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Increasing method performance of long-dimensional hydraulic cylinders for road and construction machinery

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Abstract: Single bucket excavators are one of the most frequent types of construction machines, as shown in this work (CM). Due to a variety of advantages over a mechanical drive, the vast majority of them use a hydraulic drive. The hydraulic drive, on the other hand, has a significantly poorer reliability. Hydraulic cylinders are the most significant factor limiting its dependability. One of the shortcomings of the existing design of the most popular double-acting reciprocating hydraulic cylinder on road-building machines with a one-sided rod is that it has a deflection before applying an operational longitudinal compressive force. This type of deflection is defined as the total amount of deflection caused by misalignment of the primary bearing parts (stem and sleeve).

Keyword: Excavator, Hydraulic cylinder, Hydraulic Drive, Single Bucket, Single/One-Sided Rod.

INTRODUCTION

The total deflection is a consequence of the presence of such reasons as: gaps in the hydraulic cylinder interfaces "piston - sleeve" and "rod - guide sleeve", deflection as a result of a possible initial (technological) curvature of long elements (rod and housing), regulated by a technological tolerance for the non-straightness of the manufacture of long products, as well as deflection from the action of transverse forces - the weights of these elements. After the application of an operational longitudinal compressive force, that is, when a liquid is supplied under pressure to the piston cavity of the hydraulic cylinder, the total deformation of the hydraulic cylinder increases and, being the shoulder for applying this force, leads to an increase in the total bending moment that can cause critical stresses and, accordingly, the appearance of plastic deformations in hydraulic cylinder rod and the subsequent loss of efficiency by the hydraulic cylinder as a result of jamming of the rod with the piston in the body (sleeve) of the hydraulic cylinder. Longitudinal compressive force is generally not constant throughout the working cycle of construction machines, such as a shovel excavator, and, in this case, is a function of the resistance of the soil to digging. As the friction surfaces of the elements of the hydraulic cylinder wear out, which, again, leads to an increase in its total deformation, respectively, to an increase in the acting longitudinal and transverse loads, the operating conditions of the hydraulic cylinder deteriorate with even greater intensity, resulting in a decrease in its reliability, namely, durability, both in terms of bearing and sealing ability. To a large extent, this can be attributed to the long-stroke hydraulic cylinders of road construction machines. The listed disadvantages of the traditional design can be eliminated by bringing the hydraulic cylinder design from an unstable state of longitudinal-transverse bending to a stable state or close to it through the support of the body (sleeve) of the hydraulic cylinder with an intermediate sensor support.

METHOD

This study adopted a systematic review methodology to explore and synthesize existing knowledge on improving the method performance of long-dimensional hydraulic cylinders used in road and construction machinery. The review focused on identifying effective engineering solutions aimed at reducing deflection and enhancing reliability, particularly in double-acting reciprocating hydraulic cylinders with a one-sided rod. The process followed a structured, transparent approach consistent with PRISMA guidelines to ensure rigor and replicability. A comprehensive search of scientific literature was conducted across reputable databases, including ScienceDirect, IEEE Xplore, Scopus, and ASME Digital Collection. The search combined keywords such as hydraulic cylinder performance, long-stroke hydraulic actuators, cylinder deflection, and hydraulic drive reliability to capture relevant studies. Studies selected for inclusion focused on the design, modeling, simulation, or experimental improvement of hydraulic cylinders for construction machinery. The quality of the studies was assessed based on clarity of objectives, appropriateness of methods, and validity of conclusions. Data were systematically extracted and synthesized, with particular attention to approaches that addressed deflection caused by misalignment of primary bearing components. The findings were analyzed to highlight the most promising strategies for enhancing hydraulic cylinder performance while acknowledging limitations related to language restrictions and possible publication bias within the available literature.

RESULT AND DISCUSSION

Design and parameters of DSM hydraulic cylinders

As reciprocating hydraulic motors of hydroficated working equipment of road construction machines, double-acting hydraulic cylinders with a single-sided rod are currently widely used (Fig. 1.1). Their classification and purpose, device and types of execution, principle of operation and conditions of use, as well as kinematic diagrams inclusion and hydraulic connection are described in sufficient detail in the works of these literatures [Khan (2016), Stawinski et al. (2021), Barillas et al. (2018), Hangzhou Ever-Power Transmission Co., Ltd (HZPT) (2024), Kobzov et al. (2020), Pustavrh et al. (2023), Pustavrh et al. (2025), Koskinen and Aaltonen (2013), Haonan et al. (2025), Axinte et al. (2023), Cojocaru et al. (2022), Baroiu et al. (2017), Dutu et al. (2022), Boye et al. (2017) and Mantovani (2020)]. Schemes of fastening of hydraulic cylinders are shown in fig. 1.2-1.4. The most preferred type of hydraulic cylinder attachment is an eye [Kushalivev et al. (2025), Quan and Zhang (2014), Narvydas et al. (2020), Zhang (2010), Mobley (2001)].

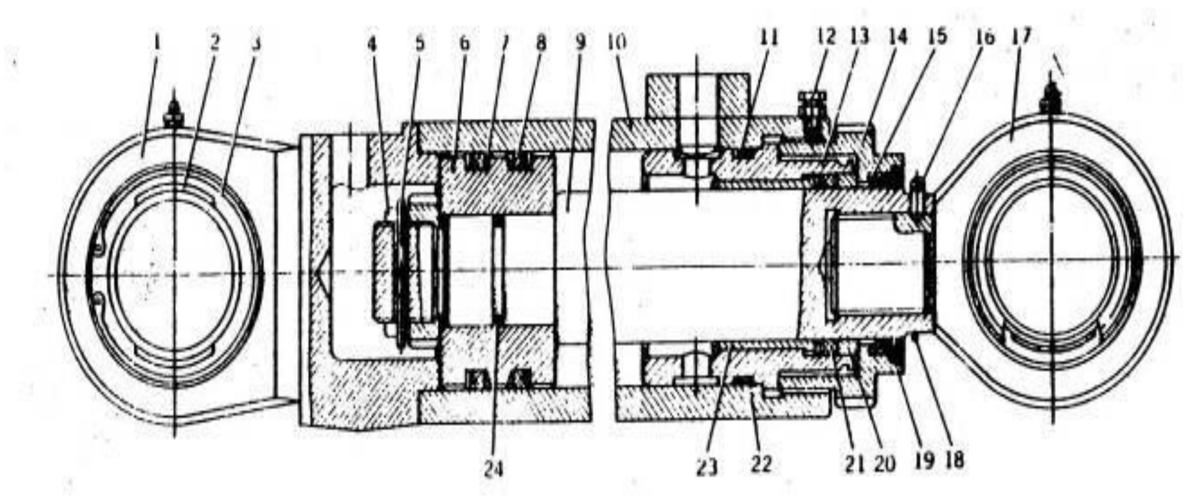


Figure 1.1 - Double-acting hydraulic cylinder with a single-sided rod:

1, 17 - lugs; 2 - ball bearing; 3, 19 - retaining rings; 4, 14 - nuts; 5 - cotter pin; 6 - piston; 7 - washer; 8, 21 - cuffs; 9 - stock; 10 - cylinder sleeve; 11, 22, 24 - rings; 12 - locking bolt; 13, 20, 23 - bushings; 15 – wiper; 16 - pin; 18 - stopper.

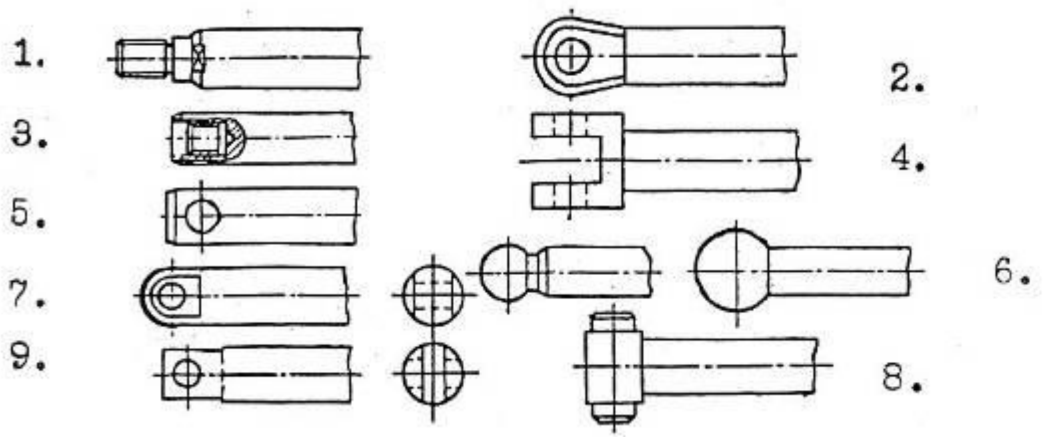


Figure 1.2 - Mounting options for the hydraulic cylinder rod.

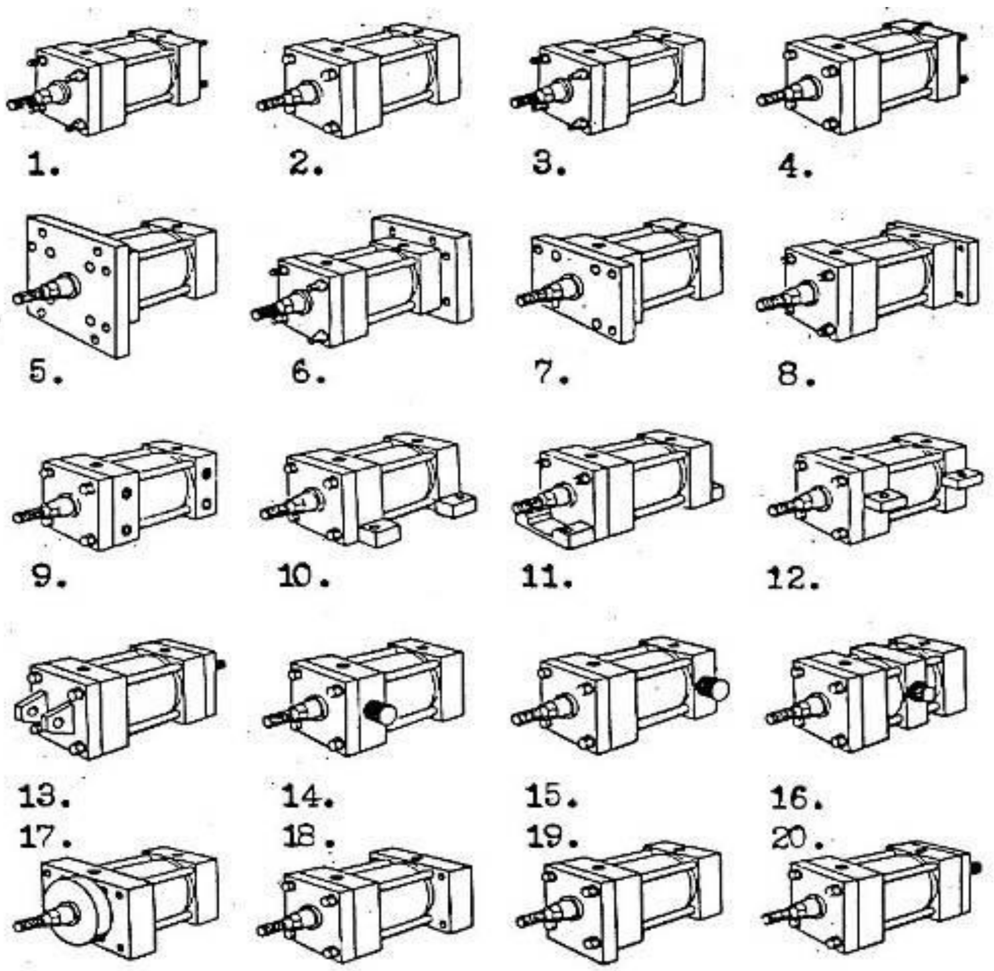


Figure 1.3 - Mounting options for the hydraulic cylinder body.

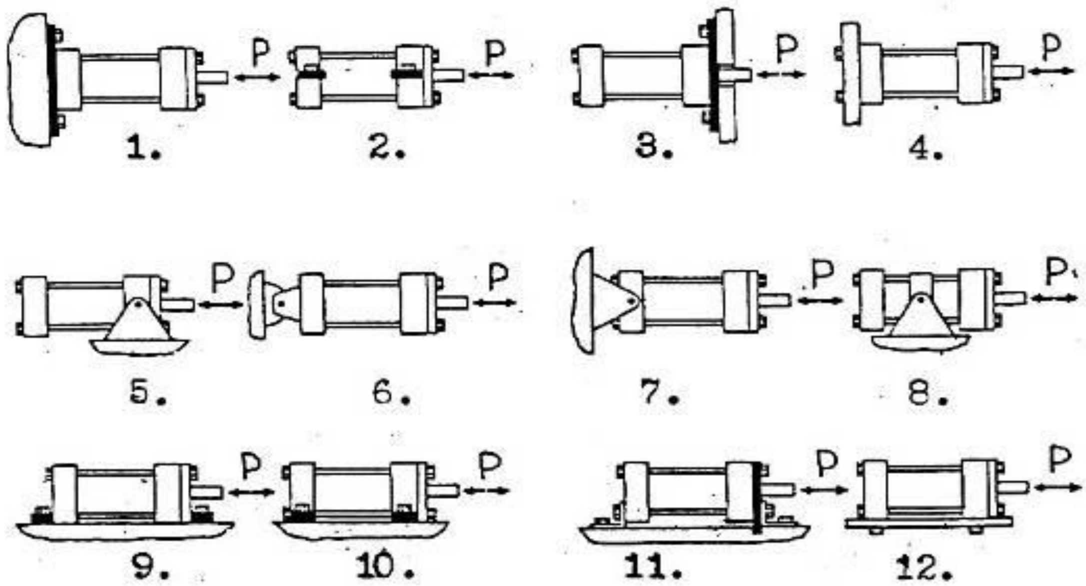


Figure 1.4 - Hydraulic cylinder mounting options.

In [Lubecki et al. (2022), Siwulski (2023)], schemes of operational loads acting on a hydraulic cylinder are given. The documents regulating the parameters of the hydraulic cylinder, in different periods of time and in different countries, were GOST 6540-68, ST SEV 3936-82, GOST 16514-96, as well as ISO 2944, 3320, 3322 and 4393, in accordance with which it is assumed the possibility of creating hydraulic cylinders for the main and additional rows (in units measurement standards) with a nominal pressure p = (0.63 ... 63) MPa, with a piston (rod) stroke z = (4 ... 10000) mm, with piston diameters D1 = (4 ... 900) mm and rod D2 = (4 ... 900) mm, with the ratio of pressure areas in the piston and rod cavities φ = (1.06 ... 5.26). In relation to DSM hydraulic cylinders, these parameters lie in the ranges: p = (2.5 ... 40) MPa; z = (50 ... 2000) mm; D2 = (32 ... 250) mm; φ = (1.33 and 1.6); the speed of movement of the rod in these documents is not specified, but lies in the range d_z/d_t = (0.1 ... 1.0) m/s, and, in relation to DSM, does not exceed 0.5 m/s.

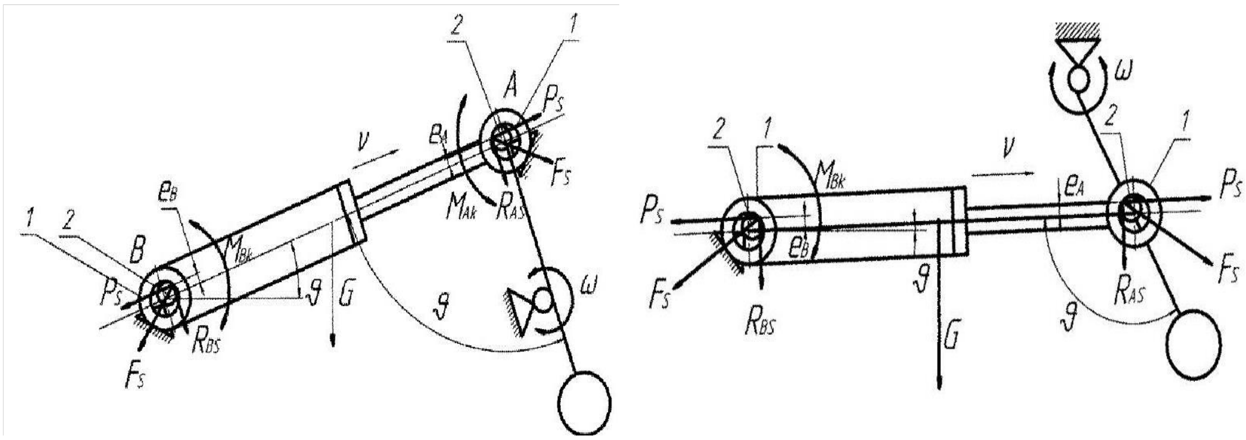
The design and manufacture of hydraulic cylinders for single-bucket hydraulic machines is carried out in accordance with the requirements of GOST 16514-79 and GOST 17411-81, in accordance to which: the sleeve, rod and cap nut of the hydraulic cylinder must be made of materials with mechanical properties not lower than steel 45 according to GOST 1050-74, GOST 4543-71, GOST 1050-74, GOST 4543-71; to ensure tightness. Hydraulic cylinders of road construction machines must have: rod and piston seals in accordance with GOST 14896-74, GOST 22704-74, GOST 1104-69, GOST 9833-73. Seals for hydraulic cylinders with a working pressure of 10 and 16 MPa must have protective rings in accordance with GOST 23825-79, GOST 10007-80, GOST 14896-84, and GOST 9833-73. It is possible both to cover the bushing and piston and to use bearing bushings for pistons and rods according to GOST 10589-73; the outer surface of the hydraulic cylinder rod must have a chromium coating with Ra = 0.160 μm according to GOST 2789-73; the roughness of the working surface of the hydraulic cylinder sleeve should not exceed Ra = 0.320 μm according to GOST 2789-73. Spherical bearings of type ShS…K or ShSP …K are determined by GOST 3635-78 and GOST 13941-48. There are two options for supplying the working fluid: nipple threaded at a nominal pressure in the hydraulic system of 10 and 16 MPa and flanged at a nominal pressure of 25 and 32 MPa.

The type of coating of the outer surfaces of hydraulic cylinders is determined depending on the operating conditions in accordance with GOST 14623-69. The diameter of the cylinder and piston should be selected from a range of 10 ... 900 mm according to GOST 6540-68, which corresponds to ISO 3320 up to 400 mm; piston stroke should be selected from a range of 4 ... 10000 mm according to GOST 6540-68, which corresponds to ISO 04393. Hydraulic cylinders for a nominal pressure up to 40 MPa are tested with a pressure of 1.5 times the nominal pressure for at least 3 minutes. Manifestations of leakage deformations are not allowed. Pistons under static load must move evenly along the entire stroke length, except for braking areas. During operation of the hydraulic cylinder, the volume of the working fluid carried out through the rod seal from 1 mm^2 of the sealing surface at nominal pressure, piston speed of at least 0.2 m/s and viscosity working fluid not more than 40 mm^2/s should not exceed the values in accordance with GOST 16514-87. The overall efficiency of hydraulic cylinders at nominal parameters must be at least 90%. During operation, hydraulic cylinders should be loaded only along their axis; full installed resource of hydraulic cylinders - at least 106 double strokes with a piston stroke of up to 500 mm or 1000 km of traveled or total distance; limit state criterion. The occurrence of leakage of the working liquids will be more than 1.2 times the value of the removal rate of the working fluid of hydraulic drives of road-building machines, in accordance with GOST 16514-87. The failure criterion is the inoperable state of the hydraulic cylinder, which requires stopping the operation of the road construction machine to eliminate this malfunction; replacement of seals is not a failure. Directly for road construction machines [Lubecki et al. (2022), Siwulski (2023)], hydraulic cylinders with a nominal pressure in the hydraulic system of 20 ... 23 MPa are most often used [Kobzov et al., 2020].

Features of the design of the working equipment of modern DSM with hydraulic cylinders

Analysis of the kinematic features of hydroficated technical objects [Kobzov et al., 2020], containing a different number of hydraulic cylinders, indicates the following:

All known schemes can be used as a drive for the working equipment of modern road-building machines. 39.7% of the total number of road construction machines have one hydraulic cylinder, 27.6% - two, 18.4% - three, 11.7% - four and 2.6% - five, which are more than 60% of the working equipment of road-building machines of multi-link schemes [Lubecki et al. (2022), Siwulski (2023)]. At the same time, work of one or more hydraulic cylinders affects the entire workflow, mode of operation and load characteristics of the rest. During the operation of a road-building machine, 90.8% of the hydraulic cylinders position in space, while in a number of schemes the operation of one hydraulic cylinder leads to a change in the spatial arrangement of others. In 75.4% of schemes of working equipment of road construction machines, the hydraulic cylinder with other parts of the drive forms a triangle (Fig. 1.5), in 22.2% - a polygon, in the remaining options - a line. The most commonly used hydraulic cylinders are single and double-acting with a single-sided rod (Fig. 1.1) (Ding et al., 2012) -1%, double-acting with a double-sided stem - 0.5% and others - 13.5%.



(a) (b)

Figure 1.5 - Excavator handle drive schemes: (a) backhoe, (b) straight Shovel.

Experimental study and justification of the nature of the occurrence of damage to hydraulic cylinders of machines

Numerous data cited in a number of domestic and foreign sources, in particular, in [Lubecki et al. (2022), Siwulski (2023), Pugin and Shayakbarov (2025), Pugin (2020), Nicoletto and Marin (2011), Lin and Gong (2023)], indicate that the reliability and performance of hydraulic cylinders of the working equipment of road construction machines is low, the percentage of failures is large and it decreases slowly. Changing such characteristics as the pressure in the process of experimental studies of failures of hydraulic cylinders of road-building machines in the conditions of their operation, the following damage to their elements was revealed:

i. Stem damage: wear of the sliding surface, formation of corrosion centers on it, scratches, scuffs and dents, stem distortion, thread breakage;

ii. Damage to the body: the appearance of ellipse and taper, the formation of scratches, scratches and scuffs on the surface to be sealed, cracks and rupture of the body;

iii. Damage to guide bushings and pistons: Uneven perimeter wears of rubbing surfaces, Hydraulic drive upwards and increasing the size of the machine further reduces the efficiency and reliability. The formation of scratches and scuffs on them;

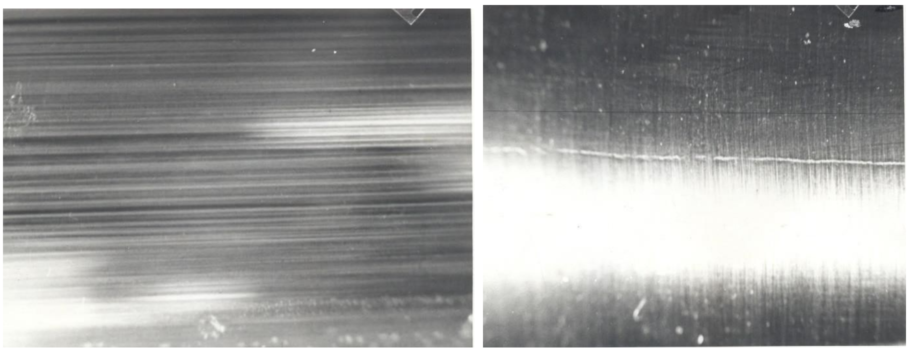
iv. Damage to seals for all purposes: aging of the material, uneven wear of sealing surfaces along the perimeter and width of the seal, the appearance of scratches and scratches on them, rupture of the seal;

v. Damage to eye bearings: wear of sliding surfaces, partial or complete destruction of components;

vi. Damage to the head - thread failure;

vii. Damage to the rod lug - thread stripping, lug breakage.

The ingress of abrasive into the hydraulic cylinder interface due to high contact pressure and poor-quality lubrication at the points of contact of the elements of the hydraulic cylinder, as well as jamming of the rod in the sleeve is the main cause of damage to the rods of the hydraulic cylinders. Scratches, risks, scuffs were found in 100% of hydraulic cylinders. Scratches appear for reasons such as abrasive particles getting stuck in the seals. The presence of rod scratches is present in 55% of the examined hydraulic cylinders. The reason for the appearance of seizures, i.e. large furrows with torn edges - this is jamming in the movable mates of the parts of the hydraulic cylinder significant abrasive. Such malfunctions, as a rule, are not repairable and the hydraulic cylinder must be replaced. Solid objects hitting the stem will cause dents to appear on the stem. The wear of such elements is considered in detail in the work of Kragelsky, 2013. The amount of wear is determined by the change in the size of the bodies. Only areas with side friction between mating parts are subject to wear [Kragelsky, 2013]. (Figure. 1.6)



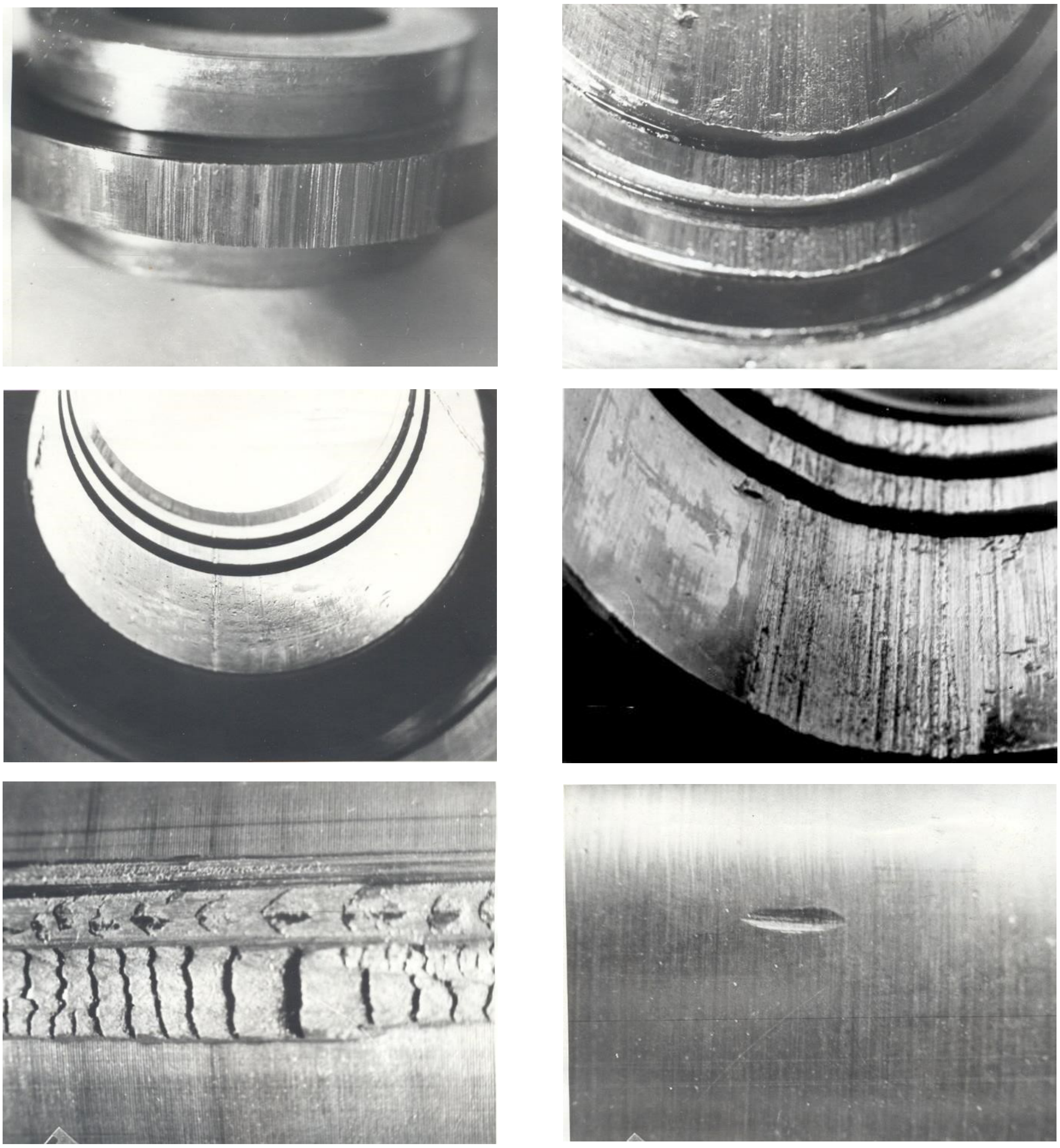


Figure 1.6 - Typical damage to hydraulic cylinder elements:

1. Scratches and knurling on the surface of the rod; 2. Scratches on the piston and guide sleeve;

3. Guide bush scuffs; and, 4. Scuffs and dents on the stem surface.

The wear intensity of each of the interface elements depends on the external friction condition (load), the mechanical properties of the wear material, the micro-geometric properties of the wear surface and friction characteristics, the driving conditions and the interface temperature

[Kragelsky, 2013].

Figure 1.7 - Characteristic wear of the piston surface in the initial period of running-in of interface elements.

In addition, the linear wear rate of the rod and sleeve ISH, G, as well as the piston and guide sleeve IP, C is inversely proportional to the friction surface area of the elements, which, in accordance with [Kragelsky, 2013], can be determined from the expressions: for piston rod and cylinder liner

ISH, G = Θ2−3 ·r2, 3 ·z (1.1)

For piston and guide bush:

IP, V = Θ1−4 ·r1.4 ·l1.4 (1.2)

Where Θ1−4 are the contact angles of mating elements, and depends on the load, material properties of the elements, their dimensions and geometry. r1, r2, r3, r4 are the radial sizes of the piston rod, sleeve or sleeves respectively; z is the stroke length of the hydraulic cylinder rod. l1 and l4 are the width of the piston and guide sleeve, respectively. The greatest wear occurs in the pistons and bushings of the hydraulic cylinder of a road-building machine. The reason is in the reactions acting in the hydraulic cylinder interfaces. Such wears and tears exhibit uneven character along the perimeter and along the length. As it is known, the value of this wear can reach values of 2.5 X $10^{-}3$ m per side [Lubecki et al. (2022), Siwulski (2023), Gamez-Montero et al. (2009)]. At the same time, the wear of rods and sleeves is insignificant. The main reasons for the violation of the performance of hydraulic cylinders of road-building machines are the bending of the rod and the deterioration of the stem surface. Bending of the hydraulic cylinder rod within the limits (3 ... 5) X $10^{-}3$ m, [Tavares et al., 2016], is recorded in 39% of the hydraulic cylinders. Bent rods were found even in small hydraulic cylinders with significant rigidity. The bends of the rods shown in Figure 1.8 are quite frequent. Rods of long-length hydraulic cylinders of road-building machines, for example, hydraulic cylinders of an excavator handle, are subject to bending to a large extent. An analysis of the condition of the hydraulic cylinder seals was also made (Fig. 1.9). At the same time, it was found that 100% of seals, wipers and guides have micro-damages on the working planes coinciding with the direction of movement of the hydraulic cylinder rod. The reason for their appearance is the ingress of abrasive particles on the surface of the seals and exposure to sharp edges of scratches and scuffs.

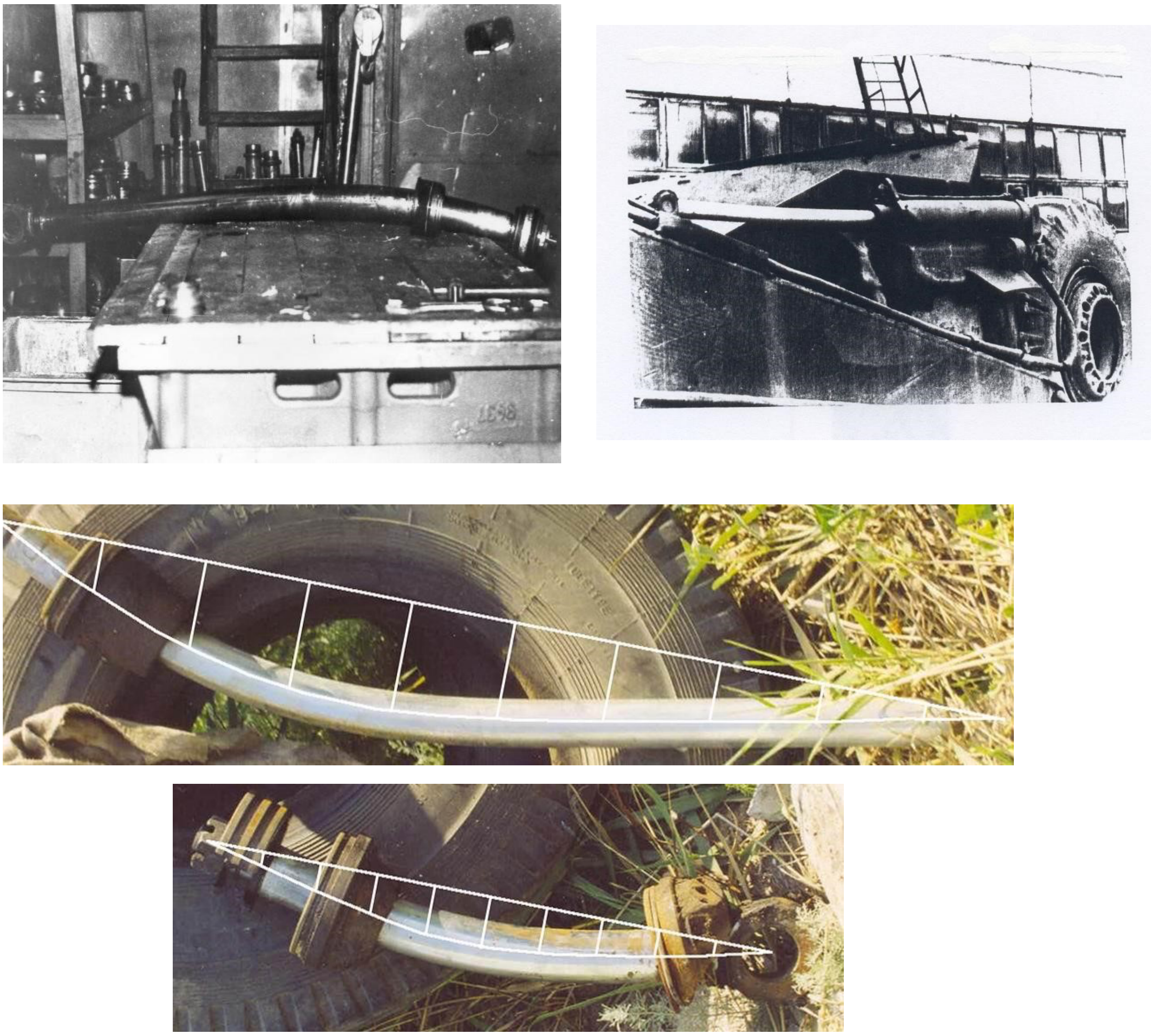


Figure 1.8 - Curvature of the rods.

It was also revealed that the opposite side of the seals wears out due to movement in the seat. It was revealed that the wear of the seals is one-sided. This circumstance is explained by the eccentric placement in the seat due to the wear of the elements, the hydraulic cylinder, such as the piston and bushing (Fig. 1.9). The wear of spherical bearings of the eyes of hydraulic cylinders of road-building machines is very common and is caused by abrasive wear (Figure 1.10). The spherical bearing is completely or partially destroyed in 6% of hydraulic cylinders (Fig. 1.11).

Figure 1.9 - Characteristic wear of the seal.

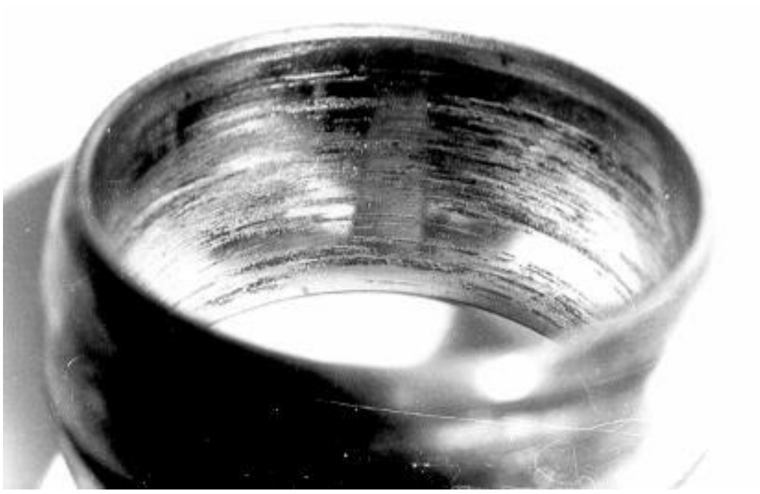


Figure 1.10 - Worn surface of the lug spherical bearing element.

Figure 1.11 - Partial destruction of the element of the spherical bearing of the eye of the rod.

To determine the amount of wear, we assume that the initial dimensions of the bearing were within the middle of the tolerance field. Quantitatively, the wear values were determined for III-IV size groups, as the most common. When carrying out measurements, the main attention was paid to the bushings and pistons of hydraulic cylinders of road-building machines, the rods of which had a bend more than the allowable value indicated in the literature [Praveen and Seok-Soon, 2021]. The measurements were carried out using a standard measuring instrument. A total of 79 hydraulic cylinders were examined, which satisfies the sample size known from the work of Tavares et al., 2016, according to the method, from the literature [Praveen and Seok-Soon, 2021]. Since the bushings have one-sided wear, the point of greatest wear was first determined. Measurements were also carried out for rods with fixed operational bending.

Statistics of failures of hydraulic cylinders of road construction machines

As follows from a number of literary sources on the share of hydraulic cylinders a significant part of failures (up to 37%) of the hydraulic drive of a road-building machine falls out. In addition, it is noted that the actual time between failures is 2-3 times lower than that guaranteed by the manufacturer [Lubecki et al. (2022), Siwulski (2023), Gamez-Montero et al. (2009), Kushalivev et al. ((2025), Lovrec and Tic (2018)]. A number of studies describe inspections of hydraulic excavators of III-V groups in real operating conditions. As a result, it was found that the percentage of out of service for hydraulic cylinders reaches 80%. One of the main reasons is a violation of the tightness of the sealing units. It has been established that the stock-sleeve mating accounts for 52%, and piston-sleeve coupling, 40% [Puqing et al., 2017]. Rod damage accounts for up to 24% of failures [Gamez-Montero et al. (2009), Tavares et al. (2016)], for sleeve damage this figure is 10% [Bednarek and Sosnowski, 2010]. An analysis of the provisions of works [Lubecki et al. (2022), Siwulski (2023)] and information gleaned from numerous literary sources [Youquan et al. (2023), Suryo and Bayuseno (2018)] made it possible to quantify the reliability of DSM hydraulic cylinders (Table 1.1-1.3). In some works, the performance of hydraulic cylinders of large sizes for special purposes, produced in small batches [Heybroek and Norlin, 2015] (Table 1.4) is considered. From all of the above, it follows that the reliability and performance of the hydraulic cylinders of the working equipment of road construction machines with a hydraulic drive is low, the percentage of failures is high, and decreases extremely slowly [Lubecki et al. (2022), Siwulski (2023)].

Table 1.1 - Reliability parameters of hydraulic cylinder elements

Name of the part or assembly unit of the hydraulic cylinder	Failure rate 10^{-6} h^{-1}	Mean time between failures, 10^{+5} cycles	Probability of failure
Sleeve (body)	0.12	8	0.096
Stock	0.20	3	0.060
Piston, cover	0.15	6	0.090
Movable seal	0.50	2	0.100
Seal is stationary	0.30	3,3	0.099
Threaded connection	0.10	8	0.080
Eyes and stops	0.08	9	0.072

After analyzing the above, we can conclude that the wear of bushings and pistons has the greatest impact on the performance of hydraulic cylinders of road construction machines.

Table 1.2 - Reliability parameters of excavator hydraulic cylinders

Types of failures	Failure Probability for Excavators			
	EO-3322	EO-4121	EO-4321	EO-5122
Leak through the stem seal	0.136-0.520	0.425	0.091	0.390-0.667
Bending of the rod: total boom handle bucket	0.024-0.1 - - -	0.1 - - -	- - - -	- 0.333 0.111 0.555
Damage to the lugs	0.080	-	0.182	1.0
Piston damage and wear	-	0.050	0.091	-
Wear of the dirt remover	-	-	0.091	-

Table 1.3 - The sequence of determining the technical condition of the hydraulic units of single-bucket excavators

Name of hydraulic unit	Probability of failure of a hydraulic unit
Twin axial piston hydraulic pump	0.133
Hydraulic distributor	0.203
Hydraulic cylinders of working equipment	0.549
Hydraulic motors	0.115

Table 1.4 - Reliability characteristics of the main elements of hydraulic cylinders of single-bucket excavators

Name of the part or assembly unit of the hydraulic cylinder	Failure rate, 10^{-6} hour^{-1}	Mean time between failures, 10^{+5} cycles	Probability of failure
Sleeve	0.12	8	0.096
Stock	0.20	3	0.060
Piston, cover	0.15	6	0.090
Movable seal	0.50	2	0.100
Seal is stationary	0.30	3.3	0.099
Threaded connection	0.10	8	0.080
Eyes and stops	0.08	9	0.072

Thus, reducing the wear intensity of the hydraulic cylinder guides will increase its sealing and bearing capacity, as well as ensure the operability and improve the reliability of the hydraulic unit as a whole.

Analysis of known design solutions for hydraulic cylinder support

The existing designs of double-acting reciprocating hydraulic cylinders with a single-sided rod (Fig. 1.1) contain a body with covers, a piston with guide elements, a rod and a rod sealing device mounted on a cover with a guide sleeve [Lubecki et al. (2022), Siwulski (2023)]. The main disadvantage of this device is that before the application of the longitudinal compressive force, that is, before the creation of the working pushing force of the hydraulic cylinder, it has a deflection, defined as the sum of the deflection as a result of the misalignment of its main long-length elements (rod and sleeve), due to the presence of gaps in its mates "piston - sleeve", "rod - guide sleeve", deflection as a result of the presence of a possible initial (technological) curvature of its elements (rod and housing), regulated by a technological tolerance for non-straightness of manufacturing lengthy parts, as well as deflection from the action of transverse forces - the weights of these elements [Ramasamy and Basha (2017), Gamez-Montero et al. (2009)].

During operation, as a rule, an inclined hydraulic cylinder is subject to longitudinal-transverse bending and is not stable. At the same time, the limiting value of the longitudinal compressive force is much less than the limiting compressive force of a stable rod, which means that a rod with an initial curvature, in our case, a power hydraulic cylinder, is more susceptible to bending and the occurrence of residual, plastic deformations in the sections of its elements than a straight, located vertically, then exists from the standpoint of strength, has less reliability [Mantovani, 2020].

After the application of a longitudinal compressive force, that is, when a liquid is supplied under pressure to the piston cavity of the hydraulic cylinder, the total deformation of the hydraulic cylinder increases [Shinde et al., 2021] and, being the shoulder for applying this force, leads to an increase in the total bending moment, which can cause critical stresses and, accordingly, the appearance of plastic deformations at the hydraulic cylinder rod and the subsequent loss of efficiency by the hydraulic cylinder as a result of the piston rod jamming in the hydraulic cylinder housing (sleeve) [Lubecki et al. (2022), Siwulski (2023), Pugin and Shayakbarov (2025), Pugin (2020), Nicoletto and Marin (2011), Lin and Gong (2023)]. The longitudinal compressive force, as a rule, is not constant throughout the working cycle of a construction machine, for example, a shovel excavator, and in this case, is a function of the soil digging resistance [Siwulski (2023), Aimukhanbet et al. (2014)]. This force can change abruptly as this resistance increases, for example, when a moving excavator bucket comes into contact with an insurmountable obstacle (rock, boulder, etc.). At the same time, such a functional arrangement of the power hydraulic cylinder under load leads to an increase in reactions in its movable sealed mates, which significantly worsens the operating conditions of the mates.

Piston-sleeve and rod-guide bushing increases the temperature in them and increases the wear intensity of their constituent elements [Lubecki et al. (2022), Siwulski (2023), Frimpong et al. (2005)]. As the friction surfaces of the elements of the hydraulic cylinder wear out, which again leads to an increase in its total deformation, respectively, to an increase in the acting longitudinal and transverse loads, the operating conditions of the hydraulic cylinder deteriorate with greater intensity [Ma et al., 2018], resulting in a decrease in its reliability and service life, as in bearing [Leonidov, 2024], and in terms of sealing ability [Dunaeva et al., 2021]. The listed disadvantages of the traditional design of the hydraulic cylinder can be eliminated, in particular, by bringing the hydraulic cylinder from the state of longitudinal-transverse bending to the state of stability or close to it through the support of the body (sleeve) of the hydraulic cylinder with an intermediate support [Nureddin et al. (2015), Uzny and Kutrowski (2019), Askarhodjaev et al. (2020), Skorek (2018)], as well as Author's certificates of the USSR No.692949, No. 1191534, No. 1386758.

Known [Skorek, 2018] long-stroke hydraulic cylinder contains a housing with two, with rear and front fastening elements. The use of a rigid attachment of the hydraulic cylinder body allows you to slightly increase the working stroke of the rod due to increasing the overall rigidity of the system. However, this design requires compliance with strict alignment of all three supports for fastening the housing and the hydraulic cylinder rod, which complicates its design. In addition, the use of a stationary intermediate support element for fastening the hydraulic cylinder body does not eliminate large reactions in the “piston-body” and “rod-guide bush” interfaces, which are the result of the own deformation of a long rod under the action of a longitudinal compressive force. In this case, in the event of a sharp change in the force on the rod of the hydraulic cylinder, the latter is not able to take a stable position due to immobility front body mount.

Known from RF Patent No. 2442028, a hydraulic cylinder containing a body with an eye and two intermediate supporting supports has a rod with an eye and a movable intermediate support. It is clear that the design with five supports requires even more strict alignment of all supports for fastening the elements of the hydraulic cylinder, which also complicates its design. However, the main drawback of the listed engineering solutions is the impossibility of using such hydraulic cylinders in the design of technical objects, the operation of which is accompanied by a change the spatial arrangement of the hydraulic cylinder relative to the elements of the working equipment, for example, in the drive of the working equipment of a single-bucket excavator, the hydraulic cylinders of which make angular movements relative to the body lug (Fig. 1.5).

This significant drawback is eliminated, for example, in the hydraulic drive proposed in the USSR Author's certificate No. 1191534, in which, in order to provide support for the power hydraulic cylinder, an auxiliary hydraulic cylinder is additionally installed, which acts as an intermediate sensor supporting support of its body. The main disadvantage of this design is its low reliability as a result of orientation when choosing a kinematic scheme for supporting the power hydraulic cylinder with an auxiliary one for bending moment, and not for a linear concentrated force directed across the axis of the power hydraulic cylinder. The consequence of this is a possible S-shaped inflection of the latter, leading to a bending of the rod, an increase in the reaction in the rubbing mates of the power hydraulic cylinder, a break in the support lugs of its rod and body, and also causing significant alternating bending stresses in the cantilever element of the kinematic connection of the power cylinder with the auxiliary one.

In addition, the hydraulic connection of the latter with the control cylinder through the use of a pipeline, a considerable length and possibly increased hydraulic resistance, reduces its speed compared to a power hydraulic cylinder. As a result, the latter is turned on, loaded and deformed before the support force is created and applied to it by the auxiliary hydraulic cylinder. The mentioned disadvantage is eliminated in the hydraulic system known from the USSR Author's Certificate No. 1386758, which uses an auxiliary hydraulic cylinder, pivotally connected to the power one and developing a variable linear concentrated support force, which ensures tracking supporting force of the power cylinder when it freely changes its spatial location.

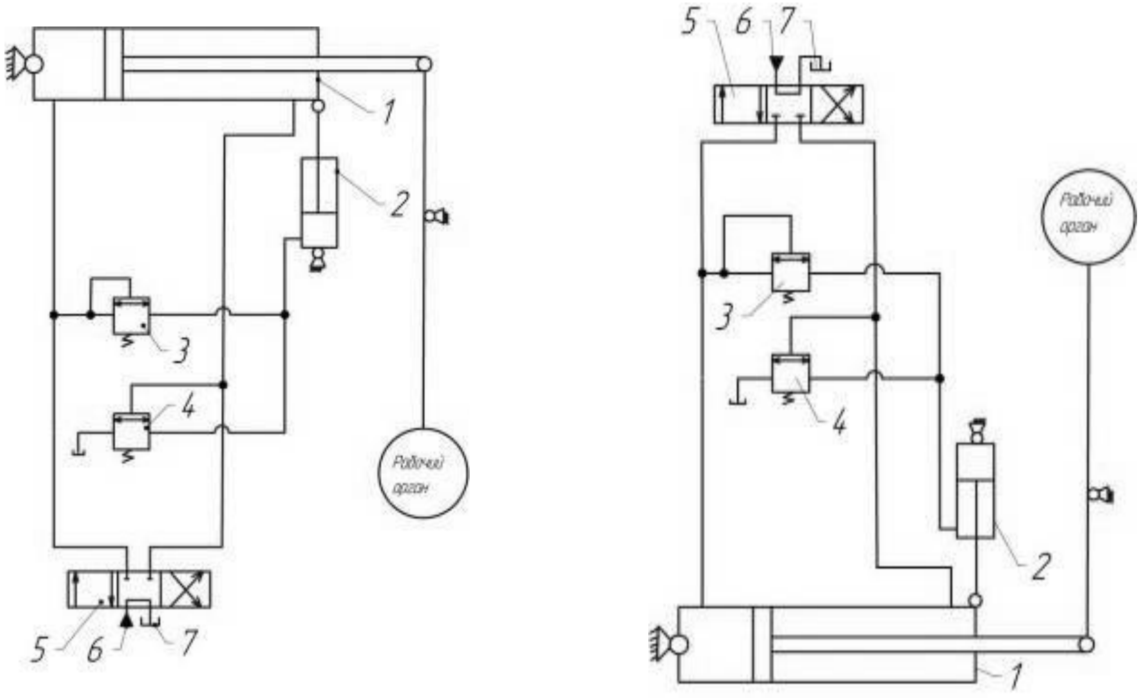


Figure 1.12 shows the Principal hydraulic system for supporting the power hydraulic cylinder with auxiliary bottom and top.

The figure labels: 1 - power hydraulic cylinder; 2 – auxiliary hydraulic cylinder; 3 - pressure valve; 4 - safety valve; 5 - hydraulic distributor; 6 - power supply; 7 - drain. The main disadvantage of this prototype is the presence of an additional hydraulic line connecting the cavity of the auxiliary cylinder through the pressure valve with a drain, as a result of which the total number of hydraulic lines connecting the hydraulic drive system of the power hydraulic cylinder with a power source and a drain increases from two to three. This drawback is even more pronounced on single-bucket hydraulic machines (single-bucket excavator, front loader, forestry manipulators, etc., containing several successively arranged hydraulic cylinders (boom, stick and bucket hydraulic cylinders. So, after the bucket, the number of hydraulic lines becomes three, after the handle, six, and after the arrow, nine, instead of two, four and six, respectively.

As a result, the complexity of the design of the hydraulic system is increasing its material consumption. In addition, the presence of a hydraulic line of considerable length contributes to an increase in the drain pressure in the cavity of the auxiliary hydraulic cylinder due to increased hydraulic resistance, especially at low ambient temperatures and an increase in the viscosity of the working fluid. In this case, the drain pressure should tend to zero. Otherwise, a supporting force of the power cylinder is created on the rod of the auxiliary cylinder when it is not desirable, since the latter works in tension and does not bend. As a result, the reliability of the hydraulic system is reduced. The listed shortcomings are eliminated by connecting the valve connected to the cavity of the auxiliary cylinder to the piston cavity of the power cylinder (Fig. 1.13).

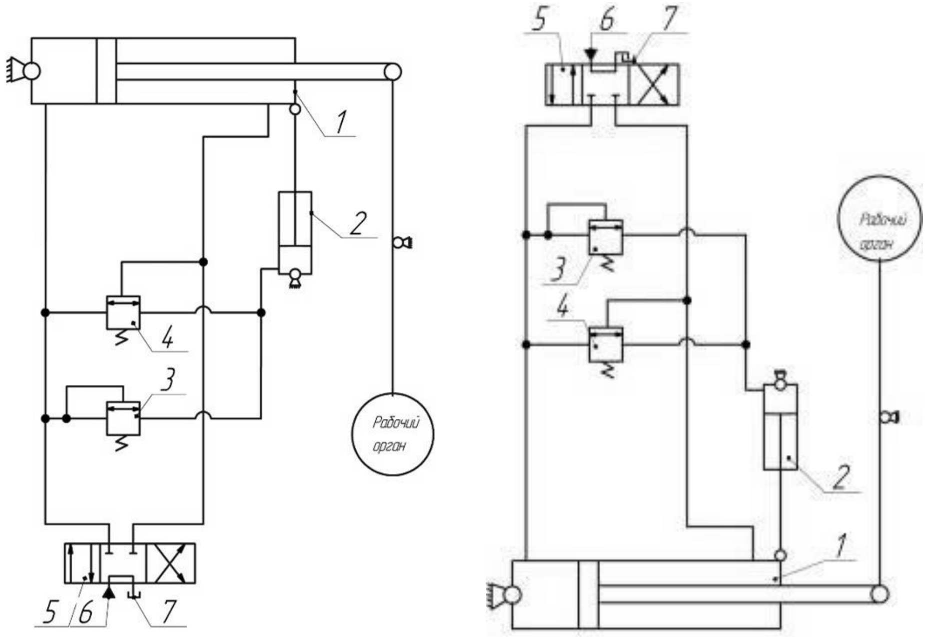


Figure 1.13 shows the Principal hydraulic system for supporting the power hydraulic cylinder with auxiliary bottom and top.

The figure labels: 1 – power hydraulic cylinder; 2 – auxiliary hydraulic cylinder; 3 - pressure valve, 4 - safety valve; 5 - hydraulic distributor; 6 - power supply; 7 - drain. When fluid is supplied to the piston cavity of the power hydraulic cylinder 1 in Fig. 1.13, which leads to its longitudinal-transverse loading and causes maximum deflection, due to the operation of the safety valve 3, the auxiliary hydraulic cylinder 2 is activated, which acts as a load-sensing supporting support of the power cylinder 1. The actuation pressure of valve 3, selected from the condition that cylinder 2 ensures that cylinder 1 is brought to a stable position, allows cylinder 2 to compensate for all possible, as well as the deflections of the hydraulic cylinder 1 accumulated during the idle period, including those that occurred due to internal leakage of the working fluid through the seals of the hydraulic cylinder 2. Displaced by the moving piston from the rod cavity of the cylinder 1, the liquid flows through the distributor, 5 to the drain 7.

The operational fluctuation of the load on the rod of the hydraulic cylinder 1 through the pressure of the liquid in its piston cavity and the cavity of the auxiliary cylinder 2 associated with the first one is reflected in the value of the required pushing, pulling supporting force on its rod, which achieves the load-sensing action of the auxiliary cylinder 2. When the working fluid is supplied to the rod end of cylinder 1 which does not require support by the auxiliary cylinder 2 due to its stretching by the liquid from it. The rod cavity includes a pressure valve 4, connecting the cavity of the cylinder 2 with the piston cavity of the power cylinder 1, already connected to the drain 7. The fluid displaced by the moving piston from the piston cavity of the power cylinder 1 through the distributor 5 also enters the drain 7.

In this case, in the case of possible angular displacements of the cylinder 1, for example, in the triangular scheme of the drive of the working body, the rod of the auxiliary cylinder 2 performs both extension and reverse stroke. In this case, the hydraulic line connecting the cavity of the latter with the piston cavity power cylinder 1 plays the role of a drain of minimum length with minimum hydraulic resistance. In the prototype, the possible suction of liquid occurs directly from drain 7 (usually from the hydraulic tank of the machine) along long articulated (metal pipelines and flexible high-pressure hoses) hydraulic lines with significant hydraulic resistance, which is undesirable and reduces the reliability of the hydraulic system and the machine as a whole. Thus, in the described hydraulic system, an increase in reliability, a simplification of the design of the hydraulic system, and a decrease in its material consumption are achieved. The main disadvantage of hydraulic systems (Fig. 1.12 and 1.13) is their low reliability due to the possible mismatch of the required supporting force on the rod of the auxiliary cylinder to bring the power from the state of longitudinal-transverse bending to the position of longitudinal stability and actually developed by the auxiliary cylinder. This is most likely when the angle of inclination to the horizon of the power hydraulic cylinder changes, accompanied by a change in the magnitude of the transverse loads, and is slightly associated with the movement of its rod, which affects the value of the deflection of the power cylinder. The force on the rod of the auxiliary cylinder, the cavity of which connected through a safety valve to the piston cavity of the power cylinder, is the result of only the fluid pressure developed in it during operation without taking into account the spatial arrangement of the power cylinder. The latter, by increasing or decreasing transverse loads, affects the amount of force required on the auxiliary cylinder rod. In addition, the disadvantage of the known hydraulic systems is their low reliability due to the possible priority activation of the power hydraulic cylinder, and not the auxiliary supporting it. This is due to the higher hydraulic resistance and a significant long line

power supply of the auxiliary cylinder compared to the power one. These shortcomings are eliminated by installing parallel-connected, multidirectional pressure and check valves between the safety valves and the piston cavity of the power hydraulic cylinder and between the pressure valves and its rod cavity (Fig.1.14). By analogy with the known ones, this hydraulic system (Fig. 1.14) contains power and auxiliary hydraulic cylinders, a safety valve and a pressure valve. The piston and rod cavities of the power hydraulic cylinder are connected through the distributor to the power source and drain, and the auxiliary hydraulic cylinder, the stem of which is kinematically connected to the power housing, is made single-cavity, the cavity of which is connected to the outlet of the safety valve, connected with the inlet to the piston cavity of the power hydraulic cylinder, and to the valve inlet, the hydraulic control cavity of which is connected to the rod cavity of the power cylinder. In contrast to the well-known named hydraulic system, in order to eliminate the above disadvantages, it is equipped with parallel-connected, multidirectional pressure and check valves installed between the safety valves and the piston cavity of the power cylinder and between pressure valves and its rod end. In addition, the pressure valve and safety valve are set to a set pressure lower than that of the valves.

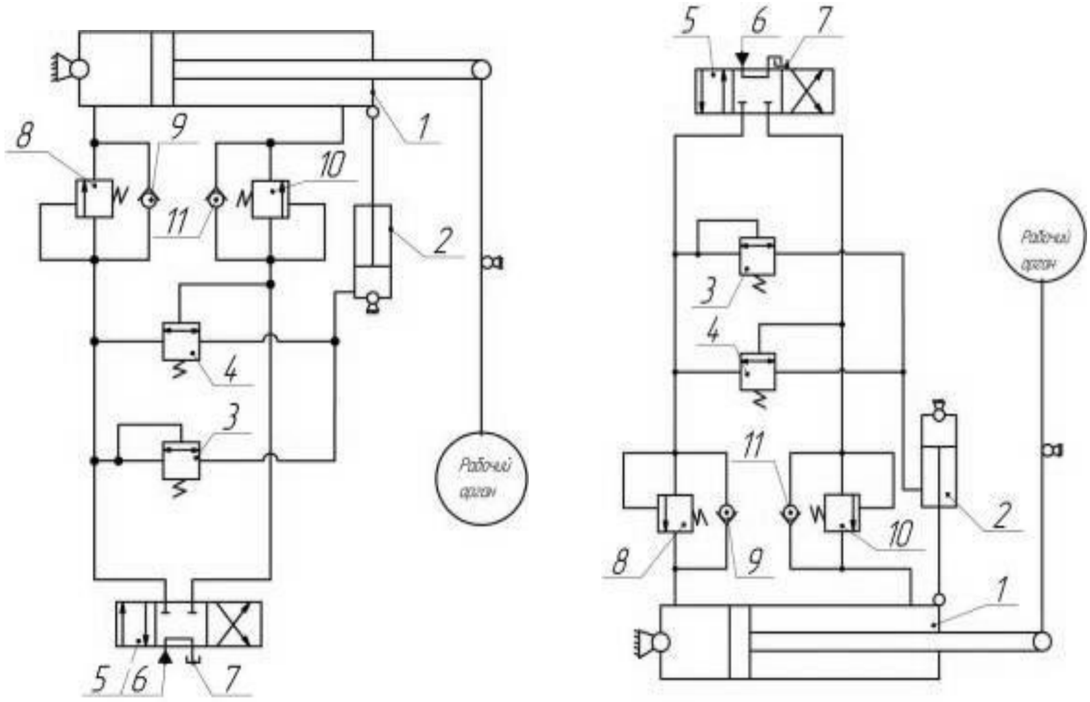


Figure 1.14 - Principal hydraulic system for supporting the power hydraulic cylinder with auxiliary bottom and top

The figure labels: 1 – power hydraulic cylinder; 2 - auxiliary hydraulic cylinder; 3 - pressure

Valve; 4 - safety valve; 5 - hydraulic distributor; 6 - power supply; 7 - drain; 8, 10 - pressure valve; 9, 11 - check valve. Thus, due to the additions and changes in the hydraulic resistance of the power hydraulic cylinder supply lines, the hydraulic resistance of the auxiliary hydraulic cylinder supply line becomes greater. When fluid is supplied to the piston cavity of the power hydraulic cylinder 1 (Fig. 1.14), which leads to its longitudinal-transverse loading and causes maximum transverse deformations in the form of deflection, due to the difference in the actuation pressure of the safety valve 3 and pressure valve 8, the first one, having opened, activates the auxiliary hydraulic cylinder 2, which acts as a load-sensing supporting support of the power cylinder 1.

The actuation pressure of the valve 3, selected from the condition of providing the cylinder 2 bringing 1 to a stable position, allows cylinder 2 to compensate for all possible deflections of hydraulic cylinder 1, as well as those accumulated during the idle period, including those that occurred due to internal leakage of the working fluid through seals of the hydraulic cylinder 2. Following this, the pressure valve 8 opens, including the power cylinder 1 which is already in a stable position due to the action of the cylinder 2. The liquid displaced by the moving piston from the rod end of cylinder 1 through the check valve 11 then flows through the distributor 5 to drain 7.

The required pushing, pulling supporting force on its rod, which achieves the load-sensing action of the hydraulic cylinder 2. When the working fluid is supplied through the distributor 5 into the rod end of the cylinder 1, which does not require, due to the extension of the latter, its support by the auxiliary 2, first, as a result of the difference in the pressure of the pressure valve 4 and the pressure valve 10, the valve 4 opens, connecting the cavity of the cylinder 2 with the drain 7, and then valve 10, which includes the already unloaded from the undesirable effect of the auxiliary 2 hydraulic cylinder 1 in this case. The fluid displaced by the moving piston from the piston cavity of the power cylinder 1 through the check valve 9 then flows through the distributor 5 to the drain 7. In this case, in the case of possible kinematically determined angular displacements of the cylinder 1 from the auxiliary 2 into as a result of the connection of its cavity through valve 4 with a drain constantly filled with working fluid displaced from the piston cavity of cylinder 1, no additional resistances act, for example, due to fluid suction directly from drain 7 (usually from the hydraulic tank of the machine), which is undesirable. Thus, the use of this hydraulic system, which ensures the speed of the auxiliary cylinder in relation to the power one without the use of any additional electrical control elements and power sources, makes it possible to increase the reliability of the hydroficated DSM as a whole. Obviously, the described schemes are of known interest and should be taken into account when developing a promising scheme for supporting the hydraulic cylinder with an intermediate sensor supporting support.

Setting the goal and defining the objectives of the study

Thus, as follows from all of the above, the main drawback of the existing design of the most common reciprocating hydraulic cylinder on the DSM with a single-sided rod is that before the application of an operational longitudinal compressive force, it has a deflection, defined as the sum of the deflection as a result of misalignment of its main bearing elements (rod and sleeve), due to the presence of gaps in its mates "piston - sleeve" and "rod - guide sleeve", deflection as a result of the presence of a possible initial (technological) curvature of long elements (rod and body), regulated by a technological tolerance for the non-straightness of the manufacture of long products, as well as deflection from the action of transverse forces - the weights of these elements.

When fluid is supplied to the piston cavity of the hydraulic cylinder, the total deformation of the hydraulic cylinder increases and, being the shoulder for applying the longitudinal pushing (compressive) force, leads to an increase in the total bending moment, which creates critical stresses and, accordingly, causes the appearance of plastic deformations at the hydraulic cylinder rod with subsequent loss of efficiency by the hydraulic cylinder as a result of jamming of the rod with the piston in the body (sleeve) of the hydraulic cylinder. Longitudinal compressive force is usually not constant throughout the operating cycle of a DSM, for example, a shovel excavator, and, in this case, is a function of the digging resistance of inhomogeneous soil. As the friction surfaces of the “piston-sleeve” and “rod-guide bushing” interface elements of the hydraulic cylinder wear out, which again leads to an increase in its total deformation and, accordingly, to an increase in acting longitudinal and transverse loads, the operating conditions of the hydraulic cylinder deteriorate with even greater intensity, resulting in a decrease in its reliability, both in terms of its bearing and sealing abilities.

To a greater extent, this applies to long hydraulic cylinders of road construction machines. The listed disadvantages of the traditional design can be eliminated by bringing the hydraulic cylinder from the state of transverse bending to the state of stability or close to it through the support of the body (sleeve) of the hydraulic cylinder with an intermediate sensor supporting support .From the foregoing, it follows that the purpose of this work is to develop a methodology for ensuring the operability of long-length hydraulic cylinders, road-building machines, by bringing them from a state of longitudinal-transverse bending to a state of stability or close to it.

This goal is achieved by solving a number of the following tasks:

i. Assessment of operating conditions, workflow, kinematic and load characteristics of hydraulic cylinders for driving the working equipment of hydroficated DSM, affecting their reliability and performance;

ii. Clarification of the complex criterion of hydraulic cylinder performance;

iii. Creation of a mathematical model of the performance of a hydraulic cylinder with an intermediate sensor supporting support;

iv. Creation of a criterion that classifies the hydraulic cylinder as long;

v. Development of a schematic diagram of an intermediate sensor supporting support of a hydraulic cylinder and a study of its characteristics;

vi. Development of evidence-based practical recommendations for the modernization of the working equipment of a multilink hydroficated DSM. At the same time, due to the fact that the most preferred option for mounting the hydraulic cylinder (Fig. 1.3), in particular, the DSM handle drive, is its fastening on the lugs (Fig. 1.15.a), and the least common - on the eye and the running on (Fig. 1.15.b), in the presented work, the variant of the intermediate sensor support (Fig. 1.3.a) is considered, suitable for the case presented in Figure 1.15.a with extrapolation of the obtained results of the study to the option of mounting the hydraulic cylinder on the eye and pin with an external sensor supporting support (Fig. 1.3.b), under the term "operability" according to GOST 27.002-89 "Reliability in engineering." Basic term concepts and definitions refers to the state of an object in which the values of all parameters characterizing the ability perform the specified functions, comply with the requirements of regulatory and technical and (or) design (project) documentation. The term "reliability", according to the same document, refers to the property of an object to retain over time, within the established limits, the values of all parameters characterizing the ability to perform the required functions in specified modes and conditions of use, maintenance, storage and transportation. At the same time, reliability is a complex property, which, depending on the purpose of the object and the conditions of its use, may include reliability, durability, maintainability and persistence, or certain combinations of these properties.

Figure 1.15 - Mounting options for the hydraulic cylinder of the handle of the single-bucket hydroficated DSM.

Here, reliability is the property of an object to continuously maintain a healthy state for some time or operating time. Durability is the property of an object to maintain a working state until the limit state occurs with the installed repair maintenance system. Maintainability is a property of an object, which consists in adaptability to maintaining and restoring a working state through maintenance and repair. Persistence is the property of an object to persist within the specified value limits. The parameters defined above characterize the ability of an object to perform the required functions during and after storage and / or transportation. Quantitatively, the above qualitative properties of reliability are evaluated by the corresponding indicators.

CONCLUSION

An analysis of the design features of hydraulic drives of road construction machines is made, the main reasons for the decrease in the performance of hydraulic cylinders of road construction machines and their elements are determined, statistics of failures are presented, an analysis of the currently known designs of hydraulic cylinders with intermediate supports is carried out, the goals and objectives of the study are determined.

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