Optimization of Oil-Hydraulic Cylinders of Large Measurements and High Output Power

Radovan S. PETROVIĆ, Jožef PEZDIRNIK, Nenad TODIĆ

Abstract: This paper features research conducted in the area of processing systems and production processes of oil-hydraulic cylinders of large measurements and high power, as specific hydraulic components in the area of fluid transmission of power, especially important in the functioning of hydroenergetic objects. The fundamental basis in the development of oil-hydraulic cylinders of large measurements and high power lies in experimental research and mathematical modelling of non-stationary, highly dynamic hydraulic processes inside the cylinder. Establishing the stability of stipulated quality of vital positions in the set of these products (cylinder tubes and piston rods) is a difficult task for engineers and technologists since these are products with high reliability. High technoeconomic effects in this field are especially pronounced in frequent repair of these products due to the damage of work surfaces following the long years of exploitation. These were sufficient reasons to approach the development of methodologies and software for engineering, simulation and optimization of oil-hydraulic cylinders of large measurements and high power. We would like to express gratitude above all to the Prva Petoletka company – factory PPT-Cilindri AD - Trstenik, Serbia, one of the leading manufacturers of hydraulic cylinders at large, which made additional experimental research possible for us. The conducted research enabled the application of new methods of engineering processing systems and processes located on the production of vital positions of these products (cylinder tubes and piston rods) by the honing procedure as the most efficient way of work surface finishing treatment. Based on the results of experimental research and mathematical modelling and with the development and application of the method for the identification of unknown parameters of the mathematical model, certain vital parameters of hydraulic cylinders of large measurements and high power were determined with sufficient precision. The desired aim, that is to apply new scientific knowledge in this complex area and the basis for high efficiency provided in achieving the desired conformity of product quality (accuracy of measurements and roughness of treated surfaces) was attained.

Keywords: Oil-hydraulic cylinder, cylinder tube, piston rod, large measurement, power, experimental research, mathematical modelling, identification methods, optimization methods, hydrodynamics, dynamics

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1 Introduction

Multidimensional analytical-experimental method allows for simultaneous-parallel research of a greater number of stationary functions, whereas due to the determination to provide research with several aspects of product quality conformity (cylinder tubes and piston rods), the selection of the following stationary functions was performed:

- $F_1 = K_{TM}\ [\mu m]$ - precision quality of work surface measurements,
- $F_2 = K_{CP}\ [\mu m]$ - cylindricality quality of work surfaces,
- $F_3 = K_{KP}\ [\mu m]$ - circularity quality of work surfaces,
- $F_4 = K_{HP}\ [\mu m]$ - roughness quality of work surfaces.

2 The choice of possible coordinates of the processing system “input”

The designed deviations of cylindricality and circularity of work surfaces, cylinder tubes and piston rods alike, are defined within limits of engineered deviations of measurement exactness (DcH8, dkf8).

The selected stationary functions are highly significant for all the types of hydraulic cylinders, especially for hydraulic cylinders of large measurements that are built into hydroenergetic objects of great strengths, where any defect in engineered quality of work surfaces leads to direct fall-off in volumetric efficiency of cylinder (η_v) and disturbance of all other working parameters, above all the speed of movement and power transmission, which can have negative consequences on carrying out its functions.

The most frequent sources of these disturbances are losses of flow through clearances between immobile parts (cylinder tube - cylinder covers) and mobile parts (piston with sealing set and piston rod), through which the hydraulic fluid returns from high pressure zones (chambers) to low pressure zones (chambers), especially when quality defects appear on working surfaces.

Apart from the above mentioned, eliminating quality defects in this type of power objects is utterly complex, rather expensive and especially problematic because of unavoidable and often longer hiatuses at work.

The actual objects of research, especially those complex objects such as the processing system and the production process of large measurement hydraulic cylinders, contain numerous coordinates of "input" - impact factors. For exact and reliable research in such circumstances, it is necessary to include their maximum number, but it is very important to choose significant coordinates while doing so, because only such an approach can secure the obtaining of an actual "picture of the state"of processes and assure avoiding of possible errors and accompanying consequences.

For such an approach in choosing coordinates, there are neither universal nor generally applicable methods, so the recommendation is to use all the prior information about a researched object from the following sources: own research experience, other researchers’ experience, data from literature. One should also strive to select as many important coordinates as possible, and find the right measure since choosing an excessive number leads to greater difficulties in the mathematical processing of results as well as to prolonged and expensive research, which is not rational.

In such an approach, however, there is another instruction of importance that indicates a better solution: in selecting coordinates, it is preferable to take some additional coordinates, even in cases when no prior information exists about their significance of impact on the process, since excluding even one influential coordinate may cause great errors in the description of the process "state".

Therefore, because the objective is exact and reliable research of the processing system with honing finishing treatment process as the most efficient for cylinder tubes and piston rods of large measurements, the choice of the following coordinates of "input" - impact factors were carried out:

- V_r - radial speed of processing,
- V_a - axial speed of processing,
- P_b - whetstone pressure on workpiece,
- N_b - number of honing head whetstones,
- F_b - fineness of honing head whetstones,
- T_b - hardness of honing head whetstones,
- S_b - structure of honing head whetstones,
- L_b - length of honing head whetstones,
- K_{hp} - quality of cooling and lubricating agents,
- K_{to} - quality of previous processing precision,
- K_{ho} - quality of roughness of previous processing surface.

The selection encompasses eleven coordinates of "input" - impact factors, which represent: work modes, tool – honing head characteristics, work conditions characteristics and characteristics of previous processing quality (processing that precedes the honing operation as finishing treatment). Unfortunately, due to technical limitations, it was not possible to include several additional potential "input" coordinates linked with the impact of structure and mechanical characteristics of workpiece material in the research process. Nonetheless, regardless, it is expected that the selection of possible influential coordinates-parameters represent a sufficient guarantee for reliable research of the processing system and hydraulic cylinder processes.

3 The structure of the cylinder processing system

The selected set and positions: cylinder tubes and piston rods, relate to oil-hydraulic cylinder measuring ϕ420/160 x 7800 mm

- **Processing system for cylinder tubes:**
  - Machine system:
  - Machine: Honing machine "WDF" (*Fig. 1*),
  - Workpiece: Cylinder tube Φ420 H8 mm (*Fig. 2*),
  - Tools and kit: Honing head Φ420 mm (*Fig. 4*),
  - Measuring-control equipment: measuring-control system for the quality of processing precision (*Fig. 12*) and measuring-control system for the quality of treatment roughness (*Fig. 14*)
  - Treatment process: Finishing treatment of opening by honing.
- **Processing system for piston rods:**
  - Machine system:
  - Machine: Honing machine "WDF" (Fig. 1),
  - Workpiece: Piston rod Φ160 f8 mm (*Fig. 3*),
  - Tools and kit: Honing head Φ160 mm (*Fig. 5*),
  - Measuring-control equipment: measuring-control system for the quality of processing precision (*Fig. 13*) and measuring-control system for quality of treatment roughness (Fig. 14).
  - Treatment process: Finishing treatment by honing.

Figure 1. *Honing machine "WDF"*

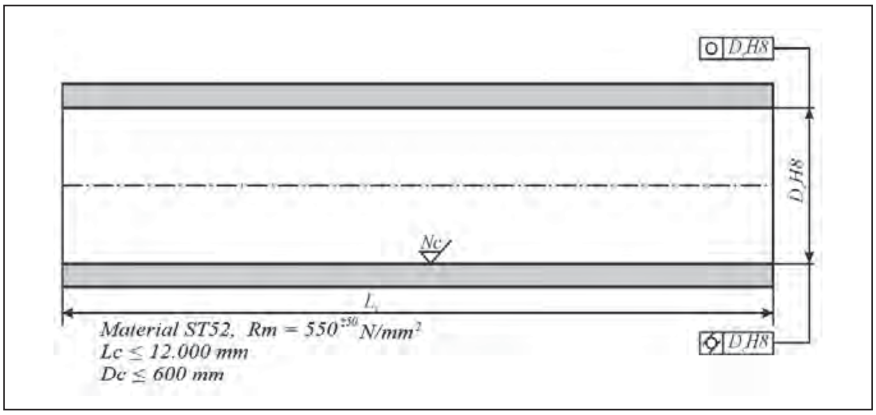

Figure 2. *Cylinder tube Φ420 H8 mm*

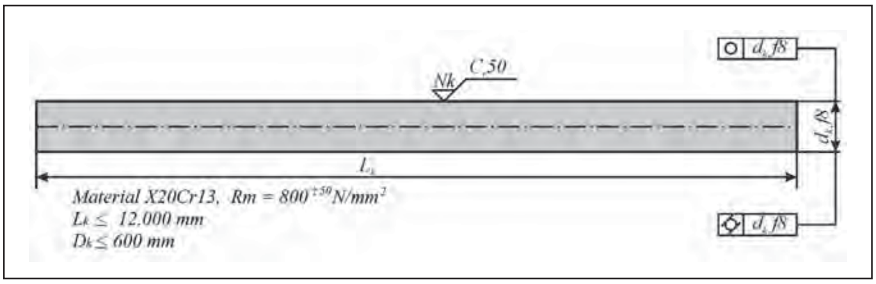

Figure 3. *Piston rod Φ160 f8 mm*

The working principle of tool (head) for treating (honing) cylinder tubes- shows Fig. 4. By way of connectors (pos. 10), the head is joint-linked to the honing machine base so as to adjust freely to the workpiece surface during treatment. Radial speed of treatment (V_r) is realized by workpiece (cylinder tube) movement, while the axial speed of treatment (V_a) by intermittent axial movement of tool (head). Whetstone pressure on the workpiece surface is realized by a hydrosystem with pressure adjustment of working fluid by way of cylinder piston - thruster (pos. 6) and whetstone elevator (pos. 3). Whetstones with support (pos. 7) move along the guides (pos. 8) and have the possibility of position adjustment. The working principle of tool (head) for treating (honing) piston rods shows Fig. 5. By way of support with guide (pos. 1), the tool is linked to the movable machine support (support). Radial speed of treatment (V_r) is realized by workpiece (piston rod) movement, while the axial speed of treatment (V_a) by intermittent axial movement of support with tool (head). Whetstone pressure on workpiece surface is realized by the chosen number (2 to 6) of hydrocylinders (pos. 4) which are managed by a separate hydrosystem with pressure adjustment. Whetstones with support (pos. 8) move along the guides (pos. 7) and have the possibility of position adjustment.

4 The selection of measuring-control system

4.1. The measuring-control system for the quality of treatment precision

The measuring-control systems, on the whole, as subsystems of processing systems, have a significant role in technological production processes since treatment and measurement are mutually conditioned and interdependent to such an extent that without their unified coupling, it is practically impossible to make quality products (parts, sets).

Demands from contemporary measuring-control systems are to perform two main tasks:

1. Measuring-control of one or more assigned values and their display on a suitable indicator (analogue or digital display, register-writer, audio or light-up signal panel).
2. Generating signal-information about measuring values in a form suitable for use and various purposes (memorizing and saving, sending to users, results processing, automatic management and control of the the production process).

Of all the structural units of the measuring-control system, especially salient role is held by feed-conversion unit and feed-sensor itself which "perceives" (generates, measures) the measurement value and converts it to a form for transmission and display on the indicator unit.

Among a great number of different types of feed-sensors, pneumatic feeders by installing are particularly of importance which, especially in the combination with electronics, enable the formation of very powerful and increasingly applied measuring-control automated systems. Their great expansion is the consequence of the following metrologic properties:

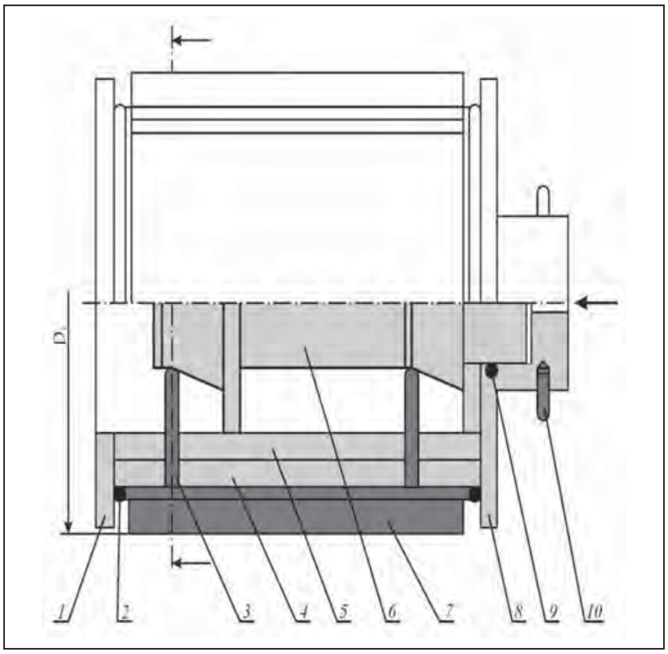

Figure 4. *Tools-kit for cylinder tube treatment: 1. Guide, 2. Fuse, 3. Elevators, 4. Whetstone support, 5. Slide, 6. Whetstone thruster, 7. Whetstone with support, 8. Guide with cylinder, 9. Seal, 10. Connector*

- Great sensitivity (increasing the measurement characteristic even up to 100.000 times),
- High accuracy of measuring-control up to 0,05 m*m,*
- Dependability measuring-control (wear and damage are excluded),
- Possibility of measuring-control in hard-to-reach places (deep apertures etc.),
- Possibility of measuring-control at greater distances (distance of feeder and indicator-show even up to 250 *m*),
- High speed of measuring-control,
- Possibility of measuring-control in circumstances of surrounding vibrations (the system behaves like a high frequency filter),
- Application in facilities where electro signals or any sparks (space with flammable gases) are not allowed,
- Great possibility of automation of processes in systems (selective automatons, reception systems etc.),

The above mentioned metrologic properties of which the majority are advantageous, and some are the only ones allowed, in relation to other conditions of alternative systems completely justify their increasingly wide aplication. That is the sufficient reason for one such system to be applied as part of cylinder processing system research.

The principle and essence of the pneumatic feed-sensors functioning is portrayed on the functional scheme *Fig. 6*.

X^T Measuring value with tolerance (T)
$\pm \Delta X$ Measuring value change (X^T)
Z Clearance (Measuring head-Measuring object)

- **The principle of the functioning measuring-control system**

Through the supply connector (1) on the grid and tap (2), pressure air (p_K) from the grid is brought into the preparation phase (vapor separation (3), filtration from mechanical impurities (4), pressure reduction (5) - from p_K to $p_m = 1{,}5\,bar$, fine stabilization of pressure (6). Air prepared in such a manner is introduced, by way of supply pipe line, into the measuring-control device (7) with movable changeable scale for diverse scopes of measurement (8) and light-up signal panel (9), then by way of a discharge pipe line (10) to the measuring head

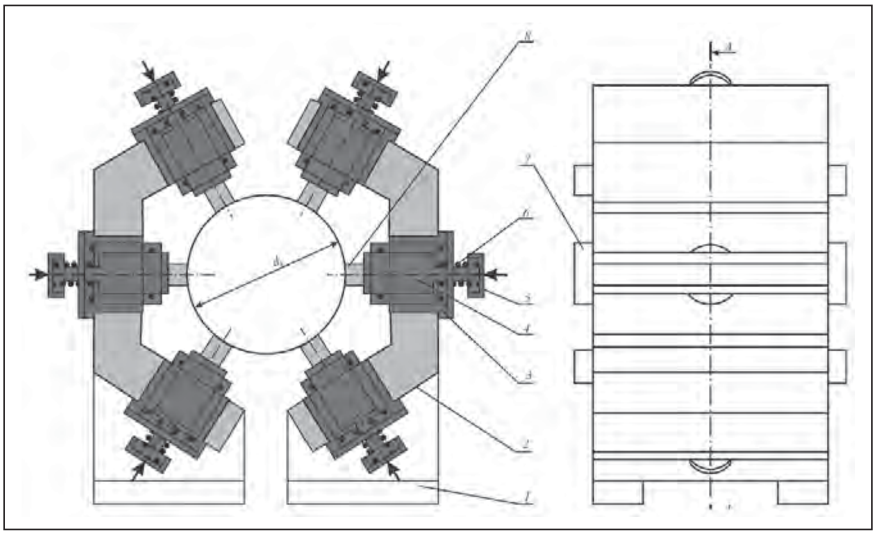

Figure 5. *Tools-kit for piston rod treatment: 1. Support with guide, 2. Cylinder support, 3. Changeable guide, 4. Hydro-cylinder, 5. Operation limiter, 6. Coil, 7. Whetstone guides, 8. Whetstones with support*

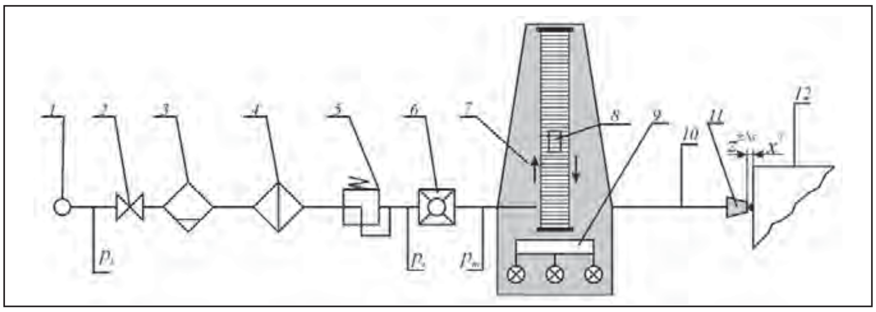

Figure 6. *Functional measuring-control scheme with pneumatic feeder: 1. Air supply from the system, 2. Tap, 3. Moisture separator (vapor), 4. Filter, 5. Pressure regulator, 6. Pressure stabilizer, 7. Measuring device, 8. Measuring scale with float, 9. Signalizing of measuring value, 10. Air pipe line, 11. Measuring head, 12. Measuring object*

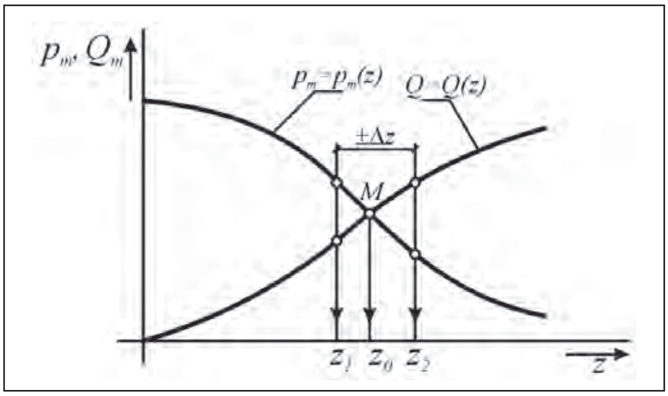

Figure 7. *Static characteristics of pneumatic feeder*

In this scope, forms of functional dependencies (p_m) and (Q) minimally (negligibly) diverge from linear form, which is why, by its selection, high linearity of measurement scale of the device is provided.

- **The principle of adjustment (standardizing) the measuring-control system**

For adjusting the measuring-control system, every measurement value (X^T) must have standards for lower and upper measurement limit within the assigned tolerance field (X).

For defining the characteristics of product (cylinder tubes, piston rods) quality, the princi-ple of system adjustment is shown in *Fig.8*.

- for cylinder tubes *(X = 420 H8)* – a
- for piston rods *(X = 160 f8)* – b

(11) which is placed along the measuring object at a precisely calculated distance-clearance (z). At the exit from the measuring head, in the gap (z), a suitable air supply is formed with parameters in accord with equation of continuity and energetic equation of fluid (air) movement.

Every change of measurement value (X^T) by $\pm\Delta X$ leads to a change in value (z), which conditions the change of parameters in formed discharged air jet (pressure p_m, speed *v*, flow rate by the following rule of conversion sequence:

$$X \uparrow\rightarrow Z \downarrow\rightarrow v \downarrow\rightarrow Q \downarrow\rightarrow p_m \uparrow$$

$$X \downarrow\rightarrow Z \uparrow\rightarrow v \uparrow\rightarrow Q \uparrow\rightarrow p_m \downarrow$$

The end result is thus the pressure (p_m) change in the jet which is registered by movement of float on measurement scale in the suitable scope.

It is very significant to indicate the designed measurement of clearance (z) so as to provide maximum accuracy of read-off on the measurement scale, which is realized by an optimal choice of static characteristics of feeder, as illustrated in the scheme *Fig.7*.

The greatest accuracy of displaying measurement value (X) is provided if the clearance (z) measures (z_0), which suits the selection of measurement point (M) position in the intersection of rule $p_m = p_m(z)$ and $Q = Q(z)$, i.e. in their curve points. Taking into account the fact that often it is not possible to determine precisely this position, the area $\pm\Delta z$ is recommended in the scope (z_1, z_2).

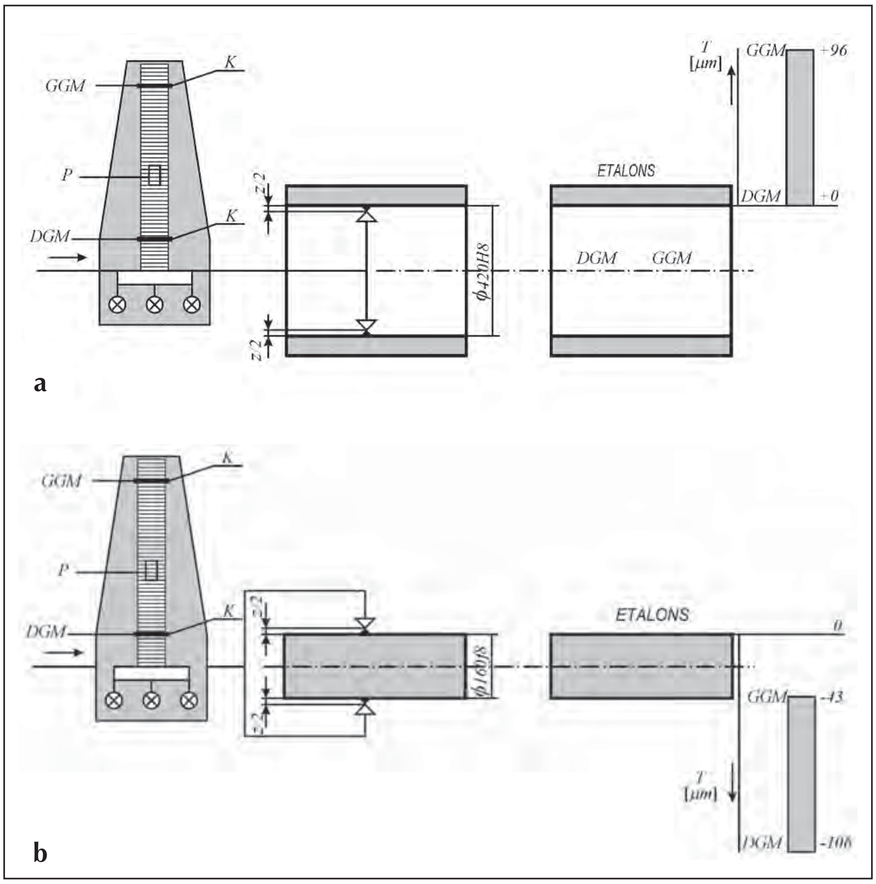

Figure 8. *Standardizing measurement values*

Figure 9. *Appearance of pneumatic device with scale*

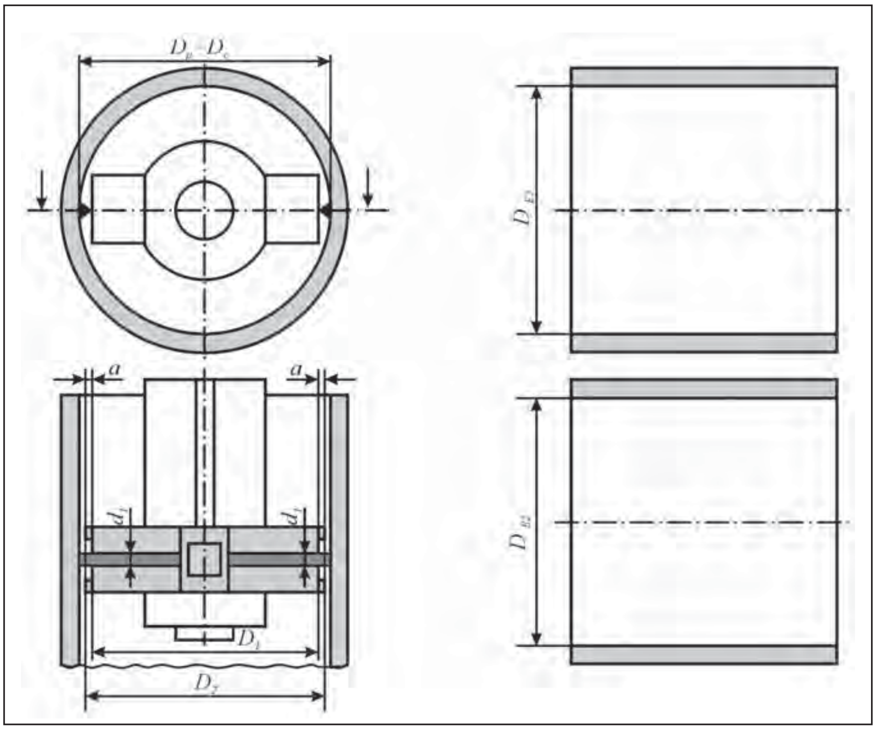

Figure 10. *Measurement-control head for cylinder tubes*

Standardizing measurement value (X) is realized by setting slide (K) in the scope of tolerance field (T), by way of bringing it to the position on the scale which suits the position of float (P) when the device is activated first with one standard (DGM), and then with another standard (GGM).

- **The calculation and construction of measuring-control head and standards**

– Measuring-control head and standards for cylinder tubes

- Measurement-control head:

Table 1. *Measurement-control head*

D_P [mm]	d_1H6 [mm]	a [µm]
$3 \le D_P \le 5$	1,1	20 - 45
$5 < D_P \le 10$	1,5	
$10 < D_P \le 150$	1,9	
$D_P > 150$	2,2	

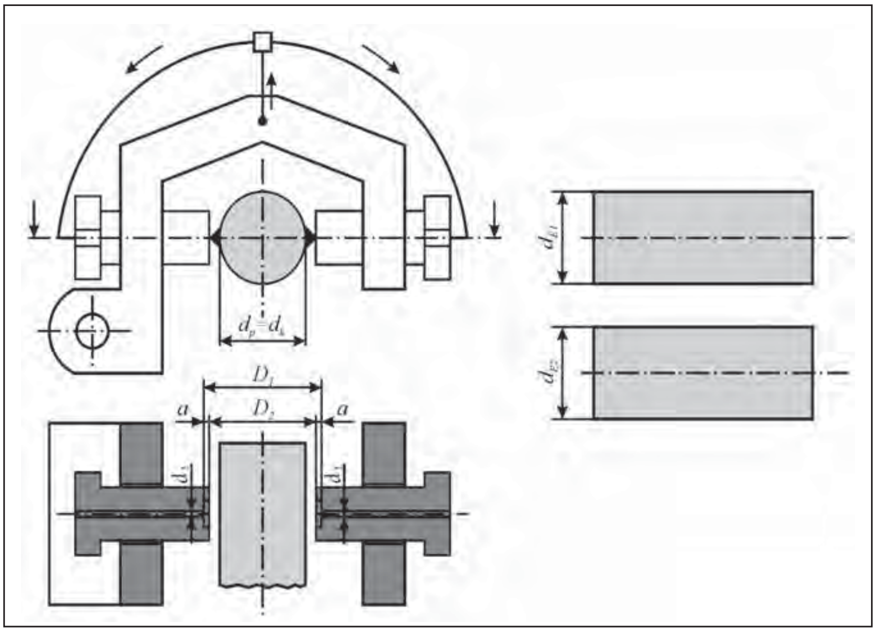

Figure 11. *Measurement-control head for piston rods*

$D_P = D_C = \phi 420H8$ measurement-control value – cylinder tube diameter

Measurement value $\phi 420H8$ is matched by measurement scale $\begin{bmatrix} DS & GS \\ -30 & +130 \end{bmatrix}$

$$D_2 = (D_P - X_g) \pm 0{,}003 = $$
$$= 420 - 0{,}040 = 419{,}960 \pm 0{,}003\,\text{mm}$$

$$D_1 = (D_2 - 2a) \pm 0{,}003 = 419{,}960 -$$
$$- 0{,}080 = 419{,}880 \pm 0{,}003\ \text{mm}$$

$$X_g = DS + 10 = 30 + 10 = 40\,\mu\text{m}$$

$a = 20 - 45\,\mu m;$ *accepted is* $a = 40\,\mu m$

- Standards:

$$D_{E1} = D_P + DGM + X_E = 420 + 0 +$$
$$+ 0{,}005 = 420{,}005^{+0{,}005}_{0}\ \text{mm}$$

$$D_{E2} = D_P + GGM - X_E = 420 + 0{,}096 -$$
$$- 0{,}005 = 420{,}031^{0}_{-0{,}005}\,\text{mm}$$

$X_E = 5\ \mu\text{m}$ (recommendation) for
$D_P = 420H8 \rightarrow DGM = 0,$
$GGM = +96\,\mu m$

- Notes:

Measurement scales are produced in several measurement scopes:

$(-30, +70)\mu m;\quad (-30, +130)\mu m;$
$(-50, +50)\mu m;\quad (-130, +30)\mu m;$

The selection is made depending on nominal measurements of measurement value and its tolerance field (T).

– Measurement-control head and standards for piston rods

- Measurement-control head:

Table 2. *Measurement-control head*

d_P [mm]	d_1H6 [mm]	a [µm]
$3 \le d_P \le 5$	1,1	20 - 45
$5 < d_P \le 10$	1,5	
$10 < d_P \le 150$	1,9	
$d_P > 150$	2,2	

$d_P = d_K = \phi 160 f8$ measurement-control value – piston rod diameter

Measurement value $\phi 160 f8$ is matched by measurement scale $\begin{bmatrix} DS & GS \\ -130 & +30 \end{bmatrix}$

$$D_2 = (d_P + X_d) \pm 0{,}003 = 160 + $$
$$+ 0{,}040 = 160{,}040 \pm 0{,}003\, mm$$

$$D_1 = (D_2 + 2a) \pm 0{,}003 = 160{,}040 + $$
$$+ 0{,}080 = 160{,}120 \pm 0{,}003\ mm$$

$$X_d = DS + 10 = 30 + 10 = 40 \mu m$$

$$a = 20 - 45\, \mu m;\ accepted\ is\ a = 40\ \mu m$$

- Standards:

$$d_{E_1} = (d_P - DGM + X_E)^{+0{,}005}_{0} = 160$$
$$- 0{,}106 + 0{,}005 = 159{,}899^{+0{,}005}_{0} mm$$

$$d_{E_2} = (d_P - GGM - X_E)^{0}_{-0{,}005} = 160$$
$$- 0{,}043 - 0{,}005 = 159{,}952^{0}_{-0{,}005} mm$$

$$X_E = 5 \mu m (\text{recommendation})$$

$$\text{for } d_p = 160 f8 \ \rightarrow\ DGM = -106 \mu m,$$
$$GGM = -43 \mu m$$

4.2. Measuring-control system for quality of surface roughness

Technical characteristics:

– possibility of measuring: $R_a, R_q, R_z, R_p, S_m, t_p$
– filtering surface corrugation
– accuracy of measurement read-out: $0{,}1\ \mu m$

5 Conclusion

By way of multidimensional analytical experimental method, it was possible to investigate, the complex inner structure of processing systems and "discover" numerous interactions of impact factors in a secure, reliable and efficient manner. The applied concept of multidimensionality through selecting a significant number of 11 coordinates of "input" - impact factors, made it possible to locate research in the domain of high reality and provided the basis for accuracy and reliability.

The multidimensional matrix [14x12], as the most reliable and efficient, what is more - in complex processes the only possible operator in research, made it possible to efficiently carry out the procedure of investigating the structure by way of an optimal arrangement of measurement points, a minimal number of measurements with maximum information about the "state" in experimental space of the system.

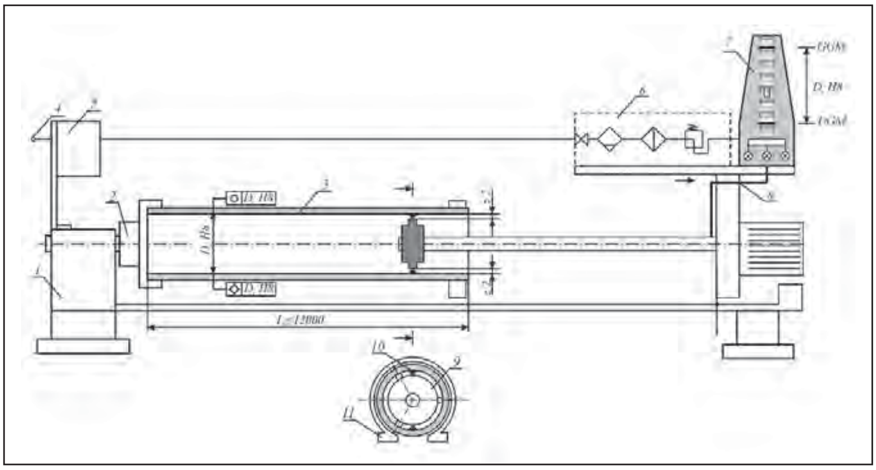

Figure 12. *Pneumatic measuring-control system for cylinder tubes. 1. Machine, 2. Vice kit, 3. Workpiece (cylinder tube), 4. Air supply, 5. Pipe line adaptor, 6. Air preparation system, 7. Measurement device, 8. Measurement pipe line, 9. Measurement head, 10. Measurement valves, 11. Measurement head adaptor*

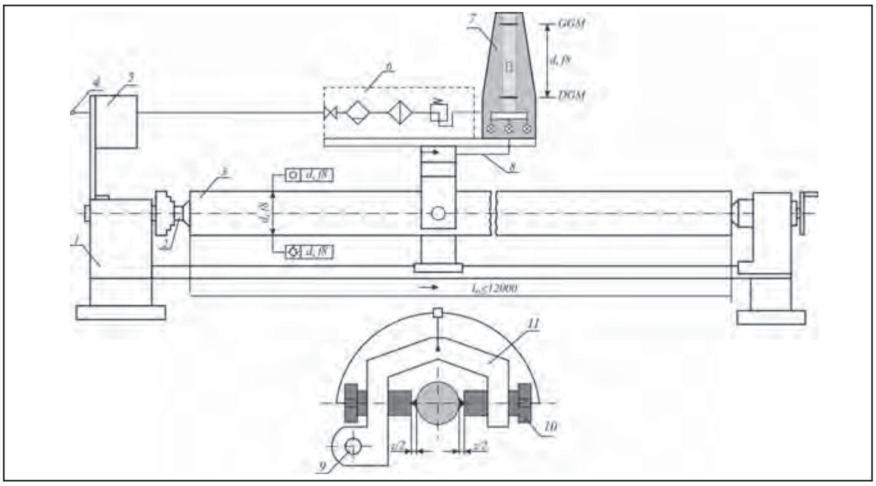

Figure 13. *Pneumatic measuring-control system for pistion rods. 1 . Machine, 2. Vice kit, 3. Workpiece (piston rod), 4. Air supply, 5. Pipe line adaptor, 6. Air preparation system, 7. Measurement device, 8. Measurement pipe line, 9. Measurement head, 10. Measurement valves, 11. Measurement head adaptor*

Figure 14. *Measuring device SURFTEST 401 - ²MITUTOYO²*

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Optimiranje hidravličnih valjev velikih dimenzij in izhodnih moči – oljna hidravlika

Razširjeni povzetek

Kot že naslov ponazarja prispevek obravnava hidravlične valje velikih dimenzij in velikih moči pri izvajanju delovnih gibov na področju oljne pogonsko-krmilne hidravlike. Prispevek se osredotoča na dimenzije valjev in izdelavne parametre, ki jih zmorejo in dosegajo v koncernu Prva Petoletka – Trstenik (PPT) in sicer podjetje oziroma tovarna *PPT »Cilindri« A.D.* Izdelajo preko 180.000 valjev letno z notranjim premerom do 600 mm in dolžino giba do 12 m. Hidravlične valje velikih dimenzij so doslej izdelovali za tlake do 250 bar, pač v skladu z zahtevami naročnikov, lahko pa izdelajo za tlake do ca 600 bar. Hidravlični valji velikih dimenzij imajo torej že ob običajnih hitrostih gibanja bata velike izhodne moči. Uporabljajo jih predvsem v hidroelektrarnah, termoelektrarnah (erdap, Kostolac) in rudarstvu (RTB – Bor). Za tovrstne objekte jih je bilo v zadnjem letu večje število poslanih tudi v Rusijo. Članek je orientiran na izdelavo in izvajanje kontrolnih meritev za valje z dimenzijami Φ 420/160 x 7800. V uvodnem poglavju so navedeni osnovni 4 parametri, ki jih je treba upoštevati v fazi izdelave in izvajanja kontrole kvalitete izdelave s poudarkom predvsem na notranjosti cevi valja in batnice. Niso pa zanemarjeni niti ostali sestavni deli valjev, saj tudi neustrezno statično tesnjenje lahko povzroči nezaželeno, največkrat nesprejemljivo notranje ali zunanje puščanje. Z okoljevarstvenega vidika je zunanje puščanje zelo problematično. Predvsem za izvajanje kontrole kvalitete izdelave je zaželeno izbrati čimveč ustreznih parametrov, vendar pa njihovo prekomerno število otežuje nadzor in še predvsem matematično modeliranje procesa. Prispevek v 2. poglavju podaja 11 parametrov, ki so igrali vlogo v fazah izdelave in izvajanja kontrole kvalitete le-te. Poglavje 3 podaja orodja za izdelavo in kontrolo kvalitete posebej za cev in posebej za batnico oljno-hidravličnega valja Φ 420/160 x 7800. Podano je opisno in v slikah *Fig. 1 do Fig. 5*. Poglavje 4 utemeljuje izbiro merilno-kontrolnega sistema ter opisno in v Sliki 6 podaja njegovo zgradbo in funkcijo.

Ključne besede: hidravlični valji za oljno hidravliko, cev valja, batnica, velike dimenzije, moč, eksperimentalno raziskovanje, matematično modeliranje, metode optimiranja, hidrodinamika, dinamika,

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