Efficient Adaptive Continuously Variable Transmission (CVT) with simplified diagnostics

Ivanov K.S., Alipbaev K.A., Miroshnichenko E.S.
Almaty University of Power Engineering and Telecommunication
e-mail: ivanovgreek@mail.ru

Abstract. The development of the automotive industry leads to the improvement of the designs of automatic transmissions and drives and to the development of methods for monitoring and diagnosing their condition. The trend of improving transmissions comes down mainly to the endless improvement of existing designs of CVTs and variators, which inevitably leads to the complication of designs and methods for their control and diagnostics.

There is a need to create a fundamentally new simplified gearbox based on the scientific achievements of mechanics. However, the created structures remained inoperable due to the lack of theoretical justification.

The adaptive gear variator developed by the author, which has CVT functions, is a mechanism with two degrees of freedom and with an additional constraint of a fundamentally new type, called a force - speed constraint. The force - speed constraint imposes a force restriction on the movement of links, while maintaining the number of degrees of freedom in the kinematics. Monitoring the state of the developed gearbox in the form of a non-switchable gear variator is greatly simplified, since the largest number of faults occur in the control system, and there is no control system in the gear variator. It seems possible to apply the digital twin method to diagnose the developed simplified CVT.

The proposed article is devoted to a theoretical description of a fundamentally new adaptive gearbox, created on the basis of the latest achievements in mechanics, with the prospect of developing a simplified monitoring and diagnostic system for it.

Keywords: adaptive CVT, two degrees of freedom, additional constraint, digital twin method for diagnosis.

Introduction

The progress of the automotive industry and robotics leads to the improvement of the designs of automatic transmissions and drives and to the development of methods for monitoring and diagnosing their condition. Currently, computer diagnostics in combination with the on-board computer of a car is becoming widespread. Computer diagnostics includes connecting the scanner to the on-board computer, reading error codes, decoding the information received and developing a troubleshooting algorithm. Improvement of designs leads to complication of diagnostics, and simplification of diagnostics requires simplification of the design.

The trend of improving transmissions comes down mainly to the endless improvement of existing designs of CVTs and variators, which inevitably leads to the complication of designs and methods for their control and diagnostics. The desire of leading auto companies to develop and improve CVT and variators once again underlines that the automotive future belongs to a continuously variable transmission.

There is a need to create a fundamentally new simplified gearbox based on the scientific achievements of mechanics.

The object of study is a kinematic chain with two degrees of freedom, which has only one input. Such a chain was used by the inventors of the self-adjusting gearbox mechanism to constantly and continuously change the torque and angular velocity on the output shaft depending on the variable moment of resistance. However, there are provisions of mechanics and the theory of machines and mechanisms that deny the possibility of creating a workable mechanism based on this chain: the number of input links must be equal to the number of degrees of freedom, the motion mode can not be uniform, kinematic and force analysis are reduced to determining the accelerations of the output links [1] .

For a long time, inventors have been trying to create a simple self-adjusting continuously variable gearbox in the form of a gear mechanism with constant meshing of gear wheels [2, 3, 4]. However, the created structures remained inoperable due to the lack of theoretical basis. There is a need to create a fundamentally new simplified gearbox based on the scientific achievements of mechanics.

Based on a comprehensive theoretical analysis and intuition, the author succeeded in creating a self-adjusting gearbox in the form of an adaptive gear variator [5, 6]. The adaptive gear variator is a mechanism with two degrees of freedom and with an additional constraint of a fundamentally new type, called a force - speed constraint. Force - velocity constraint imposes a force restriction on the movement of links, while maintaining the number of degrees of freedom in the kinematics. Such constraint takes place, for example, in a friction joint. The resulting design creates the effect of force adaptation - at a constant engine power, the output shaft of the variator rotates at a speed inversely proportional to the moment of resistance. That is, the greater the resistance to the movement of the car, the lower its speed. The created design of the adaptive gear variator is protected by a European patent.

Monitoring the state of the developed gearbox in the form of a non-switchable gear variator is greatly simplified, since the largest number of faults occur in the control system, and there is no control system in the gear variator.

It seems possible to apply the digital twin method to diagnose the developed simplified CVT.

The proposed article is devoted to a theoretical description of a fundamentally new adaptive gearbox, created on the basis of the latest achievements in mechanics, with the prospect of developing a simplified monitoring and diagnostic system for it.

1. Description of continuously variable transmission (CVT)

A stepless adaptive transmission (CVT) in the form of a two-row gear planetary variator is based on a kinematic chain with two degrees of freedom [5, 6]. This article presents an improved gearbox with an efficient additional adjustable force - velocity constraint that reliably ensures the determinability of movement.

The adaptive gear variator is a self-adjusting mechanism. The variator realizes the effect of force adaptation: the speed of the output link is inversely proportional to the variable output load. It has two degrees of freedom and only one input, which contradicts the condition for the existence of the mechanism and the definability of its motion. However, the definability of motion provides an additional link between force and speed.

The kinematic chain of the adaptive gear variator (figure 1a) contains rack 0, input carrier H_1, a closed circuit of gears 1-2-3-6-5-4 and output carrier H_2. Gear wheels 1, 2, 3, 6, 5, 4 form a movable closed circuit. Gear wheels 8, 7 form an additional parallel transmission from the carrier H_2on the wheel 7 and the satellite 5. This transmission, in the presence of a rigid connection of the wheels 7 and 5 , has a gear ratio equal to the gear ratio of the planetary gear. The closed circuit contains an input satellite 2, a block of sun wheels 1-4 , a block of annular wheels 3-6 and an output satellite 5.

The variator works as follows (figure 1a): input shaft with input carrier H_1transmits the motion to the input satellite 2. The input satellite 2 transmits the motion to the gear blocks 1-4 and 3-6. Wheel blocks 1-4 and 3-6 transmit motion to the output satellite 5 and the output carrier H_2. At the same time, the kinematic chain with additional parallel transmission of gears 8-7 transmits the movement from the input carrier $H_1$to the output satellite 5 and the carrier H_2. Parallel transmission 8-7 in the presence of a rigid connection of the wheels 7 and 5 has a gear ratio equal to the gear ratio of the planetary kinematic chain.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 November 2022 doi:10.20944/preprints202211.0570.v1

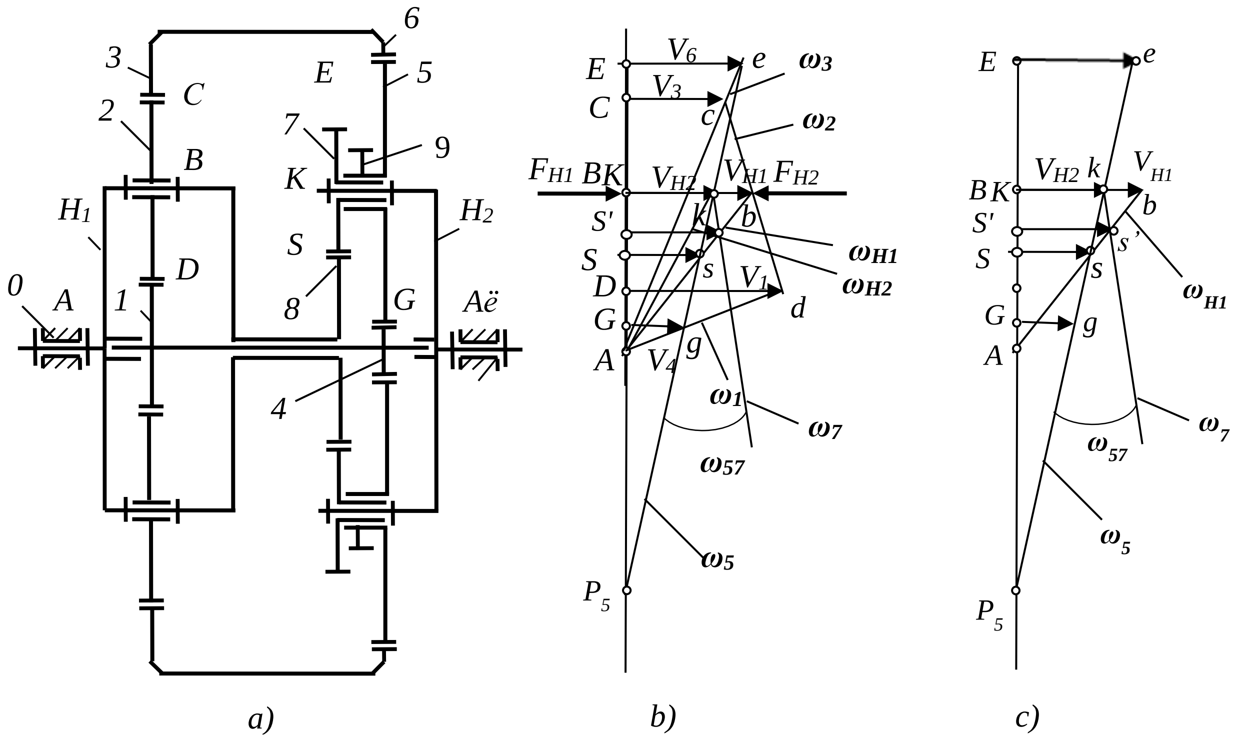

Figure 1: 1a . Adaptive gear variator, 1b . The plan of linear speeds of the variator,

1c . Determination of relative angular velocity

Parallel transmission 8-7 can create an efficient force- speed constraint [6]. This paper describes the creation of a force- speed constraint using an adjustable friction hinge Kconnecting wheels 5 and 7 using the adjusting tension screw 9. The tension screw 9 creates in the hinge Krequired to balance the normal reaction.

In the presence of a rigid connection of the wheels 7 and 5, the gearing pole of Sthe additional parallel transmission 8-7 (Fig. 1a) is located at the intersection of inclined lines of angular velocities $\omega_{H1} = \omega_8$and $\omega_5 = \omega_7$(Fig. 1b, 1c). This ensures the equality of the linear velocities of the links $H_1$and 5 in the pole. The sloping line ksdefines the angular velocity $\omega_5$link 5. If the gearing pole Sis shifted from this nominal position to position S', then the line ks'will determine the angular velocity of link 7, and the angular velocity $\omega_7$will differ from ω_5. This will lead to jamming of the movable circuit of the mechanism. The 8-7 pole-shifted gear S'eliminates one degree of freedom and allows for efficient coupling. The creation of an effective additional force-velocity constraint is performed as follows. The rigid connection of wheels 7 and 5 should be replaced by a friction connection in the connecting hinge $K$with a friction moment M_f. This relationship will ensure the relative mobility of wheels 5 and 7 with angular velocity $\omega_{57} = \omega_5 - \omega_7$and will be included in the mathematical model of the adaptive variator (into the power balance equation) in the form of an expression for the variable power spent on friction. With a small deviation of the engagement pole $S'$from the nominal position, the relative angular velocity ω_{57}will be close to zero, which will lead to low frictional power loss .

On fig. 1c shows the plan of linear velocities in a simplified form for easier visual perception.

2. Kinematic and force analysis of an adaptive gear variator

We will present the interaction of kinematic and power parameters in the form of a power balance and perform it according to the principle of virtual work using real displacements.

Interaction parameters: external forces F_{H1} and F_{H2} (corresponding to the driving moment M_{H1} and the moment of resistance M_{H2}) acting on a closed loop at points B and K , the angular velocities of the initial links ω_{H1}, ω_{H2} and the linear velocities V_{H1} and V_{H2} points B and K (Fig. 1).

A necessary condition for adaptation is provided by a movable closed circuit composed of gears. The equilibrium condition of a closed loop (without transmission 8-7) has the form

$$M_{H1}\omega_{H1} + M_{H2}\omega_{H2} = 0. \quad (1)$$

Equation (1) makes it possible to obtain an expression for force adaptation, taking into account the negative sign of the output power

$$\omega_{H2} = \frac{M_{H1} \cdot \omega_{H1}}{M_{H2}}. \quad (2)$$

The force adaptation effect has the following essence: for given constant input power parameters M_{H1}, ω_{H1} and a given output resistance torque, the M_{H2} output angular velocity ω_{H2} is inversely proportional to the variable output resistance torque M_{H2}.

The necessary adaptation condition expresses the theoretical possibility of creating an adaptation. Real adaptation can take place only if an additional sufficient adaptation condition is met.

The sufficient condition provides an additional constraint between force and velocity. The additional constraint is expressed by the formula for the power consumption for friction in the friction joint K

$$P_f = M_f\omega_{75}. \quad (3)$$

Here M_f is the required friction moment $M_f = Nf\rho$,

N is normal reaction created by the tension screw 9,

f is the coefficient of friction,

ρ is the hinge radius.

ω_{75} is the relative angular velocity of links 7 and 5.

A sufficient condition for force adaptation is represented by the power balance equation with the addition of the power spent on friction

The power balance for a kinematic chain with an additional frictional parallel connection has the form:

$$M_{H1}\omega_{H1} = M_{H2}\omega_{H2} + M_f\omega_{75}. \quad (4)$$

Force adaptation formula:

$$\omega_{H2} = \frac{M_{H1}\omega_{H1} - M_f\omega_{75}}{M_{H2}}. \quad (5)$$

The required friction moment can be preliminarily determined by the formula

$M_f = -M_{H1}\frac{z_7}{z_8}$ followed by clarification.

Equation (5) in the final account defines mathematical model of adaptive gear variator at implementation necessary and sufficient terms power adaptation .

The values of the angular velocities ω_5 and ω_7 are determined as follows:

For planetary gear

$$\omega_5 = \omega_{H2} + (\omega_3 - \omega_{H2})u_{56}^{H2}, \quad (6)$$

where $\omega_3 = \frac{\omega_{H2}(1-u_{46}^{H2})-\omega_{H1}(1-u_{13}^{H1})}{u_{13}^{H1}-u_{46}^{H2}}$, $u_{56}^{H2} = \frac{z_6}{z_5}$, $u_{46}^{H2} = -\frac{z_6}{z_4}$, $u_{13}^{H1} = -\frac{z_3}{z_1}$,

z_i – числа зубьев колес.

For additional transmission

$$\omega_7 = \omega_{H2} + (\omega_{H1} - \omega_{H2})u_{7-H1}^{H2}, \quad (7)$$

where $u_{7-H1}^{H2} = -\frac{z_8}{z_7}$.

About relative angular velocity ω_{75} is determined by the formula :

$$\omega_{75} = \omega_7 - \omega_5 \ . \quad (8)$$

The efficiency of the mechanism is determined by the formula:

$$\eta = \frac{P_{H1}-P_f}{P_{H1}} \cdot 100\% \ . \quad (9)$$

The computer mathematical model of the variator makes it possible to simply and quickly check the theoretical assumptions put forward and obtain confirmation of the reliability of the positive variant found.

3 . Stop mode

of the movement of a mechanism with two degrees of freedom , which has only one input, is ensured by the introduction of a fundamentally new force - velocity constraint, which introduces a force limitation, but retains kinematic properties. A special case of force- speed coupling takes place when the permissible force load on the output shaft is exceeded. The presence of two degrees of freedom leads to the stop of the output shaft when the engine is running (without damage to the drive). The resulting mode of motion with one degree of freedom is called the stop mode of motion.

This mode can be used for a short stop when braking without stopping the engine, for example, on a hill, when it is undesirable to use the clutch.

4 . New CVT diagnosis

The fundamentally new simplified CVT is a two-row planetary gear mechanism with an additional internal parallel transmission.

In this gearbox, there is no control system together with an executive control mechanism. Therefore, the diagnosis of such a gearbox is extremely simplified. It boils down to simplified sensor-based fault modeling. The control of motion modes can be based on taking into account noise excitation. An increase in the intensity of the force interaction with an increase in the moment of resistance leads to an increase in the noise intensity and is controlled by the corresponding on-board diagnostic control algorithms.

It seems possible to apply the digital twin method for diagnosing the developed simplified CVT containing a non-mechanical part in the form of a friction force- speed constraint.

The digital twin method in gear diagnostics was applied to bevel gears [7], and the digital twin simulation did not consider the simulation of non-mechanical parts [8]. A detailed description of the current application of digital twin technology that provides theoretical guidance for use in diagnostics planetary gearboxes, is presented in [9, 10]. Since planetary gearboxes are widespread and large industrial equipment contains planetary gearboxes that are significantly different from the applications presented in the above studies, and there are currently no models that take into account the influence of non-mechanical factors on the dynamic performance of planetary gearboxes, it is necessary to apply digital dual technology to systems planetary gearboxes.

A fundamentally new action is the diagnostics of the stop mode of movement, in which the output shaft of the gearbox is stopped, and the input shaft continues to rotate transmitted by the engine. In this case, there is an increased intensity of internal movement, which must be controlled by an on-board computer with increased requirements for the thermal regime.

Some fundamentally new requirements are presented related to the two- shift driving mode and the expansion of the functions of the adaptive gearbox (using the stop mode).

Conclusion

The performed research, based on a deep analysis of the laws of applied mechanics, made it possible to create a simple self-regulating CVT with simplified diagnostics. The adaptive gear variator is a mechanism with two degrees of freedom and with an additional fundamentally new force - speed constraint. Force - velocity constraint imposes a force restriction on the movement of links, while maintaining the number of degrees of freedom in the kinematics. The resulting design creates the effect of force adaptation - at a constant engine power, the output shaft of the variator rotates at a speed inversely proportional to the moment of resistance. It is proved that a prestressed closed loop ensures the definability of the movement of a kinematic chain with two degrees of freedom and turns it into a mechanism in which equilibrium occurs when there is only one input.

The stop mode of movement eliminates the possibility of overloading the engine.

A theory has been developed for creating fundamentally new mechanical systems - self-regulating mechanisms. The main advantages of a self-adjusting mechanism are the simplicity of the design, which does not have a control system, and full adequacy to a variable power load.

practical definability of the mechanism is achieved by introducing a force-velocity constraint into the closed loop , corresponding to the input force and creating a power stress state of the closed loop.

The diagnosis of the new type of gearbox is greatly simplified. Some fundamentally new requirements are presented related to the two- shift driving mode and the expansion of the functions of the adaptive gearbox (using the stop mode).

It seems possible to apply the digital twin method to diagnose the developed simplified CVT .

The performed studies determine the theory of creating fundamentally new gearboxes in the form of self-regulating mechanisms with simplified diagnostic requirements.

Source of financing

The research was supported by grant No. AR09258712 "Development of self-adjusting electric drives for spacecraft", planned at the Almaty University of Power Engineerng and Telecommunication.

Conflict of interest

Authors state that he has no conflict of interest**.**

Reference

1. Artobolevsky I.I. Theory of mechanisms and machines. Moscow. Nauka. 1988. 640 p .

2. Crockett Samuel J. Shiftless, continuously-aligning transmission. US Patent 4,932,928, Cl. F16H 47/08, US Cl. 475/51; 475/47.1990, 9 p.

3. Harries John. Power transmission system comprising two sets of epicyclic gears. Patent of Great Britain GB2238090 (A). 1991, 11 p.

 doi:10.20944/preprints202211.0570.v1

4. Vedeneev S.A. Automatic geared variator for changing gear ratio without disengaging gears and without control devices or therewith. European patent application EP 2 348 231 A1. Date of publication: 27.07.2011 Bulletin 2011/30. Priority: 09/11/2008 RU 2008136621. 28 p.

5. Ivanov K.S. Theory of Continuously Variable Transmission (CVT) with Two Degrees of Freedom. Paradox of mechanics. Proceedings of the American Society of Engineers Mechanics (ASME) International Mechanical Engineering Congress & Exposition (IMECE 2012). Houston, Texas, USA. 2012. PP 933 - 942.

6. Ivanov K.S. Theory of Adaptive Mechanical Drive. Journal Theoretical and Applied Mechanics Letters. Elsevier. 2021. Article number 100281. Reference TAML 100281. PII S2095-0349 (21)00088-X.

7 . Rong Kaibin, Ding Han, Kong Xiannian, Huang Rong, Tang Jinyuan. Digital twin modeling for loaded contact pattern-based grinding of spiral bevel gears. Advanced Engineering Informatics. Volume 2021.49: 101305.

8. Pang Yu. Simulation study on Dynamics and Fault diagnosis of Digital twin in Planetary Gearbox[D]. Master's degree, North University of China, 2020.

9. Moghadam Farid K., Nejad Amir R. Online condition monitoring of floating wind turbines drivetrain by means of digital twin. Mechanical Systems and Signal Processing, Volume, 2022,162: 108087.

1 0. Farid K. Moghadam, Geraldo F. de S. Reboucas, Amir R Nejad. Digital twin modeling for predictive maintenance of gearboxes in floating offshore wind turbine drivetrains . Forschung im Ingenieurwesen. 2021, 85(2): 273-286.