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Identification of circulation effects in a closed loop of a hydrostatic-mechanical transmissions with a planetary mechanism on the input and output links

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Abstract

INTRODUCTION: Modern trends in the development of mobile machinery, particularly heavy tracked vehicles, tractors and military vehicles, focus on improving the energy efficiency, controllability and reliability of transmission systems. In this context, hydrostatic-mechanical transmissions (HMCVTs) with a closed energy transmission loop demonstrate significant potential as an alternative to traditional mechanical and hydrodynamic systems by combining smooth speed control with increased efficiency.

A key feature of closed HMCVTs is circulation power transmission, which arises from the interaction of the hydraulic and mechanical circuits. Using planetary mechanisms on both the input and output links of the transmission creates internal closed power flows, or circulations, which affect torsional rigidity, energy losses and dynamic stability.

Currently, the scientific literature pays insufficient attention to identifying circulation effects in transmissions with such a layout. This complicates the design and optimisation of HMCVTs that take internal circulation loads into account, as this can lead to the overloading of individual transmission elements, increasing the temperature in the circuit or reducing efficiency.

Therefore, this study is relevant because it provides an in-depth analysis of circulation effects in closed HMCVTs with planetary mechanisms at the input and output of the transmission system. The results of such an analysis could inform the development of methods for identifying and compensating for harmful circulation flows. This would contribute to extending the service life, improving the energy efficiency and enhancing the control accuracy of HMCVTs.

OBJECTIVES: This work aims to develop and analyse the mathematical basis for describing circulation effects in the closed loop of the HMCVT, with the planetary mechanism located on the input and output links. This goal can be achieved by identifying patterns and forming a mathematical model of the transmission's operation in a closed loop with the planetary mechanism located on the input and output links. The presented mathematical equations describe changes in the kinematic and power indicators of the transmission. These equations are used to structure the internal gear ratio equation of the closed loop of the HMCVT with the planetary mechanism located on the input and output links of the transmission.

METHODS: The study used methods of differential and integral calculus to create a mathematical model of the operation of the hydrostatic-mechanical transmission. This model is based on fundamental equations that describe the kinematic, power and energy indicators of continuously variable transmissions with planetary mechanisms. Due to the means of digitization, namely three-dimensional (3D) technologies, it is possible to determine the patterns of distribution of the internal gear ratio by the hydraulic pump control parameter and the planetary mechanism design parameter. This increases the accuracy of the results obtained.

RESULTS: The main results of this study are the development of a mathematical model for analyzing changes in the internal gear ratio of the closed loop HMCVT, based on the control parameter of the hydraulic machine and the design parameter of the planetary mechanism. In addition, the analysis of the obtained results using modern digitalization tools, namely spatial drawings, demonstrated the effectiveness of 3D technologies in determining the optimal combinations of transmission schemes that avoid circulation effects.

CONCLUSION: This article concludes that, by using spatial illustration, dependencies of the internal gear ratio on the hydraulic pump control parameter and the design parameter of the planetary mechanism have been constructed. This provides the possibility of a broader analysis of patterns. Based on the analysis of circulation effects in the closed loop of the HMCVT, the range of changes to the planetary mechanism's design parameter has been obtained, which alters the internal gear ratio of the closed loop over a wide range.

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1. Introduction

When studying the design features of the transmission systems of heavy tracked vehicles, it should be noted that the main, system-forming component is the planetary gear. During the design of such transmission units, the planetary gear is configured according to the established operating conditions. When analysing the power flow diagrams of transmissions with planetary gears, circulation effects can be seen, which must be avoided. After all, the efficiency of operation decreases under such conditions compared to conventional gear transmissions.

The existence of transmission operating modes involving power circulation in modern HMCVTs means that we must solve the problem of selecting circuit solutions for the transmission structure. Circulating power does not generate useful output energy. This power usually creates several times more energy consumption in the planetary transmission than the input power.

The presence of circulation effects in the transmission can be determined through a qualitative assessment of heat generation in the hydrostatic transmission, which has a significant impact on the reliability of heavy tracked vehicles. Theoretical research into the structural design of the transmission involves mathematical modelling of the processes occurring in the HMCVT and allows for variation of the transmission's structural elements.

2. Objective and Research Tasks

This study aims to develop and analyse the mathematical basis describing circulation effects in the input and output links of a closed-loop HMCVT with a planetary mechanism.

To achieve this, the following tasks must be performed:

- identify patterns and form a mathematical model of the operation of a closed-loop transmission with a planetary mechanism on the input and output links.

- analyse the developed model to provide recommendations for using certain combinations of flow connections in a planetary transmission to prevent circulation effects in a closed loop.

3. Research Tasks

Considering the schematic design of the HMCVT and the placement of the planetary mechanism and other components, it is possible that the transmission has moving elements that affect its ability to transmit power in different directions [1]. This creates the effect of locking the power in the planetary mechanism, forming a closed transmission loop. The presence of this effect can cause an overload of the gears, shafts and/or bearings in the closed loop [2, 3]. In addition, an unfavourable distribution of closed power on the branches – hydraulic and mechanical in the case of the HMCVT – results in decreased efficiency and productivity. The primary task, therefore, is to establish the direction of power transmission; various methods are used for this purpose.

Thus, works [4–6] perform a full static analysis of power and kinematic indicators, based on which power losses are determined. Work [7–9] also determined the sensitivity of the speed ratio in determining the direction of the power flow. A notable feature of these studies is that the direction of power flow in a closed transmission circuit is determined by calculating the internal (circular) gear ratio in the planetary mechanism.

Several concepts have been applied using kinematics to determine the direction of power flows at each gear element. In [10], the efficiency equation of the 2K–2H planetary gear is derived based on the latent power theorem. In [11] presents an analytical expression for the efficiency of a complex epicyclic gear with power splitting, using a virtual power approach. The power splitting ratio and the virtual power splitting ratio are introduced as new concepts to handle the complex gear. In [12], potential energy efficiency is defined as the efficiency of an epicyclic gear measured in any moving frame of reference. Conventional efficiency can be calculated in a moving carrier frame, where the gear carrier appears to be stationary.

In [13] states that general formulas for describing the operation of a planetary gear consider a two-stage epicyclic gear to be two devices with one degree of freedom, connected in parallel and intersected by a power flow. These formulas are derived by applying the general formula for the mechanical efficiency of a system of two parallel devices with a given efficiency and direction of power flow. However, the introduction of the concepts of virtual [11] or potential [12] power reduces the mechanical efficiency of an epicyclic gear to that of a conventional gear. This is achieved by introducing a kinematic inversion in such a way that the observed motion of the gear carrier is cancelled out. The orientation of the power flow resulting from such a kinematic inversion may not coincide with that in the epicyclic arrangement. This situation requires special attention, and the algebraic expression of the overall mechanical efficiency must be consistent.

4. Materials and methods

First of all, when studying the change in the structural structure of the planetary mechanism, it is meant to take into account its variable structural structure. This makes it possible to provide a change in the structural parameter of the planetary mechanism k ϵ [-5; 5]. The implementation of the ranges of change in the structural parameter k ϵ [-1; 1] can be ensured by a combination of two planetary mechanisms, one of which has one blocked link. In the course of the study, the structural diagrams of the GOMT shown in Fig. 1 are used, which, according to the principle of the structure, have the location of the planetary mechanism on the output link (Fig. 1 a) and on the input link (Fig. 1 b).

The internal closed-loop gear ratio is determined by calculating the formula

$$i_{cir} = -\frac{N_{\mathrm{hyd}}}{N_{\mathrm{meh}}}, \tag{1}$$

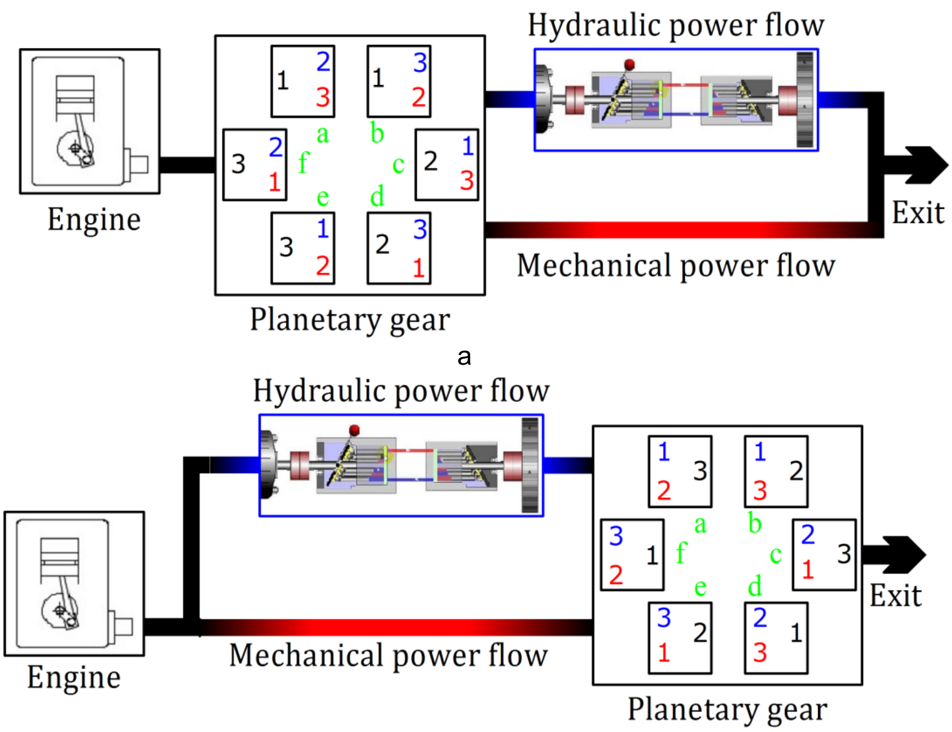
where N_{hyd} is power flowing through the HMCVT hydraulic branch; N_{meh} is power flowing through the mechanical branch of the HMCVT.

When i_{cir} is less than zero, the directions of hydraulic and mechanical power flow along the parallel branches of the HMCVT are the same. When i_{cir} is greater than zero, however, power is transmitted in opposite directions along the branches of the HMCVT, which is characterised by energy dissipation through the hydraulic branch and heat generation.

This study presents a mathematical model describing the kinematic and power work of the HMCVT based on fundamental equations. For example, the kinematic description of the parameters is based on Willis's equation, given below [13, 14]:

$$w_1 - k \cdot w_2 + (k-1) \cdot w_3 = 0, \tag{2}$$

where $\omega_{1,2,3}$ are angular velocities of the links of the planetary mechanism, namely the sun and epicyclic gears, the carrier; k is the internal gear ratio of a planetary gear set is based on the angular velocity ratio of the components in motion relative to the carrier.



B

Figure 1. Block diagrams showing the HMCVTs operating as a power flow distributor (a) and adder (b)

The power description of the HMCVT operation is based on the power balance equation of the planetary gear train, but does not take into account friction torque losses during planetary gear engagement [15, 16]

$$M_1 w_1 + M_2 w_2 + M_3 w_3 = 0; \tag{3}$$

$$M_1 + M_2 + M_3 = 0, \tag{4}$$

where $M_{1,2,3}$ are torques on the links of the planetary mechanism (namely the sun and epicyclic gears and the carrier) without taking mechanical losses in the gearing into account.

Formulas (2) to (4) can be used to calculate the torques acting on the components of the planetary mechanism. By blocking the carrier of the planetary mechanism in formulas (3) and (4), we obtain [17]:

$$M_1 \cdot \frac{w_1 - w_3}{w_2 - w_3} + M_2 = 0 \quad \text{or} \quad M_1 \cdot k + M_2 = 0. \qquad (5)$$

The paper simplifies the study of the hydraulic transmission link by not taking the working volume of hydraulic machines into account. This is because hydraulic machines are all the same standard size. The study focuses on hydrostatic transmission, consisting of a regulated hydraulic pump and an unregulated hydraulic motor. Hydromechanical losses in hydraulic machines are also not considered in the study. This is because, to assess the transmission's efficiency, its ability to transmit power with a diverse structural configuration of the transmission power adder is taken into account first. To make things more convenient and clearer, we will create a mathematical model to determine the internal gear ratio of a closed loop, taking the circuit structure into account. When calculating this ratio, we will use the unit power of the internal combustion engine and the unit power of the hydrostatic transmission as the initial data. Additionally, we will neglect the efficiency of gear connections and hydromechanical losses in hydraulic machines, treating them as equal to 1. We assume that the hydraulic machines are the same size and that only the hydraulic pump is controlled.

We will isolate the necessary components in order to determine the internal gear ratio of the closed loop. The obtained result will be summarised in Table 1.

Table 1. Determining the components of the internal, closed-loop gear ratio

Scheme (Fig. 1)		Kinematic indicator	Power indicator	Internal gear ratio
Planetary mechanism power flow distributor (Fig. 1a)	→1 2→ 3→	$1/e$	$k/(1-k)$	$i_{\Sigma aa} = -k/[e \cdot (1-k)]$
	→1 3→ 2→		$(1-k)/k$	$i_{\Sigma ab} = -(1-k)/(e \cdot k)$
	→2 1→ 3→		$1/(1-k)$	$i_{\Sigma ac} = -1/[e \cdot (1-k)]$
	→2 3→ 1→		$1-k$	$i_{\Sigma ad} = -(1-k)/e$
	→3 1→ 2→		$-1/k$	$i_{\Sigma ae} = 1/(e \cdot k)$
	→3 2→ 1→		$-k$	$i_{\Sigma af} = k/e$
Planetary mechanism power flow adder (Fig. 1b)	→1 →2 3→	e	$-1/k$	$i_{\Sigma ba} = e/k$
	→1 →3 2→		$1/(1-k)$	$i_{\Sigma bb} = e/(1-k)$
	→2 →1 3→		$-k$	$i_{\Sigma bc} = e \cdot k$
	→2 →3 1→		$k/(1-k)$	$i_{\Sigma bd} = e \cdot k/(k-1)$
	→3 →1 2→		$1-k$	$i_{\Sigma be} = e \cdot (k-1)$
	→3 →2 1→		$(1-k)/k$	$i_{\Sigma bf} = e \cdot (k-1)/k$

Fig. 2 shows the results of determining the circulation ratio by calculating the internal gear ratio in a closed loop of HMCVT when the planetary mechanism is located on the input link. Evaluating the results in Fig. 2, we can see that a change in the value of the internal gear ratio ($0 < |i_{\Sigma a}| < 1$) indicates dominance of the mechanical branch of HMCVT over the hydraulic branch, and a change in the value of the internal gear ratio ($-1 < |i_{\Sigma a}| < +\infty$) indicates dominance of the hydraulic branch over the mechanical branch. This dominance indicates the sensitivity of HMCVT control in the onboard transmission. The desired value of the internal gear ratio is $i_{\Sigma a} = -1$; however, in further studies, we will cover all HMCVT schemes with a wide range of values of $i_{\Sigma a}$ between 0 and -100.

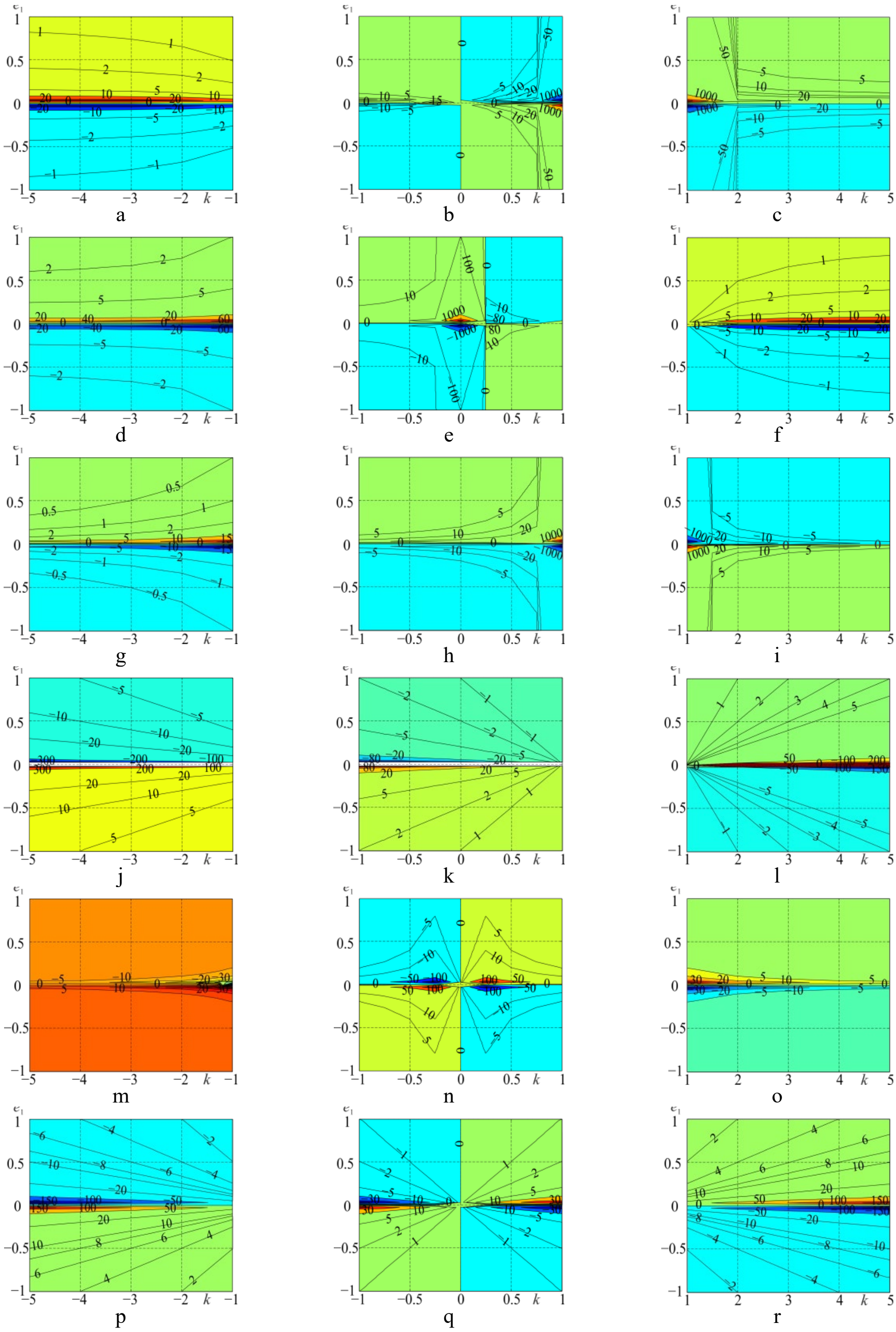


Figure 2. Dependence of the internal gear ratio on the hydraulic pump control parameter e_1 and the design parameter k:
a, b, c – Fig. 1aa; d, e, f – Fig. 1ab; g, h, i – Fig. 1ac; j, k, l – Fig. 1ad; m, n, o – Fig. 1ae; p, q, r – Fig. 1af

The following HMCVT schemes will be examined in relation to the design parameter *k*:

– Fig. 1aa: at e_1 ϵ [0; -1] – *k* ϵ [-5; 0] U [1; 5] and at e_1 ϵ [0; +1] – *k* ϵ [0; 1];

– Fig. 1ab: at e_1 ϵ [0; -1] – *k* ϵ [-5; 0,25] U [1; 5] and at e_1 ϵ [0; +1] – *k* ϵ [0,25; 1];

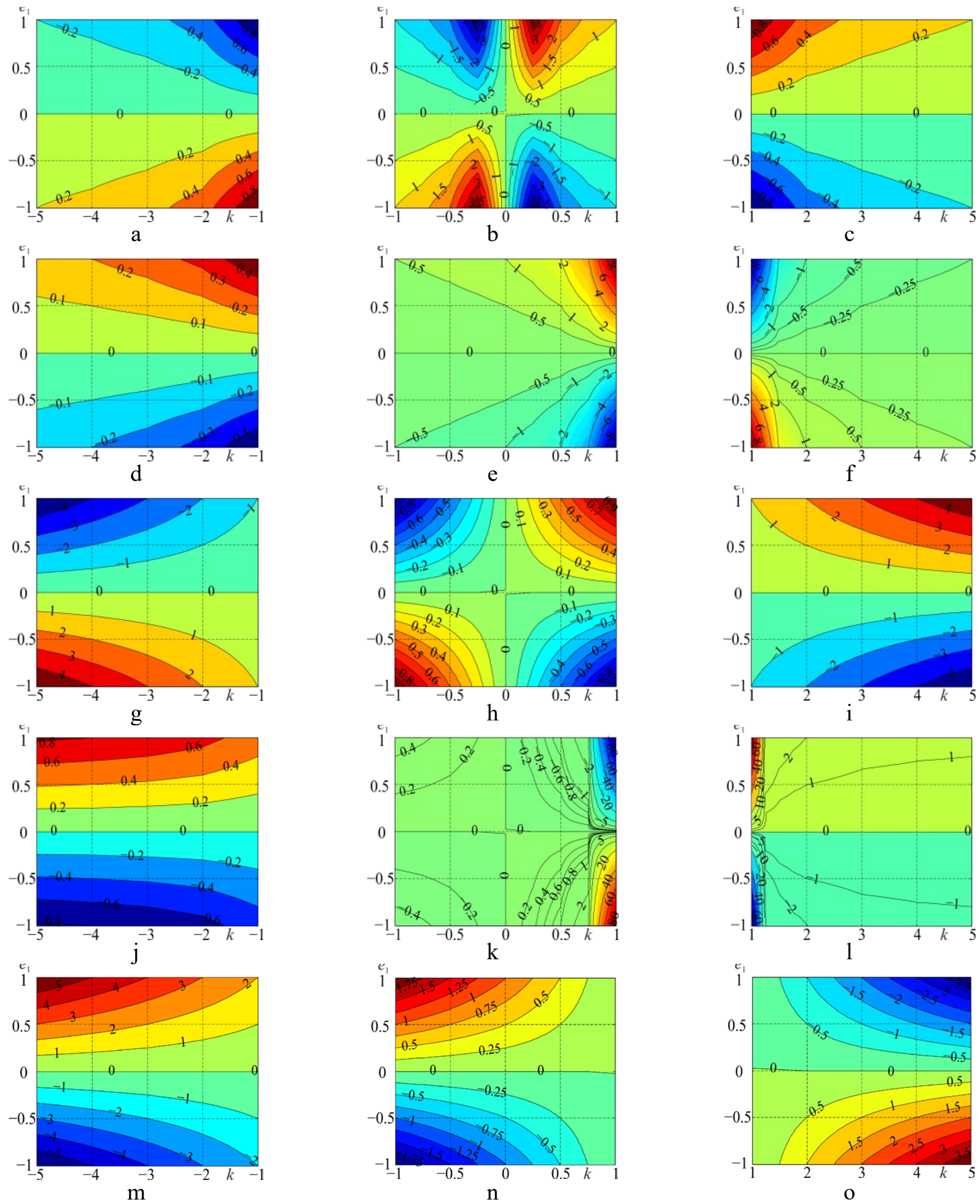
– Fig. 1ac: at e_1 ϵ [0; -1] – *k* ϵ [-5; 1] and at e_1 ϵ [0; +1] – *k* ϵ [1; 5];

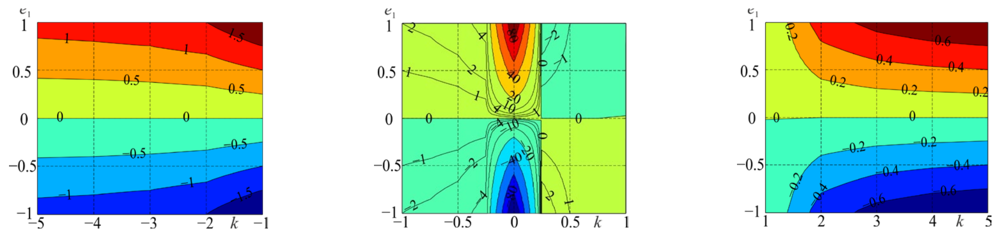
– Fig. 1ad: at e_1 ϵ [0; -1] – *k* ϵ [1; 5] and at e_1 ϵ [0; +1] – *k* ϵ [-5; 1];

– Fig. 1ae: at e_1 ϵ [0; -1] – *k* ϵ [0; 5] and at e_1 ϵ [0; +1] – *k* ϵ [-5; 0];

– Fig. 1af: at e_1 ϵ [0; -1] – *k* ϵ [0; 5] and at e_1 ϵ [0; +1] – *k* ϵ [-5; 0].

Fig. 3 shows of determining the circulation ratio when the planetary mechanism is located on the output link.





p q r

Figure 3. Dependence of the internal gear ratio on the hydraulic pump control parameter e_1 and the design parameter k:
a, b, c – Fig. 1ba; d, e, f – Fig. 1bb; g, h, i – Fig. 1bc; j, k, l – Fig. 1bd; m, n, o – Fig. 1be; p, q, r – Fig. 1bf

Using the same evaluation principle as for HMCVT with the planetary mechanism on the input link, we can see that operating HMCVT with the planetary mechanism on the output link is not possible with an initial change to the hydraulic pump control parameter of $e_1 = 0$.

In practice, the hydraulic pump, which is part of the HMCVT with the planetary mechanism on the output link, is controlled by belonging to the range $e_1 \in [-1, +1]$ or [+1, -1]. Therefore, it is impossible to isolate HMCVT schemes from Fig. 1b where circulation effects are absent. In the future, all possible design combinations for operating HMCVT schemes with a planetary mechanism on the output link will be considered. An analysis has been performed to identify circulation effects in the closed loop of HMCVT with the planetary mechanism on the output link.

5. Conclusions

The identification of circulation effects present in the closed loop of the HMCVT, with the planetary mechanism located on the input and output links of the transmission, has been analysed. Mathematical equations describing changes in the kinematic and power indicators of the transmission have been presented. The internal gear ratio equations of the closed loop of the HMCVT with the planetary mechanism located on the input and output links of the transmission have been isolated and structured. Using spatial illustration, dependencies of the internal gear ratio on the hydraulic pump control parameter and the design parameter of the planetary mechanism have been constructed, providing the possibility of broader pattern analysis. Based on the analysis of circulation effects in the closed loop of the HMCVT, the range of changes in the planetary mechanism's design parameter has been obtained, which varies the internal gear ratio of the closed loop over a wide range: $0 < i_{\Sigma} < -100$. The research results obtained have a sufficiently high practical value, as they enable the most effective structural scheme for the transmission to be chosen even at the design stage. This decision can also be based on the value of the internal gear ratio: if $i_{\Sigma} = -1$, the hydraulic and mechanical energy flows are summed equally. If $0 \leq i_{\Sigma} < 1$, the mechanical flow prevails over the hydraulic energy flow. If $1 < i_{\Sigma} < 100$, the hydraulic flow prevails over the mechanical energy flow. These results may be useful in future studies of offshore wind generators.

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