechanisms, which is the scientific basis for the creation of new mechanisms. The fundamental course of the theory of machines and mechanisms [7] (p. 12) says, "The development of the theory of automatic machines is mainly associated with the improvement of methods for constructing a scheme of the control system of executive bodies. Of particular value is the creation of methods for building self-adjusting control schemes, in which the control program automatically adjusts as the workflow changes."

The self-adjusting mechanism, as the study shows, independently (without a control system) adapts to changes in the working process, which significantly expands the possibilities of its use in automatic machines.

The task of the proposed research is to develop the main provisions of the structural analysis of the chain of a self-adjusting mechanism, to deeply analyze the interaction of force and kinematic parameters of the structural chain with one input based on a creative approach, as well as to determine the new capabilities of such a system.

2. Description of the Main Structural Elements

The article presents new structural elements.

A structural pair is a mobile connection of two contacting links, which allows their relative movement with the overcoming of force resistance.

The most common are single-mobility structural pairs: translational and rotational.

A translational structural pair (Figure 1) with links 1 and 2 is created by adding force resistance (e.g., frictional force F_f) to the linear kinematic pair, which prevents relative translation motion. The resistance is created by a tension screw 3, which causes a normal reaction N and, in the presence of friction, a frictional force

$$F_f = Nf. \quad (1)$$

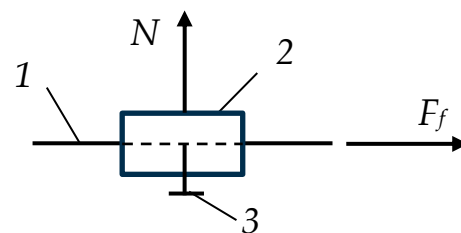


Figure 1. Translational structural pair.

A translational structural pair allows for relative translational motion of links 1 and 2 (1 degree of freedom) and simultaneously imposes one coupling condition.

A rotational structural pair or force joint (Figure 2) is created by adding a rotational force resistance (e.g., frictional moment M_f) to the joint links 1 and 2 to prevent relative rotation. The resistance is created by a tension screw 3 that causes a normal reaction N in the joint and, in the presence of friction, a frictional moment

$$M_f = Nfd. \quad (2)$$

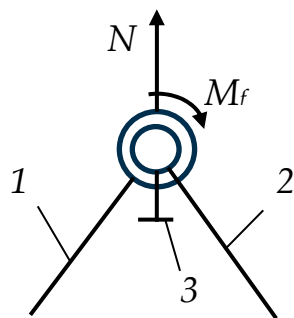


Figure 2. Rotational structural pair.

Here d is the diameter of the trunnion.

A rotational structural pair allows for relative rotational motion of links 1 and 2 (1 degree of freedom) and simultaneously imposes one force constraint (coupling condition).

The introduction of new structural elements into structural analysis allows us to introduce some new definitions.

A structural chain is a system of links connected by kinematic and force pairs.

A mechanism is a structural chain with one fixed link, in which, with a given movement of one or more links, the rest of the links perform certain movements, which may depend on the forces of resistance.

It should be noted that resistance to the relative motion of the structural pair links can also be created in other possible ways: hydraulic (using hydraulic cataracts), magnetic (using the magnetic material niobium), electromagnetic (using electromagnetic interaction), and other methods.

3. Description of the Mechanism with Structural Pairs

The basis of a mechanism with structural pairs is a structural chain.

A plane kinematic chain with two degrees of freedom can be transformed into a structural chain with one degree of freedom by converting one of the simplest kinematic pairs into a structural pair.

Figure 3 shows a structural self-adjusting mechanism. The mechanism contains a rack 0, an input link 1, an intermediate link 2, and an output link 3. The links are connected by kinematic pairs A, B, C, D . The rotary kinematic pair at point C is converted into a structural pair by means of a tension screw 4, which produces a normal reaction N and a frictional moment of resistance M_{f32} —force connection (force constraint). The frictional moment M_{f32} replaces the moment of the unaccounted reaction $N = F_{f32} = R - F$. In the instantaneous velocity center p value of the moment, $M_{f32} = F_{f32} y = (R - F)y$. The addition of a one force constraint turns the mechanism's two-movable kinematic chain into a structural chain with one degree of freedom. Such a chain, in the presence of one input, has the definability of motion and fundamentally new properties.

Let us consider the interaction of kinematic and force parameters of the simplest structural mechanism.

Let us designate—desaxial $BC = e$.

V_i $i = 1, 3$ are the input and output linear velocities.

$PC = y$ is a variable parameter for the location of the instantaneous center of velocities, determined from the condition or $PC/PB = V_3/V_1$ or $y/(y + e) = V_3/V_1$.

From here $y = V_3 e / (V_1 - V_3)$.

External forces: F —driving force; R —resistance force.

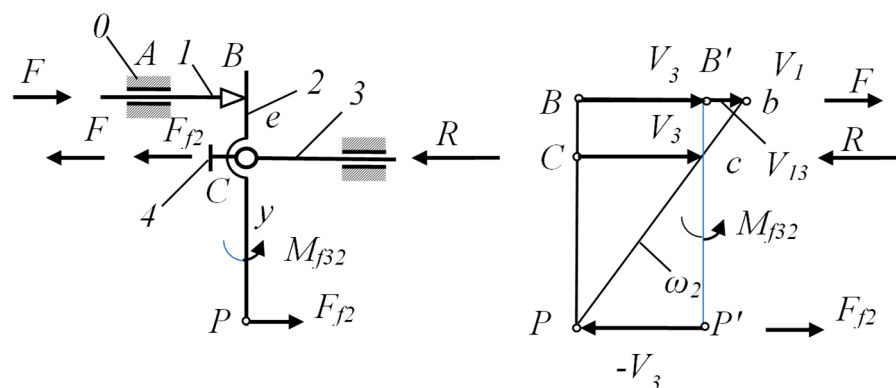


Figure 3. Structural self-adjusting mechanism and linear velocity plan.

To study the interaction of kinematic and force parameters, we will use the principle of virtual work (power): a necessary and sufficient condition for the equilibrium of the system is that the virtual work (power) of the active forces on all arbitrary virtual displacements of the system is equal to zero [7,8].

Let us make a power balance equation of link 2, based on the principle of virtual work (power). Link 2 is affected by the motive force F with a given velocity V_1 , the drag force R with velocity V_3 , and the frictional moment $M_{f32} = (R - F)y$ with angular velocity ω_2 around the fixed point C , defined by the vector— V_3 at point P . The equilibrium equation of link 2 has the form

$$\begin{aligned} FV_1 &= M_{f32}\omega_2 + RV_3. \text{ Or} \\ FV_1 &= (R - F)V_3 + RV_3. \end{aligned} \quad (3)$$

The input power of the engine is equal to the sum of the power expended to overcome the frictional moment and to overcome the output resistance force. Hence

$$FV_1 = (2R - F)V_3. \quad (4)$$

Equation (3) is the force balance equation of the mechanism.
From this we obtain the expression of the variable gear ratio

$$u_{13} = \frac{V_1}{V_3} = (2R - F)/F. \quad (5)$$

From Equation (5) we obtain the equation of force adaptation of a self-regulating mechanism to a variable external load.

$$V_3 = FV_1/(2R - F). \quad (6)$$

With constant input power parameters, the output linear velocity V_3 is inversely proportional to the variable output resistance force R .

An important qualitative indicator is the efficiency factor—the ratio of useful power P_e to the power expended P_u . Using Equation (3), we get

$$\eta = P_e/P_u = FV_1 - (R - F)V_3/FV_1. \quad (7)$$

4. Determination of the Interacting Parameters of Structural Self-Adjusting Mechanism. Numerical Example

Problem statement.

The structural self-adjusting mechanism (Figure 3) has the following specified parameters: Geometric parameters $e = 0.01$ m, $d = 0.002$ m.

External forces $F = 12 \text{ N}$, $R = 16 \text{ N}$.

Input velocity $V_1 = 0.4 \text{ m/s}$.

Coefficient of friction in the friction joint C, which provides the definability of motion $f = 0.6$.

Determine the velocities of the links V_3 and ω_2 , the position y of the instantaneous center of velocities P of link 2, the required frictional torque M_{f32} , the tension force N in the friction joint C, the gear ratio $u_{13} = \frac{V_1}{V_3}$, and efficiency η .

Solution

- (1) $V_3 = FV_1 / (2R - F) = (12 \times 0.4) / (2 \times 16 - 12) = 0.24 \text{ m/s}$.
- (2) $\omega_2 = (V_1 - V_3) / e = (0.4 - 0.24) / 0.01 = 16 \text{ s}^{-1}$.
- (3) $y = V_3 e / (V_1 - V_3) = 0.24 \times 0.01 / (0.4 - 0.24) = 0.015 \text{ m}$.
- (4) $M_{f32} = (R - F)y = (16 - 12) \times 0.015 = 0.06 \text{ Nm}$.
- (5) $N = (R - F)y / fd = (16 - 12) \times 0.015 / 0.6 \times 0.002 = 50 \text{ N}$.
- (6) $u_{13} = \frac{2R - F}{F} = \frac{2 \times 16 - 12}{12} = 1.66$.
- (7) $\eta = P_e / P_u = \frac{FV_1 - (R - F)V_3}{FV_1} = \frac{12 \times 0.4 - (16 - 12) \times 0.24}{12 \times 0.4} = 0.8$.

5. Conclusions

Let us formulate the foundations of the theory of self-adjusting mechanisms by considering the force adaptation of a mechanical system.

- (1) The basis of an adaptive system is a structural mechanical chain containing links and connections between them.
- (2) Links between links are kinematic and force constraints in the relative movement of links.
- (3) Kinematic connections limit the degrees of freedom; force connections impose force restrictions on the relative movement of links.
- (4) The motion of a structural chain is expressed analytically by the condition of interaction of kinematic and force parameters based on the principle of virtual work (or power) or the law of conservation of energy.
- (5) The definability of the motion of a structural chain is expressed by the following condition: the number of total degrees of freedom equal to the number of kinematic degrees of freedom minus the number of force connections must be equal to the number of input links.
- (6) A force coupling is created in a kinematic pair by adding a force constraint, for example, friction, on the relative motion of the links. Adding a force coupling does not change the number of kinematic degrees of freedom, but it does change the total number of degrees of freedom of the structural chain.
- (7) A structural chain with two kinematic degrees of freedom and with one force coupling has the definability of motion in the presence of one input.
- (8) The definable structural chain has the property of force adaptation to the variable external load—with constant input power, the output speed is inversely proportional to the variable external load.

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