Power and energy ratios in mechanical CVT drive control

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Abstract. Being based on the principle of providing the systems with adaptation property to the real parameters and operational condition, the mechanical system capable to control automatically the components of convertible power is offered and this allows providing stationary operation of the vehicle engine in the terms of variable external loading. This is achieved by drive control integrated in the power transmission, which implements an additional degree of freedom and operates on the basis of the laws of motion, with the energy of the main power flow by changing automatically the kinematic characteristics of the power transmission, this system being named CVT. The power and energy ratios found allow performing the necessary design calculations of the sections and the links of the mechanical CVT scheme.

1. Introduction
The implementation of the mechanical design principle by adapting to the real-world settings of the mechanical systems and operating mode at design phase allows, for example, creating power transmission with the auto control of transforming power components [1]. In traditional systems [2-6] in the context of variable external loading, this function is performed by an operator or an automatic control system (ACS) based on the elements of automation and with self-contained power supply. In vehicles equipped with ACS, there are nodes and components operating in the same site that are based on the use of physically heterogeneous environments or fields, which is always problematic and complicates the system and reduces its reliability.

In the proposed system design, there is an internal adapting link that implements the degree of freedom added to the main section movement. Additional section motion is used to control the characteristics of the system, including purpose autochange of its velocity transfer function. The adapting link activity involves the use of laws of motion and the energy adapting movement is performed by the variable component of the force characteristic of the main force flow. The additional motion is implemented by mechanical drive control integrated into power transmission that takes the power flow, compares it with a nominal value, and forwards the formed difference to change automatically the kinematic characteristics of the mechanical system.

The principle of designing mechanical systems with adaptive properties has been theory-based and is contained in numerous publications of the scientific and pedagogical staff of the Machine Department of the Omsk State Technical University, for example, [1]. However, the solutions of applied tasks to create adaptive systems of specific application are relevant, because even during the design phase of such systems, it is necessary to know the levels of sections force loading and the links of both the main chain and the adapting mechanical drive control.
The study subject is power transmission based on the friction CVT with automatically changeable velocity transfer function.

2. Problem Statement
Now we clarify the structure and operation of the mechanical system based on the engineering solution [7]. Figure 1 shows the CVT driven unit node. CVT works as follows. When the resistance on the driven shaft increases, the semi-pulleys 4 and 6 and the nuts 3, respectively, receive relative angle motion that due to multidirectional thread in the screw joint causes semi-pulley axial approaching and pushing the belt to the periphery of active semi-pulley surfaces, thus increasing the kinematic size of the driven unit.

![Figure 1. V-belt CVT with helical block control [5]:](image)

1-the support of the driven shaft; 2-helical surface with right and left threads; 3-nuts (left and right); 4 and 6 – semi-pulleys; 5 – belt; 7 – springs.

The axial rapprochement of the semi-pulleys produces the deformation of the elastic element 7, elastic force of which is used to reverse the evolution of the detail node while reducing the external load of the driven shaft.

The driving unit can be formed using similar design elements, but in the first approaching we state the driving unit having the unchanged kinematic size, with belt tension in evolution being provided by the tension looper, for example by [8].

The intermediate can be performed either by a cone synthetic or rubber-cord belt or by a flexible metallic solid or section belt.

The drive control, consisting of semi-pulley, screw joint and elastic elements, is integrated into the main scheme. In addition to the main movement the adapting one occurs due to the energy of the transformed main force flow generated by the operating member of the machine.

Our task is to define power and energy ratios in the sections of the given CVT depending on the variable characteristics of external force load, as it is needed to evaluate its useful evolution parameters and calculate drive elements.

3. Theory
The automatic control by components of convertible power allows a stationary, economical running of the Power plant (engine) in the context of a variable external force load.
The denoted $M_1$, $\omega_1$, and $M_2$, $\omega_2$ are the power elements and the speed of engine shafts and operating member of the machine. Without taking into account the losses variational relation is:

$$M_1 \omega_1 = M_2 \omega_2,$$

where

$$\omega_2 = \frac{M_1 \omega_1}{M_2}.$$  \hspace{1cm} (2)

If, under the conditions of the problem, $M_1 = \text{const}$ and $\omega_1 = \text{const}$, then the mechanical system output velocity $\omega_2$ at variable $M_2$ is connected with it by hyperbolic law, but the automatic CVT transfer function $IT^\omega$

$$IT^\omega = U_{1,2} = \frac{\omega_1}{\omega_2}$$  \hspace{1cm} (3)

is linear relating to $M_2$, i.e. a multiple change of $M_2$ requires a multiple modification of $IT^\omega$ that is provided by adapting evolution of the automatic CVT kinematic characteristic.

Figure 2 shows the design model of the driven unit with integral drive control.

![Figure 2](image)

**Figure 2.** The design model of the driven unit with integral drive control.

In figure 2 $R_2$ is a changeable kinematic size of auto CVT driven unit; $M_{ex} (= M_{el})$ is a variable part of force external load from the operating member (OM); $\delta$ - is the axial movement of the nuts due to axial force $P_{ax} (= P_{el})$, derived by $M_{ex}$; $c$ is the stiffness of the elastic elements, other symbols are clear.

The known force ratio in the screw joint is:

$$P_{ac} = \frac{2M_{el}}{d_c \tan(\beta + \theta)},$$

(4)
where $d_{cp}$ is a pitch diameter of the helicoidal surface; $\theta$ is $arctg f'$, with $f'=f/cos\alpha$, where $f$ is the friction coefficient of active screw joint surfaces, and $\alpha$ is the thread angle of helicoidal surface; $\beta$ is the thread angle of helical line.

The screw joint is proposed to be executed by ball screw one with sliding friction replaced by rolling friction, therefore, the friction is minimized. Besides, the joint is to be nonlocking with reverse movement, so $\beta > \theta$ and in the design calculation the value $\theta$ can be deleted.

Figure 3b shows

$$\tan \beta = \frac{T}{\pi d_{cp}}$$

(5)

where $T$ is a helix lead in the screw joint.

We substitute (5) into (4), dividing $M_{av}$ into every nut evenly, and obtain axial force values $P_{ax}$, acting on each semi-pulley:

$$P_{av} = \frac{2M_{av}}{2} \frac{\pi d_{cp}}{T} = \frac{\pi M_{av}}{T}$$

(6)

The axial force operation $A$ on each screw joint point is:

$A=P_{av}d$, and in general $A=2P_{av}\delta$ taking into account (6)

$$A = \frac{2\pi M_{av}d}{T} \delta$$

(7)

Axial force $P_{av}$ on the semi-pulleys generates radial force $P_r$ (Fig.2), pushing out the belt to the cone pulley periphery on semi-pulley approaching;

$$P_r = 2P_{av}\tan \gamma$$

(8)

where $\gamma$ is the angle of active semi-pulley cone surface (Fig.2), taking into account (6) we obtain:

$$P_r = 2\frac{\pi M_{av}}{T} \tan \gamma$$

(9)

Distributed across the active semi-pulley cone surface, buoyancy $P_r$ is to ensure force $S_o$ overcoming for belt pre-tensioning, i.e. $P_r \geq 2S_o$, taking into account (9)

$$\frac{\pi M_{av}}{T} \tan \gamma \geq S_o$$

(10)

Belt pre-tensioning defines belt-pulley friction sufficient to transmit both the constant and variable parts of the power flow. If the aggregate value of the transformed moment is stated $M$, then

$$S_1 - S_2 = M \frac{R_z}{R_z}$$

(11)

$S_1 + S_2 = 2S_o$, where $S_1$ and $S_2$ are the effort in pulling and idling branches respectfully.

With values $M$ and $R_2$ the ratios (11) enable to define $S_o$ and maintain its value by automatic tension looper [8].

Axial force $P_{av}$ generates potential strain energy of integral elastic elements. During semi-pulley approaching equal to $2\delta$ energy relation is:

$$P_{av} \geq 2c\delta$$

(12)
Under the axial force $P_{ax}$, the evolution of the driven unit design is accompanied with additional irreversible friction losses very significant in the belt-semi-pulley contact. Friction force $F_{fr}=fN$, where $f$ is the friction coefficient of belt material and active pulley surface, $N$ is a normal force in the belt-pulley contact, defined as (Fig.3a): $N=P_{ax}/\cos\gamma$, or taking into account (6) $N=\pi M_{ev}/T\cos\gamma$, hence

$$F_{mp} = \frac{f\pi M_{med}}{T\cos\gamma}.$$  \hspace{1cm} (13)

The operation of buoyancy $P_{r}$ to overcome pretension forces $S_o$ on the movement $\pi \Delta R_2$, $\Delta R_2 = \frac{\delta}{\tan \gamma}$ is equal to (figure 3c)

$$A_r = \pi S_o \frac{\delta}{\tan \gamma}.$$  \hspace{1cm} (14)

The work of the integral elastic components under semi-pulley approaching is equal to:

$$A_{\text{med}} = c \delta^2.$$  \hspace{1cm} (15)

The friction work with evolution is:

$$A_{mp} = F_{mp} \frac{\delta}{\sin \gamma} + \frac{\pi f M_{med} \delta}{T \cos \gamma \sin \gamma}.$$  \hspace{1cm} (16)

The energy balance equation is as follows:

$$\frac{2\pi M_{med}}{T} = \frac{\pi S_o \delta}{\tan \gamma} + c \delta^2 + \frac{\pi f M_{med} \delta}{T \cos \gamma \sin \gamma}.$$  \hspace{1cm} (17)

after transformations we express $\delta$ with convertible $M_{ev}$ and taken drive control settings:

$$\delta = \frac{M_{ev} \left[ \frac{2\pi}{T} - \frac{\pi f}{T \cos \gamma \sin \gamma} \right] \frac{\pi S_o}{\tan \gamma}}{c}.$$  \hspace{1cm} (18)

Changing discretely $c$, in (18) with known $f$, $T$, $\gamma$, $S_o$ we obtain dependencies «$\delta$» with the variable value of the power flow, generated by operating process in the operating member of the machine.
4. Result discussion
According to (18) the obtained value of semi-pulley approaching δ, depending on M ex and accepted constants is easily transformed into the change of kinematic size $\Delta R_2 = \frac{\delta}{\tan \gamma}$ that defines the transfer function of the auto CVT velocity. Therefore, power and energy ratios in the drive control enable to perform the task of synthesizing auto CVT scheme in a given range of the transfer function change, and consequently, the range of transformed power component auto control.

It is obvious that the regulatory range can be extended by embedding the drive control into the design of the auto CVT driving unit.

It is clear that friction losses in the evolution of the main sections, especially with the relative belt movements on the active semi-pulley surfaces, should be clarified to take into account the need for transmission and the constant friction of the force moment. In the second approximation during choosing elastic element stiffness $c$, the general semi-pulley approaching should be divided into the constant and variable parts. The former is defined by constant power moment component, the latter - by the variable one.

The power and energy ratios are dependent on both the kinematic diagram of the auto CVT as a whole and the scheme of the integral drive control.

5. Results and summary
• The power and energy ratios in the drive control of the mechanical auto CVT based on V-belt diagram with expanding semi-pulleys have been obtained.
• It has been given the principled feasibility of CVT structure capable to regulate the components of the transformed power that operates using the laws of mechanics through the energy of the main force flow in a variable load case.
• It has been shown that the drive control is able to ensure linear dependence of CVT velocity transfer function on the variable external force load.
• On the base of power and energy ratios one can perform the needed amount of unit design calculations and CVT elements of the offered scheme.

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