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Redundant Constraints in Purifiers Centrifugal Clutch Mechanisms: Influence of Presence and Elimination Options

V. Protsenko[1,*], V. Malashchenko[2], M. Babii[3], S. Rusanov[4], O. Kliuiev[5], V. Nastasenko[6], O. Voitovych[7]

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ABSTRACT

The article deals with the structure of centrifugal purifier friction clutch mechanisms. It is shown that the presence of misalignment of the engine and purifier shafts significantly affects the operation of the clutches due to the peculiarities of their mechanisms. Operating experience shows that the wear of the pad is unevenly distributed both along its length and width. Thus, the character of the pads' wear indicates the lack of possibility of self-installation of the pad relative to the semi-clutches, which has as its cause the presence of redundant constraints in the clutch mechanisms. It is proved that a reduction in the number of redundant constraints can be achieved by organizing the connection of the seated semi-clutch with the pads through flexible links, for example, steel ropes or 1-class kinematic connections.

1. Introduction.

The equipment of ship power plants is the most stressful and responsible since it has high power and productivity with small dimensions, and the safety of the crew and the environment depends on its reliability [1].

In view of this, ensuring the reliability of this equipment creates a reserve for increasing the safety of maritime transport and passenger transportation.

[1]Doctor of Technical Sciences, Professor of the Department of Transport Systems and Technical Service of Kherson National Technical University, Ukraine. E-mail Address: 1904pvo@gmail.com.

[2]Doctor of Technical Sciences, Professor of the Institute of Mechanical Engineering and Transport, Lviv Polytechnic National University, Ukraine. E-mail Address: volod.malash@gmail.com.

[3]Ph.D., Associate Professor of the Department of Ship Technical Systems and Complexes of Kherson State Maritime Academy, Ukraine. E-mail Address: m_babiy@ukr.net.

[4]Ph.D., Associate Professor of the Department of Transport Systems and Technical Service of Kherson National Technical University, Ukraine. Tel. (+380) 950727192. E-mail Address: ohvpbm@i.ua.

[5]Ph.D., Associate Professor of the Department of Transport Systems and Technical Service of Kherson National Technical University, Ukraine. E-mail Address: kluevoi@ukr.net.

[6]Doctor of Technical Sciences, Professor of the Department of Transport Technologies and Ship Repair of Kherson State Maritime Academy, Ukraine. E-mail Address: nastasenko2004@ukr.net.

[7]Ph.D., Associate Professor of the Department of Transport Systems and Technical Service of Kherson National Technical University, Ukraine. E-mail Address: olgavoytovich@ukr.net.

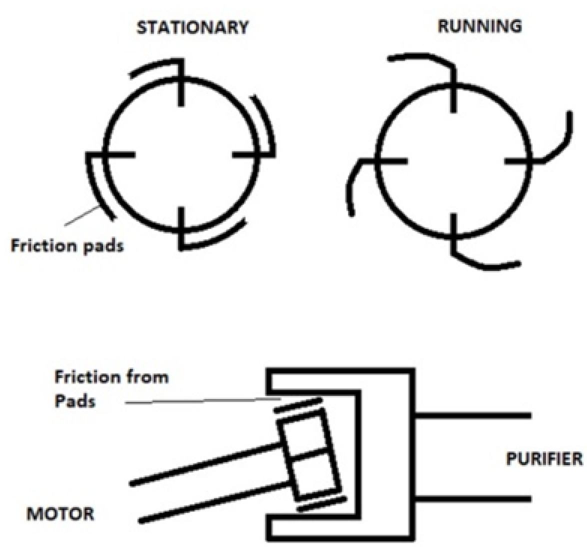
*Corresponding author: V. Protsenko. Tel. (+380) 504947472. E-mail Address: 1904pvo@gmail.com.

2. Problem Statement.

One of the most loaded elements of ship power plants are diesel engines [2, 3] and centrifugal fuel and oil purifiers that service them. Thus, circulating oil purifiers of diesel engines using heavy fuel operate almost continuously. Fuel purifiers operate with periodic starts and stops. Since the purifier drum has a large moment of inertia, to avoid starting overloads, their drive is usually equipped with a friction clutch of the centrifugal principle of action, which ensures smooth acceleration of the drum and prevents overloads during the operation of the purifier. The design of such clutches can be diverse, but their main elements are the pads, which, with their outer friction surface, are in contact with the inner surface of the cup-shaped semi-clutch. The durability of the clutch pads (namely their friction surfaces) determines the reliability and maintenance interval of the entire purifier since the percentage of pad failures reaches

20% of the total number of failures in the purifiers. The presence of misalignment of the engine and purifier shafts (Fig. 1), similar to brakes [5, 6], significantly affects the operation of the clutches due to the peculiarities of their mechanisms. Formally, the sliding of the pads relative to the cylindrical surface of the driven semi-clutch occurs only during the start-up of the purifier.

Figure 1: Purifier clutch operation features.



Source: https://muckymariners.com.

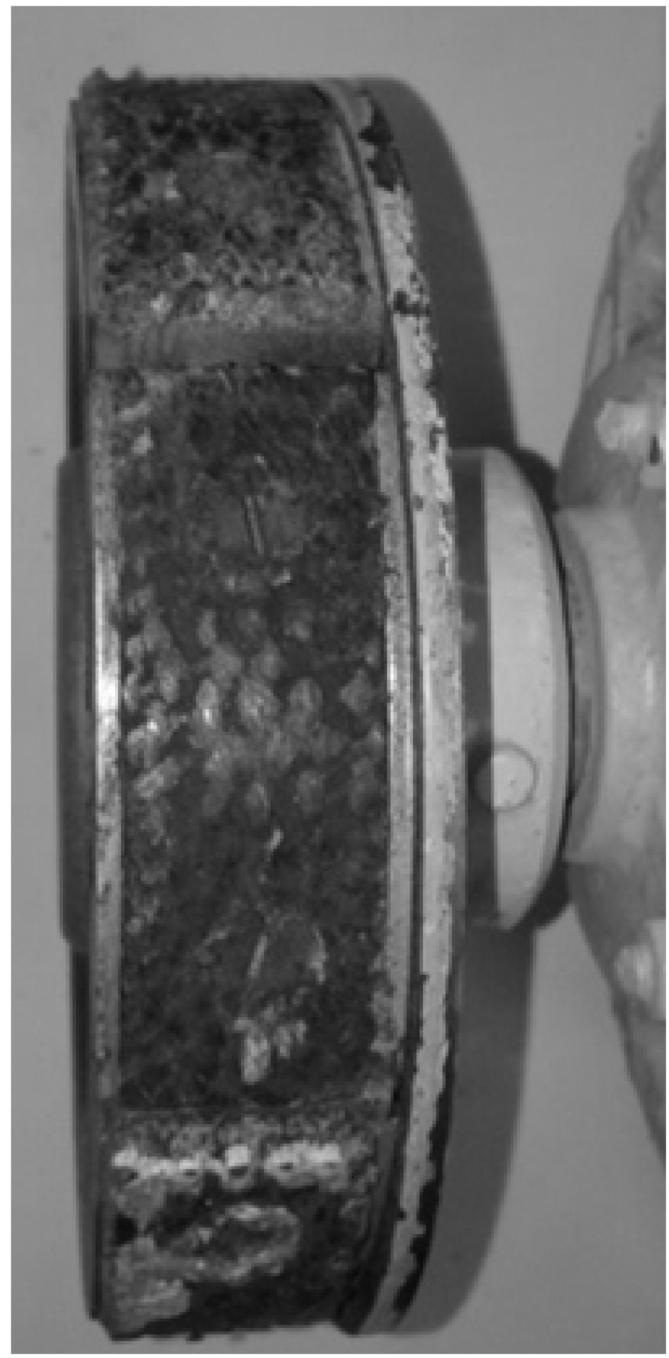
In fact, even after the purifier has been accelerated, at a constant speed of the electric motor and the driving semi-clutch, there is slipping in this nominally stationary contact caused by dynamic phenomena in the purifier drive and structural defects in the clutch mechanisms. Without going into the analysis of a wide range of these influences on the condition of the friction linings, let us consider the result of their action - wear of the pads working surfaces. Fig. 2 shows the condition of the pad after a short period of operation. The photo shows that the wear of the pad is unevenly distributed both along its length and width. This wear indicates the lack of possibility of self-installation of the pad relative to the semi-clutches.

In view of this, the aim of this work is to analyze and establish the causes of failures of centrifugal friction clutches using the example of clutches of fuel and lubricant purifiers of ship power plants, as well as to develop proposals for improving the mechanisms of these clutches.

3. Main Material Statement.

For example, let's consider the clutch of the centrifugal purifier SC-1.5, which is quite common on ships of the transport fleet. It (Fig. 3) contains a driving semi-clutch mounted on the shaft of the driving electric motor, in the radial holes of which, with their cylindrical spikes, pads are installed, which have friction linings screwed onto their outer surface. The pads, due to the gaps in the fit of their spikes in the radial holes of the driving semi-clutch, have the ability to move radially under the action of centrifugal forces that arise during the rotation of the clutch. Their outer surface contacts the inner cylindrical surface of the driven semi-clutch mounted on the horizontal shaft of the purifier.

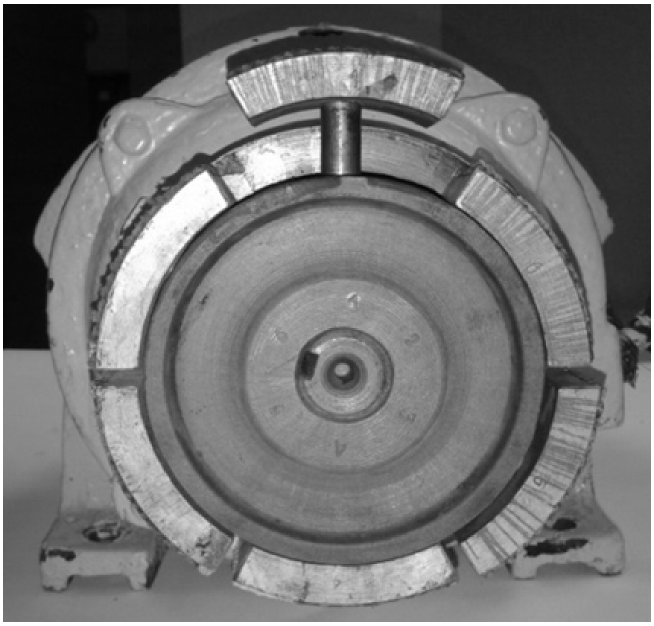
Figure 2: Purifier clutch friction linings wear character.



Source: Authors.

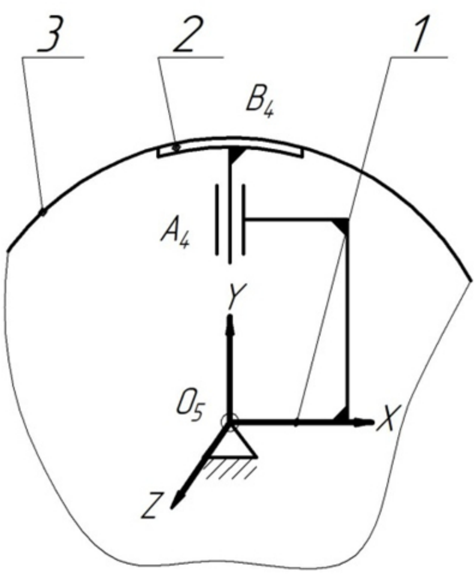
To establish the directions of improvement of centrifugal friction clutches, let us draw up a structural diagram of the elementary mechanism "driving semi-clutch-pad-driven semi-clutch," which form a friction clutch (Fig. 4) and check it for the presence of redundant constraints.

Figure 3: Purifier SC-1.5 friction clutch general view.



Source: Authors.

Figure 4: Structural diagram of the SC-1.5 purifier basic clutch mechanism during start-up.



Source: Authors.

At the beginning of the operation of the purifier and the clutch (start-up), the driven semi-clutch (link 3) remains stationary, link 1 (driving semi-clutch) and pads 2 moves, which are pressed by centrifugal forces to the inner surface of the semi-clutch 3, sliding along it. In this case, the number of moving links is $n = 2$ (links 1 and 2), the number of kinematic pairs of the fifth class $P_5 = 1$ *(O_5)*, the number of kinematic pairs of the fourth class $P_4 = 2$ *(A_4, B_4)*.

The total kinematic pairs number is [7]:

$$P = P_5 + P_4 = 1 + 2 = 3. \tag{1}$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 = 1 \times 1 + 2 \times 2 = 5. \tag{2}$$

Number of independent locked circuits by Gohman formula [8, 9]:

$$k = P - n = 3 - 2 = 1. \tag{3}$$

The Independent locked circuit is $O_5A_4B_4O_5$.

Total mechanism mobility by Voinea and Atanasiu equation [10]:

$$W = f - \sum r_i = 5 - 4 = 1 \tag{4}$$

where:

$r_i = 4$ - independent locked circuit $O_5A_4B_4O_5$ axis rank.

Then clutch mechanism redundant constraints number during start-up by Somov and Malyshev formula [4]:

$$\begin{aligned} q_{SM} &= W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n \\ &= 1 + 5 \times 1 + 4 \times 2 + 3 \times 0 + 2 \times 0 + 0 - 6 \times 2 = 2. \end{aligned} \tag{5}$$

where:

Redundant constraints number by Ozols formula [6]:

$$q_{OZ} = W + 6k - f = 1 + 6 \times 1 - 5 = 2. \tag{6}$$

Thereby, the total redundant constraints number in the analyzed SC-1.5 purifier basic clutch mechanism during start-up is:

$$q = q_{SM} = q_Z = 2. \tag{7}$$

Using the contour method confirms the presented calculations (table 1).

Therefore, for all clutches with 6 pads, the total redundant constraints number will be $q_\Sigma = 12$.

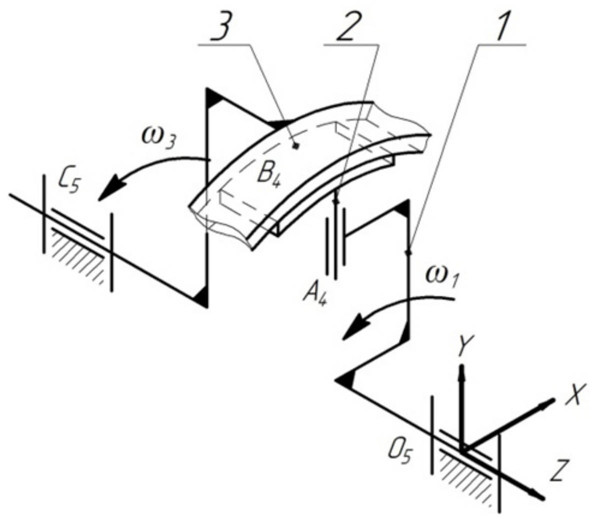
When the clutch starts to operate in a steady state (Fig. 5), the semi-clutch 3 gains mobility, and one additional pair of the fifth class appears - C_5. In this case, the number of moving links will be $n = 3$, the number of kinematic pairs of the fifth class $P_5 = 2$ (O_5, C_5), the number of kinematic pairs of the fourth class $P_4 = 2$ *(A_4, B_4)*.

Table 1: Circuit method application to SC-1.5 purifier basic clutch mechanism during start-up (Fig. 4).

Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f_x'	f_y'	f_z''	f_x''	f_y''	f_z'
$O_5A_4B_4O_5$	Ø $\downarrow q_1$	A	0 $\uparrow W_b$ B	Ø $\downarrow q_2$	A	B
$W = 1$, $q = 2$						

Source: Authors.

Figure 5: Structural diagram of the SC-1.5 purifier basic clutch mechanism during steady operation.



Source: Authors.

The total kinematic pairs number is:

$$P = P_5 + P_4 = 2 + 2 = 4.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 = 1{\times}2 + 2{\times}2 = 6.$$

Number of independent locked circuits by Gohman formula:

$$k = P - n = 4 - 3 = 1.$$

The Independent locked circuit is $O_5A_4B_4C_5O_5$.

Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum r_i = 6 - 4 = 2,$$

where:

$r_i = 4$ - independent locked circuit $O_5A_4B_4C_5O_5$ axis rank.

Total mechanism mobility:

$$W = W_b + W_l = 1 + 1 = 2,$$

where:

$W_b = 1$ – basic mechanism mobility;

$W_l = 1$ – local link 3 mobility.

Then clutch mechanism redundant constraints number during steady operation by Somov and Malyshev formula:

$$q_{SM} = W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n =$$
$$= 2 + 5 \times 2 + 4 \times 2 + 3 \times 0 + 2 \times 0 + 0 - 6 \times 3 = 2.$$

Redundant constraints number by Ozols formula:

$$q_{OZ} = W + 6k - f = 2 + 6 \times 1 - 6 = 2.$$

Thereby, the total redundant constraints number in the analyzed SC-1.5 purifier basic clutch mechanism during steady operation:

$$q = q_{SM} = q_Z = 2.$$

Using the contour method confirms the presented calculations (table 2).

Therefore, for all clutch with 6 pads, total redundant constraints number will be also $q_\Sigma = 12$.

Table 2: Circuit method application to SC-1.5 purifier basic clutch mechanism during steady operation (Fig. 5).

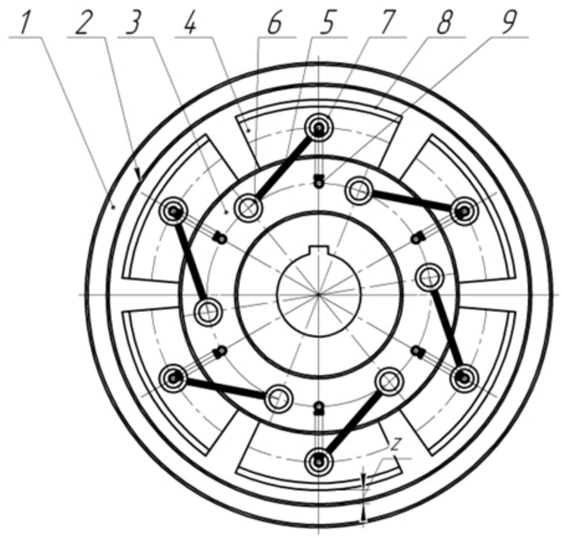
Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f_x'	f_y'	f_z''	f_x''	f_y''	f_z'
$O_5A_4B_4C_5O_5$	Ø $\downarrow q_1$	A	0 $\uparrow W_b$ BC $\uparrow W_l$	Ø $\downarrow q_2$	A	B
$W = 2,\ q = 2$						

Source: Authors.

Thus, in all modes of operation of the clutch, its mechanism is not devoid of 12 redundant constraints, the presence of which causes uneven wear of the pads due to the presence of angular misalignment between the semi-clutches. To reduce the number of redundant constraints and increase the durability of the friction clutch, it is possible to propose an increase in the class of kinematic pairs of the clutch mechanism, for example, by connecting the pads to the driving semi-clutch with flexible elements, in particular steel ropes. In Fig. 6 shows a clutch developed by the authors, consisting of an outer cup-shaped semi-clutch 1 with a cylindrical hole 2, installed inside its inner semi-clutch 3, on which pads 4 are installed, which are connected to the inner semi-clutch 3 by flexible elements 5, which are fixed in the semi-clutch 3 and the pad 4 by hinges 6 and 7.

The pads 4 have the ability to interact with their cylindrical friction surfaces 8 with the cylindrical hole 2 of the outer cup-shaped semi-clutch 1, and are attracted to the semi-clutch 3 by springs 9. The springs 9, which are fixed with one of their ends to pads 4 and the other in the semi-clutch 3 and in a stationary state, provide a gap z between the outer surface of pads 8 and hole 2 of the semi-clutch 1. The clutch in works as follows (Fig. 7). The driving semi-clutch 3 is the one that, rotating in the direction of tension of the flexible links 5, causes the rotation of the pads 4, which, rotating together with the semi-clutch 3, under the action of centrifugal force move in the radial direction, tensioning the springs 9, and are pressed with their friction surfaces 8 against the surface of the cylindrical hole 2 of the outer cup-shaped semi-clutch 1, causing a friction force that creates a friction moment that causes the rotation of the driven outer cup-shaped semi-clutch 1. In this case, a gap z is

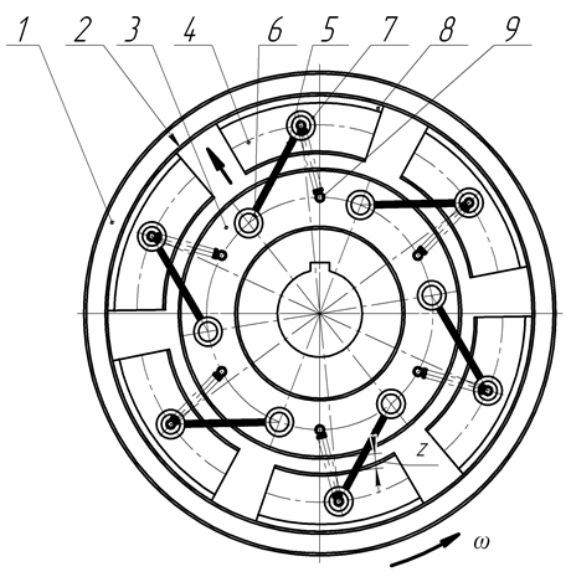
Figure 6: General view of the proposed rope clutch in a stationary state.



Source: Authors.

formed between the pads 4 and the surface of the semi-clutch 3.

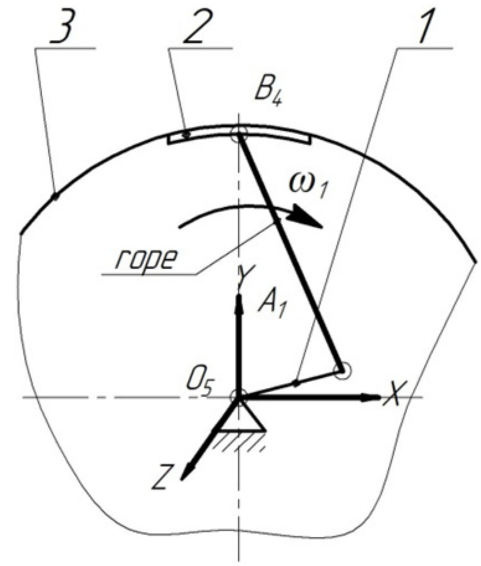
Figure 7: General view of the proposed rope clutch during steady operation.



Source: Authors.

In the next step, we will analyze the structure of the clutch with rope elements also for two cases of operation - starting and steady-state modes. At the start-up stage of such a clutch (Fig. 8) the number of moving links is $n = 2$ (links 1 and 2), the number of kinematic pairs of the fifth class $P_5 = 1$ (O_5), the number of kinematic pairs of the fourth class $P_4 = 1$ (B_4). We will consider the flexible link in the form of a rope as a pair of the first class $P_1 = 1$ (A_1).

Figure 8: Structural diagram of the proposed rope clutch mechanism during start-up.



Source: Authors.

The total kinematic pairs number is:

$$P = P_5 + P_4 + P_1 = 1 + 1 + 1 = 3.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 + 5P_1 = 1 \times 1 + 2 \times 1 + 5 \times 1 = 8.$$

Number of independent locked circuits by Gohman formula:

$$k = P - n = 3 - 2 = 1.$$

The Independent locked circuit is $O_5A_1B_4O_5$.

Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum r_i = 8 - 6 = 2,$$

where:

$r_i = 6$ - independent locked circuit $O_5A_1B_4O_5$ axis rank.

Total mechanism mobility:

$$W = W_b + W_l = 1 + 1 = 2,$$

where:

$W_b = 1$ – basic mechanism mobility;

$W_l = 1$ – local link 2 mobility.

Then clutch mechanism redundant constraints number during start-up by Somov and Malyshev formula:

$$q_{SM} = W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n = \\ = 2 + 5 \times 1 + 4 \times 1 + 3 \times 0 + 2 \times 0 + 1 - 6 \times 2 = 0.$$

Redundant constraints number by Ozols formula:

$$q_Z = W + 6k - f = 2 + 6 \times 1 - 8 = 0.$$

Thereby, the total redundant constraints number in the analyzed clutch mechanism during start-up:

$$q = q_{SM} = q_Z = 0.$$

Using the contour method confirms the presented calculations (table 3).

Therefore, for all proposed rope clutch with 6 pads, total redundant constraints number will be also $q_\Sigma = 0$.

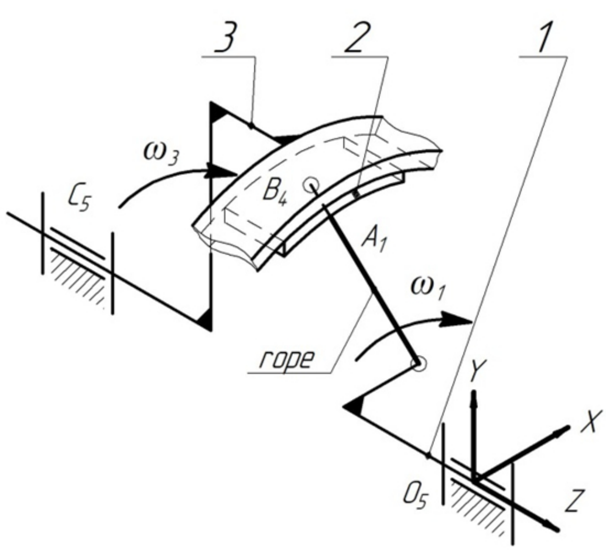
Table 3: Circuit method application proposed rope clutch mechanism during start-up (Fig. 8).

Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f_x'	f_y'	f_z''	f_x''	f_y''	f_z'
$O_5A_1B_4O_5$	A	Ø	0 / AB W_b	A	A	AB W_l
$W = 2,\ q = 0$						

Source: Authors.

When the clutch starts to operate in a steady state (Fig. 9), the number of moving links became $n = 3$ (links 1, 2 and 3), the number of kinematic pairs of the fifth class became $P_5 = 2$ (O_5, C_5), the number of kinematic pairs of the fourth class $P_4 = 1$ (B_4), the number of pairs of the first class $P_1 = 1$ (A_1).

Figure 9: Structural diagram of the proposed rope clutch mechanism during steady operation.



Source: Authors.

The total kinematic pairs number is:

$$P = P_5 + P_4 + P_1 = 2 + 1 + 1 = 4.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 + 5P_1 = 1\times 2 + 2\times 1 + 5\times 1 = 9.$$

Number of independent locked circuits by Gohman formula:

$$k = P - n = 4 - 3 = 1.$$

The Independent locked circuit is $O_5A_4B_4C_5O_5$.

Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum r_i = 9 - 6 = 3.$$

where:

$r_i = 4$ - independent locked circuit $O_5A_4B_4C_5O_5$ axis rank.

Total mechanism mobility:

$$W = W_b + W_l = 1 + 2 = 3,$$

where:

$W_b = 1$ – basic mechanism mobility;

$W_l = 2$ – local links 2 and 3 mobility.

Then, the proposed rope clutch mechanism redundant constraints number during steady operation by Somov and Malyshev formula:

$$q_{SM} = W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n =$$
$$= 3 + 5 \times 2 + 4 \times 1 + 3 \times 0 + 2 \times 0 + 1 - 6 \times 3 = 0.$$

Redundant constraints number by Ozols formula:

$$q_Z = W + 6k - f = 3 + 6 \times 1 - 9 = 0.$$

Thereby, the total redundant constraints number in the analyzed rope clutch mechanism during steady operation:

$$q = q_{SM} = q_Z = 0.$$

Using the contour method confirms the presented calculations (table 4). Therefore, for all clutch with 6 pads, total redundant constraints number will be also $q_\Sigma = 0$.

Thus, due to the presence of an improved design of rope elastic elements in the clutch, its mechanism is devoid of redundant constraints in all modes of operation of the clutch, which ensures uniform load distribution between the pads in conditions of misalignment.

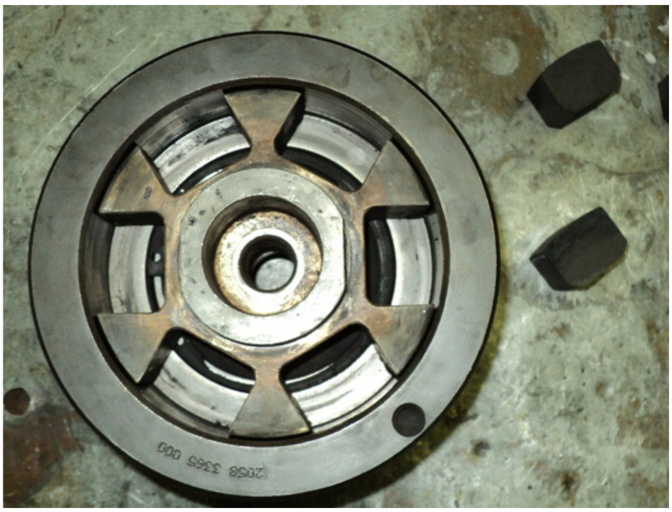
Table 4: Circuit method application for proposed rope clutch mechanism during steady operation (Fig. 9).

Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f_x'	f_y'	f_z''	f_x''	f_y''	f_z'
$O_5A_1B_4C_5O_5$	A	Ø	AO W_b / BC W_l	A	A	AB W_l
$W = 3,\ q = 0$						

Source: Authors.

Let's consider another example - a friction clutch of the purifier of the "WESTFALIA" company, which connects the electric motor with the transmission. The design of this clutch is clear from Fig. 10.

Figure 10: General view of the "WESTFALIA" purifier friction clutch.



Source: Authors.

Such clutches, along with advantages, have a disadvantage similar to the previous design, associated with uneven wear of the friction pads. We will also look for the cause of this disadvantage by examining the structure of the clutch mechanism and calculating the number of redundant constraints in it. We will determine the number of redundant constraints in each elementary mechanism, "cross-pad-inner semi-clutch," at each stage of the clutch operation. During driving start-up, the number of moving links is $n = 2$ – this is the crosspiece 1 and the block 2 (Fig. 11), the number of kinematic pairs of the fifth class is $P_5 = 1$ (O_5), the number of kinematic pairs of the fourth class is $P_4 = 1$ (B_4), the number of kinematic pairs of the third class is $P_3 = 1$ (A_3).

The total kinematic pairs number is:

$$P = P_5 + P_4 + P_3 = 1 + 1 + 1 = 3.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 + 3P_3 = 1 \times 1 + 2 \times 1 + 3 \times 1 = 6.$$

Number of independent locked circuits by Gohman formula:

$$k = P - n = 3 - 2 = 1.$$

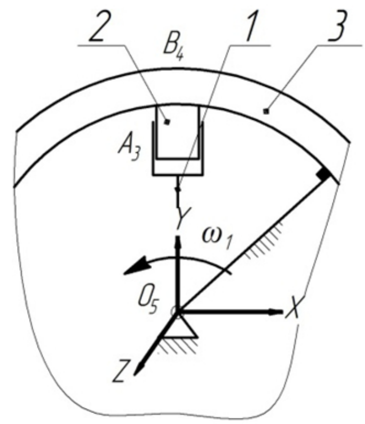
The Independent locked circuit is $O_5A_3B_4O_5$.

Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum r_i = 6 - 4 = 2,$$

where:

Figure 11: Structural diagram of the "WESTFALIA" purifier basic clutch mechanism during start-up.



Source: Authors.

$r_i = 4$ - independent locked circuit $O_5A_3B_4O_5$ axis rank.

Total mechanism mobility:

$$W = W_b + W_l = 1 + 1 = 2,$$

where:

$W_b = 1$ – basic mechanism mobility;

$W_l = 1$ – local link 2 mobility.

Redundant constraints number during start-up by Somov and Malyshev formula:

$$q_{SM} = W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n = \\ = 2 + 5 \times 1 + 4 \times 1 + 3 \times 1 + 2 \times 0 + 0 - 6 \times 2 = 2.$$

Redundant constraints number by Ozols formula:

$$q_Z = W + 6k - f = 2 + 6 \times 1 - 6 = 2.$$

Using the contour method confirms the presented calculations (table 5). Therefore, for all clutch with 6 pads, total redundant constraints number will be $q_\Sigma = 12$.

Table 5: Circuit method application for "WESTFALIA" purifier basic clutch mechanism during start-up (Fig. 11).

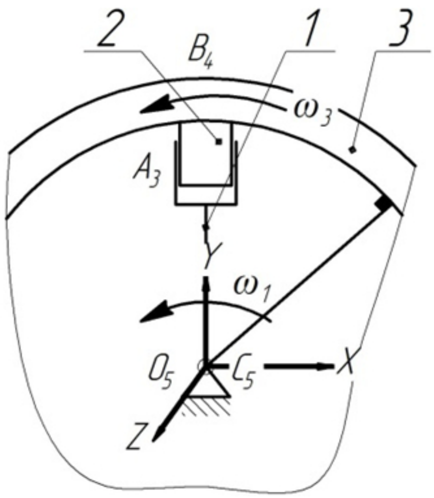
Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f'_x	f'_y	f''_z	f''_x	f''_y	f'_z
$O_5A_3B_4O_5$	Ø $\downarrow q_1$	A	O B W_b	A	Ø $\downarrow q_2$	AB W_l
$W = 2,\ q = 2$						

Source: Authors.

When the clutch starts to operate in steady state (Fig. 12), the number of moving links became $n = 3$ (links 1, 2 and 3), number of kinematic pairs of the fifth class became $P_5 = 2$ (O_5,

C_5), the number of kinematic pairs of the fourth class $P_4 = 1$ (B_4), the number of pairs of the third class $P_3 = 1$ (A_3).

Figure 12: Structural diagram of the "WESTFALIA" purifier basic clutch mechanism during steady operation.



Source: Authors.

The total kinematic pairs number is:

$$P = P_5 + P_4 + P_3 = 2 + 1 + 1 = 4.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 + 3P_3 = 1 \times 2 + 2 \times 1 + 3 \times 1 = 7.$$

Number of independent locked circuits by Gohman formula:

$$k = P - n = 4 - 3 = 1.$$

The Independent locked circuit is $O_5A_3B_4C_5O_5$.

Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum r_i = 7 - 4 = 3.$$

where:
$r_i = 4$ - independent locked circuit $O_5A_3B_4C_5O_5$ axis rank.
Total mechanism mobility:

$$W = W_b + W_l = 1 + 2 = 3,$$

where:
$W_b = 1$ – basic mechanism mobility;
$W_l = 2$ – local links 2 and 3 mobility.
Then clutch mechanism redundant constraints number during steady operation by Somov and Malyshev formula:

$$\begin{aligned} q_{SM} &= W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n \\ &= 3 + 5 \times 2 + 4 \times 1 + 3 \times 1 + 2 \times 0 + 0 - 6 \times 3 = 2. \end{aligned}$$

Redundant constraints number by Ozols formula:

$$q_{OZ} = W + 6k - f = 3 + 6 \times 1 - 7 = 2.$$

Using the contour method confirms the presented calculations (table 6). Therefore, for all clutch with 6 pads, total redundant constraints number will be $q_\Sigma = 12$.

Table 6: Circuit method application for "WESTFALIA" purifier basic clutch mechanism during steady operation (Fig. 12)

Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f'_x	f'_y	f''_z	f''_x	f''_y	f'_z
$O_5A_3B_4C_5O_5$	Ø $\downarrow q_1$	A	B $\uparrow W_b$ OC $\uparrow W_l$	A	Ø $\downarrow q_2$	AB $\uparrow W_l$
$W = 3$, $q = 2$						

Source: Authors.

So, in all modes of operation of the clutch, each elementary mechanism is not devoid of two redundant constraints, which causes uneven wear of the pads due to the presence of angular misalignment between the semi-clutches. The identified defect in the structure of the clutch mechanism can be eliminated by adding one additional mobility, which requires improving the structural scheme of the clutch mechanism. For example, it is possible to provide a connection of the pads and the cross-piece due to a complex kinematic connection of a higher class than the basic kinematic pair A_3. For example, the pads can be made composite where the friction element 2 (Fig. 13) will be connected to the prismatic body of the pad 4 by a cylindrical-spherical hinge. Due to this, we will obtain a connection formed by the sequential connection of pairs of the third, third and fifth classes, and in the case of such a connection of kinematic pairs in the connection, their mobilities are added [5]. Thus, we obtain a five-moving connection of the first class A_1 with internal local redundant movability (spherical sleeve rotation). Let us consider the operation of such an improved clutch design. During drive start-up, the number of moving links is $n = 2$ - this is the cross 1 and the block 2 (Fig. 13), the number of kinematic pairs of the fifth class is $P_5 = 1$ (O_5), the number of kinematic pairs of the fourth class $P_4 = 1$ (B_4), the number of kinematic pairs (constraints) of the first class $P_1 = 1$ (A_1).

The total kinematic pairs number is:

$$P = P_5 + P_4 + P_1 = 1 + 1 + 1 = 3.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 + 5P_1 = 1 \times 1 + 2 \times 1 + 5 \times 1 = 8.$$

Number of independent locked circuits by Gohman formula:

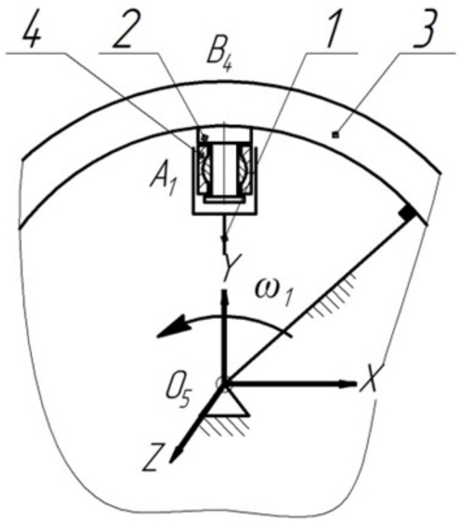
$$k = P - n = 3 - 2 = 1.$$

The Independent locked circuit is $O_5A_1B_4O_5$.

Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum_{i=1}^{n} r_i = 8 - 6 = 2.$$

Figure 13: Structural diagram of the “WESTFALIA” purifier improved clutch mechanism during start-up.



Source: Authors.

where:
$r_i = 4$ - independent locked circuit $O_5A_1B_4O_5$ axis rank.
Total mechanism mobility:

$$W = W_b + W_l = 1 + 1 = 2.$$

where:
$W_b = 1$ – basic mechanism mobility;
$W_l = 1$ – local link 2 mobility.
Redundant constraints number during start-up by Somov and Malyshev formula:

$$\begin{aligned} q_{SM} &= W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n \\ &= 2 + 5 \times 1 + 4 \times 1 + 3 \times 0 + 2 \times 0 + 1 - 6 \times 2 = 0. \end{aligned}$$

Redundant constraints number by Ozols formula:

$$q_{OZ} = W + 6k - f = 2 + 6 \times 1 - 8 = 0.$$

The application of the contour method (Table 7) confirms the obtained results. For all clutch with 6 pads, total redundant constraints number also will be $q_{\Sigma} = 0$.

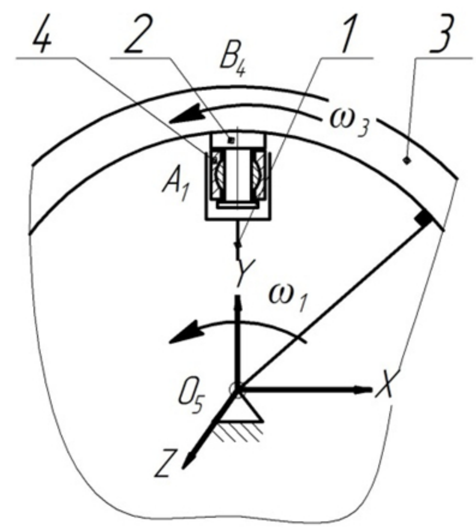
Table 7: Circuit method application for “WESTFALIA” purifier modified clutch mechanism during start-up (Fig. 13)

Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f_x'	f_y'	f_z''	f_x''	f_y''	f_z'
$O_5A_1B_4O_5$	Ø	A	AB W_b / 0	A	A	AB W_l
$W = 2,\ q = 0$						

Source: Authors.

During steady operation, the number of moving links increases to $n = 3$ – this is the crosspiece 1, the block 2 and the driven semi-clutch 3 (Fig. 14), the number of kinematic pairs of the fifth class is $P_5 = 2$ ($O_5 + C_5$), the number of kinematic pairs of the fourth class $P_4 = 1$ (B_4), the number of kinematic pairs of the second class $P_1 = 1$ (A_1).

Figure 14: Structural diagram of the “WESTFALIA” purifier improved clutch mechanism during steady operation.



Source: Authors.

The total kinematic pairs number is:

$$P = P_5 + P_4 + P_1 = 2 + 1 + 1 = 4.$$

The sum of kinematic pairs movabilities:

$$f = 1P_5 + 2P_4 + 5P_1 = 1 \times 2 + 2 \times 1 + 5 \times 1 = 9.$$

Number of independent locked circuits by Gohman formula:

$$k = P - n = 4 - 3 = 1.$$

The Independent locked circuit is $O_5A_1B_4C_5O_5$.
Total mechanism mobility by Voinea and Atanasiu equation:

$$W = f - \sum r_i = 9 - 6 = 3$$

where:
$r_i = 4$ - independent locked circuit $O_5A_1B_4C_5O_5$ axis rank.
Total mechanism mobility:

$$W = W_b + W_l = 1 + 2 = 3$$

where:
$W_b = 1$ – basic mechanism mobility;
$W_l = 2$ – local links 2 and 3 mobility.
Redundant constraints number during steady operation by Somov and Malyshev formula:

$$\begin{aligned} q_{SM} &= W + 5P_5 + 4P_4 + 3P_3 + 2P_2 + P_1 - 6n \\ &= 3 + 5 \times 2 + 4 \times 1 + 3 \times 0 + 2 \times 0 + 1 - 6 \times 3 = 0. \end{aligned}$$

Redundant constraints number by Ozols formula:

$$q_{OZ} = W + 6k - f = 3 + 6 \times 1 - 9 = 0.$$

The application of the contour method (Table 8) confirms the obtained results. For all clutch with 6 pads, total redundant constraints number will be $q_{\Sigma} = 0$.

Table 8: Circuit method application for "WESTFALIA" purifier modified clutch mechanism during steady operation (Fig. 14)

Circuit	Planar movabilities f_p			Non-planar movabilities f_n		
	f'_x	f'_y	f''_z	f''_x	f''_y	f'_z
$O_5A_1B_4C_5O_5$	Ø	A	AB W_b OC W_l	A	A	AB W_l
$W = 3, \; q = 0$						

Source: Authors.

Thus, the proposed improvement of the clutch mechanism by equipping the friction pads with a 1-class kinematic connection allows for eliminating redundant constraints and can become a reserve for increasing the reliability of the whole clutch.

Conclusions.

1. Centrifugal friction clutches of purifiers are characterized by uneven wear of their pads due to the presence of redundant constraints in their mechanisms.
2. Redundant constraints lead to the sensitivity of the clutch to angular and parallel displacements of the axes of the semi-clutches, which is the cause of uneven wear of the linings of the pads.
3. It is shown that a reduction in the number of redundant constraints can be achieved by organizing the connection of the seated semi-clutch with the pads through flexible links, for example, steel ropes or 1-class kinematic constraints.

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