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Sila trenja v pnevmatičnem valju

Friction Force in the Pneumatic Cylinder

NIKO HERAKOVIČ — JOŽE DUHOVNIK — DRAGICA NOE

0. UVOD

Pnevmatični pogoni in krmilni sistemi, kljub prevladujočim električnim pogonom, ohranjajo svoj pomen, na določenih področjih pa ga celo pridobivajo [1], [4], [11], [12].

Pomembna pomanjkljivost pnevmatičnih pogonov je premajhna natančnost pozicioniranja in neenakomernost gibanja oz. trzavo drsenje pri majhnih hitrostih [1], [12]. Odločilen vpliv na natančnost pozicioniranja in neenakomernost gibanja pri majhnih hitrostih ima sila trenja v pnevmatičnem valju [5]. Številne raziskave obravnavajo vpliv različnih parametrov: tlaka, hitrosti, mazanja, oblike in materiala tesnil na sile trenja. Pri tem skušajo razviti matematične modele sil trenja in celotnega pogona ter nasploh razjasniti dogajanje v komponentah pnevmatičnega pogona pri gibanju bata v valju [1], [3], [5], [6], [7], [11], [13].

Dosedanje raziskave [1], [5], [6], [7], [13] so pokazale, da je sila trenja v pnevmatičnem valju močno odvisna od hitrosti bata, tlačne razlike v komorah valja, mazanja, geometrične oblike in materiala tesnil; vendar sila trenja ni bila analizirana v območju majhnih hitrosti pod 1 mm/s, prav tako pa tudi ne v območju velikih hitrosti.

Na podlagi teoretičnih izhodišč in že poprejšnjih raziskav so v nadaljevanju prikazani rezultati preizkusov, ki so bili opravljeni na domačih pnevmatičnih komponentah. Rezultati podajajo vplive posameznih parametrov, npr. hitrosti, mazanja, tlakov v komorah valja in temperature okolice na silo trenja, podrobneje pa je raziskan tudi pojav trzavega drsenja. Sila trenja v pnevmatičnem valju je analizirana z vidika trenja elastomerov s poudarkom viskoelastičnosti.

1. CILJ RAZISKAV IN IZVEDBA MERITEV

Natančnost pozicioniranja pnevmatičnih pogonov in enakomernost gibanja pri majhnih hitrostih kakor tudi natančnost matematičnih modelov za simuliranje pnevmatičnih oziroma servopnevmatičnih pogonov je v največji meri odvisna od sile trenja v pnevmatičnem valju.

Sila trenja se v valju pojavlja predvsem na dveh mestih: med tesnili bata in stenami valja ter med batnico in tesnili pokrova valja. Znano je, da se v izračunih uporablja podatek, da sila trenja v

0. INTRODUCTION

In spite of predominating electrical drives, pneumatic drives and control systems justify their use and, in certain fields of work, are becoming even more important [1], [4], [11], [12].

An important drawback of pneumatic drives is inadequate accuracy of positioning and non-uniformity of movement, called stick-slip phenomena at low velocities [1], [12]. The friction force in the pneumatic cylinder has a decisive effect on the accuracy of positioning and non-uniformity of movement at low velocities [5]. Extensive research has been done into the influence of various parameters on the friction force: pressure, velocity, lubrication, form and material of the seals, etc. There have also been some attempts to derive mathematical models of friction force and the entire drive, and to clarify what is going on in pneumatic drive componennts when the piston is moving in the cylinder [1], [3], [5], [6], [7], [11], [13].

Research done so far [1], [5], [6], [7], [13] has shown that the friction force in the pneumatic cylinder depends very much on piston velocity, pressure difference in the cylinder chambers, lubrication, geometrical form and the material of the seals; however the friction force was not analysed within the range of low velocities below 1 mm/s, likewise it was not analysed within the range of high velocities.

The results of experiments made using domestic components are presented in this paper on the basis of theoretical experience and previous research. The results show the influence of particular parameters like velocity, lubrication, pressures in the cylinder chambers and the influence of the temperature of the surroundings on the friction force. The stick-slip phenomena are also examined in greater detail. The friction force in the pneumatic cylinder is analysed from the aspect of viscoelactic friction of elastomers.

1. THE AIM OF THE RESEARCH AND PERFORMING THE EXPERIMENTS

The accuracy of the positioning of pneumatic drives and the uniformity of movement at low velocities as well as the accuracy of mathematical models for simulating pneumatic or servopneumatic drives depend mostly on the friction force in the pneumatic cylinder.

In the pneumatic cylinder, the friction force appears mainly in two areas, between the piston seals and the cylinder walls and between the piston rod and the seals of the cylinder ends. It is pnevmatičnem valju zavzame okrog 10 odstotkov vrednosti koristne sile [5] in da ima konstantno vrednost, vendar je lahko to samo osnovna informacija. Za natančno določitev sile trenja v valju je treba upoštevati, da se sila trenja spreminja, poznati je treba vse vplivne parametre ter ugotoviti, kako vplivajo na silo trenja.

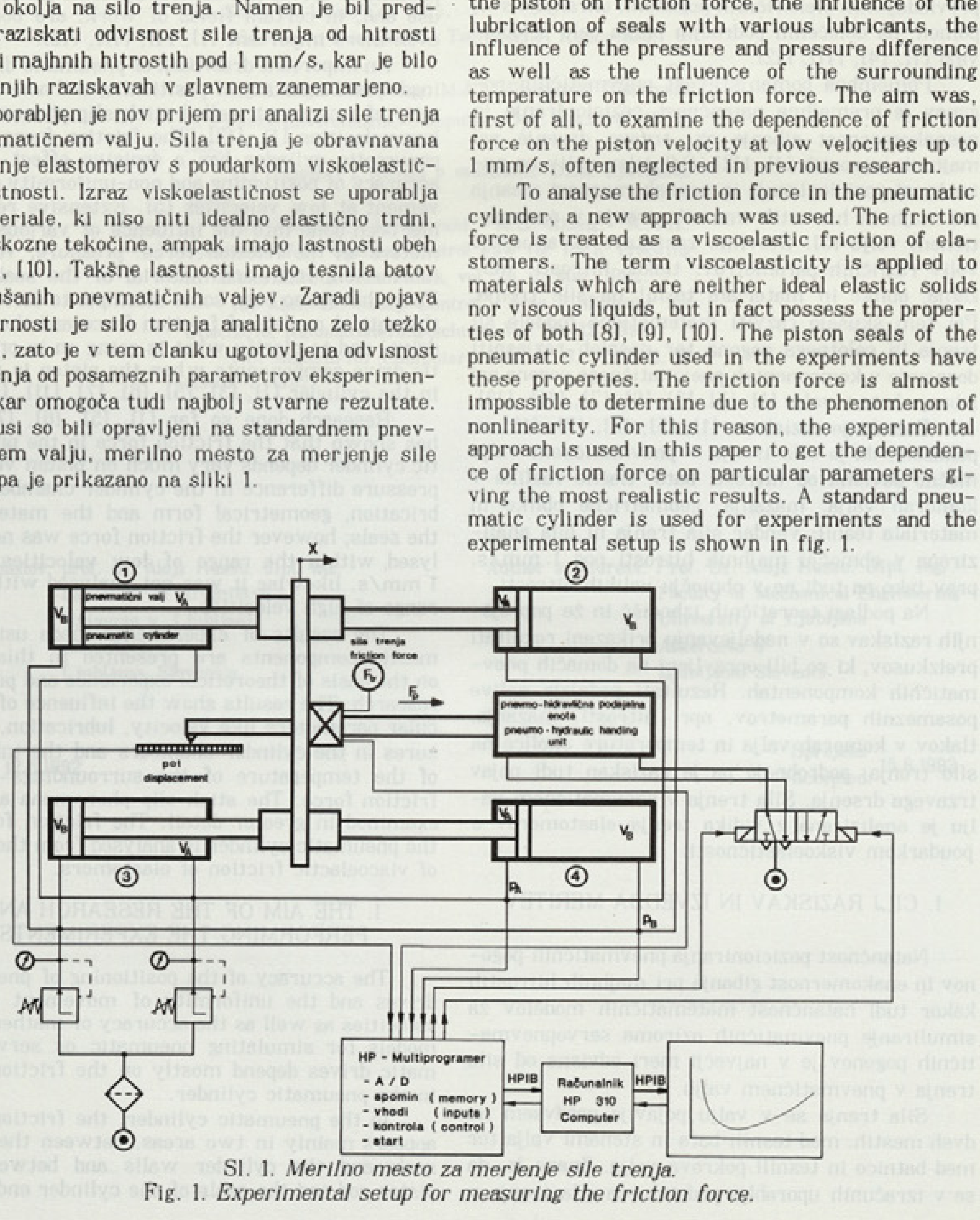
V tem članku so prikazane raziskave, v katerih so bili upoštevani vpliv drsne hitrosti bata na silo trenja, vpliv mazanja tesnil z različnimi mazivi, vpliv tlaka in tlačne razlike ter vpliv temperature okolja na silo trenja. Namen je bil predvsem raziskati odvisnost sile trenja od hitrosti bata pri majhnih hitrostih pod 1 mm/s, kar je bilo v prejšnjih raziskavah v glavnem zanemarjeno.

Uporabljen je nov prijem pri analizi sile trenja v pnevmatičnem valju. Sila trenja je obravnavana kot trenje elastomerov s poudarkom viskoelastičnih lastnosti. Izraz viskoelastičnost se uporablja za materiale, ki niso niti idealno elastično trdni, niti viskozne tekočine, ampak imajo lastnosti obeh [8], [9], [10]. Takšne lastnosti imajo tesnila batov preizkušanih pnevmatičnih valjev. Zaradi pojava nelinearnosti je silo trenja analitično zelo težko določiti, zato je v tem članku ugotovljena odvisnost sile trenja od posameznih parametrov eksperimentalno, kar omogoča tudi najbolj stvarne rezultate. Preizkusi so bili opravljeni na standardnem pnevmatičnem valju, merilno mesto za merjenje sile trenja pa je prikazano na sliki 1.

well known that friction force in the pneumatic cylinder takes about 10 percent of the value of useful force [5] and that it has a constant value used in the calculations. However, this represents only basic information. For the exact determination of friction force in the cylinder, the fact that the friction force changes all the time has to be taken into account. Likewise, all influential parameters have to be determined as well as their influence on the friction force.

The research presented in this paper takes into account the influence of sliding velocity of the piston on friction force, the influence of the lubrication of seals with various lubricants, the influence of the pressure and pressure difference as well as the influence of the surrounding temperature on the friction force. The aim was, first of all, to examine the dependence of friction force on the piston velocity at low velocities up to 1 mm/s, often neglected in previous research.

To analyse the friction force in the pneumatic cylinder, a new approach was used. The friction force is treated as a viscoelastic friction of elastomers. The term viscoelasticity is applied to materials which are neither ideal elastic solids nor viscous liquids, but in fact possess the properties of both [8], [9], [10]. The piston seals of the pneumatic cylinder used in the experiments have these properties. The friction force is almost impossible to determine due to the phenomenon of nonlinearity. For this reason, the experimental approach is used in this paper to get the dependence of friction force on particular parameters giving the most realistic results. A standard pneumatic cylinder is used for experiments and the experimental setup is shown in fig. 1.



Sl. 1. *Merilno mesto za merjenje sile trenja.*
Fig. 1. *Experimental setup for measuring the friction force.*

Odvisnost sile trenja od posameznih vplivnih parametrov, posebej pa od hitrosti bata, je najlaže določiti, če ima bat ves čas trajanja giba enakomerno hitrost. Nespremenljivo hitrost bata zagotavlja v tem primeru, kakor je prikazano na sliki 1, pnevmo-hidravlična podajalna enota, ki hkrati omogoča različne nastavitve hitrosti, od zelo majhnih, do večjih vrednosti. V ta namen je postavljeno merilno mesto s štirimi pnevmatičnimi valji, kar omogoča vodenje, batnice pnevmatičnih valjev pa so pripete na togo letev, ki je povezana z batnico pnevmo-hidravlične podajalne enote. Ta zagotavlja prek toge letve enakomeren pogon vseh štirih pnevmatičnih valjev. Valji so vpeti tako, da je omogočeno samocentriranje, hkrati pa so izločeni vplivi upogibnih momentov na batnicah. Z zaznavalom sile, ki je členkasto pritrjen med batnico podajalne enote in letvijo, ki trdno povezuje batnice pnevmatičnih valjev, je omogočeno neposredno merjenje sile trenja. To je vidno iz bilance sil sistema na sliki 1 v primeru, ko obstaja gibanje v smeri x. Zapis gibalnih enačb za vsak pnevmatični valj posebej omogoča Newtonov zakon:

The easiest way to determine the dependence of friction force on particular influential parameters, especially piston velocity, is for the piston to have a constant velocity during movement. A constant velocity is assured, as shown in fig. 1, by a pneumohydraulic handling unit, which assures different levels of velocity from very small to greater values. For this purpose, an experimental setup using four pneumatic cylinders enabling guidance is used. The pneumatic cylinders are fastened to the rigid holder, which is connected to the piston rod of pneumohydraulic handling unit which, because of the rigid holder, assures a uniform drive of all four pneumatic cylinders. A particular way of mounting enables the self centering of pneumatic cylinders and prevents the influences of bending moments. With the dynamometer, mounted with the help of knuckle joints between the piston rod of the handling unit and the rigid holder, which firmly ties the piston rods of the pneumatic cylinders together, the friction force can be measured directly. This can be seen from the balance of forces for the system in fig. 1 where there is motion in direction x. Separate records of motion equations for each pneumatic cylinder can be determined using Newton's law:

$$F = m \cdot \ddot{x} \tag{1}$$

Gibalne enačbe valjev so naslednje:

The motion equations for the cylinders are:

$$\sum F_1 = -m_1 \cdot \ddot{x} \pm p_{A1} \cdot A_{A1} \pm p_{B1} \cdot A_{B1} \pm p_{at} \cdot A_{b1} - F_{tr1} + F_1 = 0 \tag{2}$$

pri tem pomenijo:
$F_{1(1=1...4)}$ — sile na batnice pnevmatičnih valjev zaradi pogona, $F_{tr1(1=1...4)}$ — sile trenja v pnevmatičnih valjih, $p_{A1} \cdot A_{A1}$, $p_{B1} \cdot A_{B1}$ — sile na bate zaradi tlakov, $p_{at} \cdot A_{b1}$ — sile atmosferskega tlaka na batnice, m_1 — mase batov in batnic, $\ddot{x}$ — pospešek.

Indeksi $1\,(1=1...4)$ pomenijo prvi do četrti pnevmatični valj.

Valji imajo enake pospeške in hkratne gibe, zato so gibalne enačbe skoraj enake. Ločijo se samo po predznakih nekaterih sil, ker sta si po dva in dva valja postavljena nasproti.

Za pogon lahko zapišemo naslednjo bilanco sil:

whereby:
$F_{1(1=1...4)}$ — the forces on the piston rods of pneumatic cylinders due to the drive, $F_{tr1(1=1...4)}$ — the friction forces in pneumatic cylinders, $p_{A1} \cdot A_{A1}$, $p_{B1} \cdot A_{B1}$ — the pressure forces acting on the piston, $p_{at} \cdot A_{b1}$ — the forces of atmospheric pressure acting on the piston rods, m_1 — the masses of pistons and piston rods, $\ddot{x}$ — represents the acceleration.

Indexes $1\,(1=1...4)$ represent the first to fourth pneumatic cylinders respectively.

Since the cylinders have equal accelerations and simultaneous movements, the motion equations are almost equal. They differ only due to different signs of some forces, because two couples of cylinders are mounted opposite to each other.

For the drive, the forces balance can be expressed:

$$F_p - F_1 - F_2 - F_3 - F_4 = 0 \tag{3}$$

kjer je F_p — sila pogona.

Kakor je prikazano na sliki 1, so komore valjev povezane med seboj s poliuretanskimi cevmi, tako da ostajata skupni prostornini V_A in V_B med gibom konstantni. S tem ostajata konstantna tudi tlaka p_A in p_B in sta v vseh štirih valjih enaka [6]:

where is F_p — the motive force.

As shown in fig. 1, the cylinder chambers are connected with each other by polyurethane pipes, so that the common volumes V_A and V_B remain constant during the movement. Considering this fact, the pressures p_A and p_B also remain constant and are equal in all four cylinders [6]:

$$p_{A1} = p_{A2} = p_{A3} = p_{A4} = \text{konst.}$$

$$p_{B1} = p_{B2} = p_{B3} = p_{B4} = \text{konst.}$$

Poudariti je treba, da je dodatno trenje, ki nastane zaradi pretakanja zraka po ceveh med komorami valjev, zaradi majhnih hitrosti in večjih premerov cevi, zanemarljivo. Vsekakor pa je treba to trenje upoštevati pri večjih hitrostih zraka oziroma batov valjev. Pri uporabi enakih valjev (z enako geometrično obliko in značilnostmi) dobimo s seštevanjem enačb (2) in (3) in ob upoštevanju enačbe (4) in (5) zvezo:

$$F_p = F_{tr1} + F_{tr2} + F_{tr3} + F_{tr4} + m_s \cdot \ddot{x} \qquad (6)$$

kjer je:
m_s – skupna masa vseh štirih batov in batnic.

Če je izveden gib s konstantno hitrostjo, pomeni, da je pospešek nič ($\ddot{x}$ = 0). Z upoštevanjem tega enačba (6) pove, da je pogonska sila oziroma sila, ki jo zazna merilnik sile, enaka skupni sili trenja v štirih valjih. Zaradi večjih sil je uporabljen merilnik sile z območjem od 0 do 5 kN. Sila trenja v enem valju pa je enaka četrtini skupne sile trenja.

2. SILA TRENJA IN VPLIVNI PARAMETRI

Uporabljeni pnevmatični valji za eksperimente so premera 100 mm in z gibljajem 200 mm. V posameznem valju je uporabljen bat s teflonskim obročem in simetričnima tesniloma (manšetama), kakor je prikazano na slikah z rezultati. Tesnila so izdelana iz elastomera na osnovi butadien-akrilonitrilnega kavčuka (NBR). Meritve so bile izvedene z merilnim sistemom HP in programsko opremo, ki je bila uporabniško razvita v laboratoriju za pnevmatiko na Fakulteti za strojništvo v Ljubljani. Za merjenje sile trenja je bil uporabljen merilnik sile HBM tip U2 A z merilnim območjem od 0 do 5 kN.

Vrednost sile trenja se med gibom bata nekoliko spreminja, kljub enakomerni hitrosti bata in nespremenljivima vrednostima tlaka zraka v komorah valja. Odvisna je namreč od natančnosti izdelave valja oz. od notranjega premera valja [5]. Meritve sile trenja so izvedene pri gibu 100 mm, kolikor dovoljuje podajalna enota. Iz posameznih merilnih točk je nato izračunana srednja vrednost sile trenja pri določeni konstantni hitrosti bata ali tlaku zraka. Za določitev sile trenja v odvisnosti od hitrosti bata, se mora hitrost spreminjati. Sila trenja je merjena v dolžini največjega giba podajalne enote zunaj območja končnega dušenja pri različnih hitrostih, v območju med 0 in 70 oziroma 100 mm/s.

It should be emphasized that the additional friction due to air flow through pipes between cylinder chambers is neglected due to small velocities of air and greater diameters of pipes. This friction should be taken into account when there are greater air or cylinder piston velocities. If equal cylinders are used (with equal geometrical shape and characteristics), relation can be derived by the summation of equations (2) and (3) bearing in mind equations (4) and (5):

where:
m_s – the total mass of all four pistons and rods.

When movement is implemented wth constant velocity, the acceleration is zero ($\ddot{x}$ = 0). Considering this fact it can be seen from equation (6) that the motion force, i.e. the force detected by the dynamometer, is equal to total friction force in four cylinders. Due to bigger forces, the dynamometer with a range from 0 to 5 kN is used. The friction force in one cylinder is equal to one quarter of total friction force.

2. THE FRICTION FORCE AND THE INFLUENTIAL PARAMETERS

Pneumatic cylinders used in experiments have a diameter of 100 mm and a stroke of 200 mm. In an individual cylinder the piston with a teflone ring and symmetrical seals (cuffs) is used, as shown in figures with results. The seals are made of elastomer on the basis of butadien-acrylonitrile caoutchouc (NBR). The experiments were implemented with an HP measuring system. For measuring the friction force, the dynamometer HBM type U2 A with a measuring range from 0 to 5 kN was used.

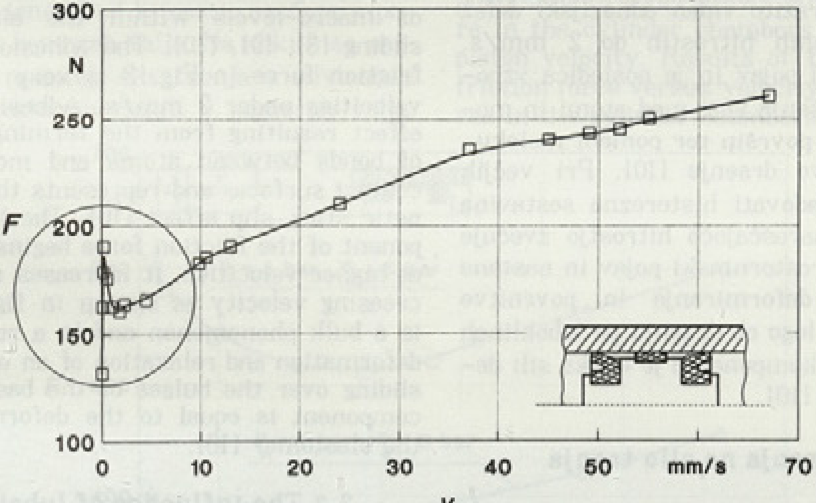
The value of the friction force changed slightly during the piston movement despite invariable cylinder speed and constant air pressure in the cylinder chambers, as it depends on the accuracy of the cylinder construction, especially the inner cylinder bore [5]. Measurements of friction force were made at a movement of 100 mm allowed by the handling unit. The average friction force at constant piston velocity or air pressure was calculated at the measured points. To determine the dependence of friction force on piston velocity, the velocity has to be variable. The friction force was measured outside the range of the air throttling at the end of the stroke at different velocities in the range from 0 to 70 or 100 mm/s.

2.1 Viskoelastično trenje v pnevmatičnem valju — vpliv hitrosti na silo trenja

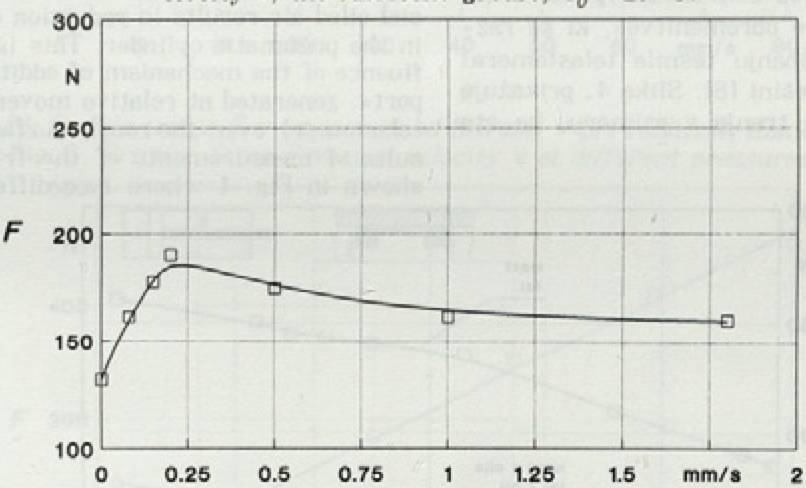
Na sliki 2 so predstavljeni rezultati meritev, ki prikazujejo odvisnost sile trenja od hitrosti bata v razmerah, ko je v valjih relativni tlak enak nič, za mazivo je uporabljena mast INT 436, dodana pri montaži valja, zrak v valjih je suh in ni naoljen. Sila trenja pri različnih hitrostih leži v območju med 160 in 260 N. Potek krivulje je podoben Stribeckovi krivulji, takšno odvisnost sile trenja od hitrosti pa je mogoče zaslediti v nekaterih člankih, ki obravnavajo to problematiko [1], [3], [5], [7], [13].

2.1 Viscoelastic friction in the pneumatic cylinder — the influence of velocity on friction force

The results that show the dependence of friction force on piston velocity are presented in Fig. 2. They are valid for conditions in the cylinder when the value of relative pressure is zero and the grease INT 436, added at the assembly of the cylinder, is used as a lubricant. The air used in the cylinder is dry and unoiled. The friction force at different velocities lies in the range between 160 and 260 N. The curve is similar to the Stribeck's curve and such dependence of friction force on velocity can also be found in some papers dealing with these problems [1], [3], [5], [7], [13].



Sl. 2. *Sila trenja F v valju brez tlakov v odvisnosti od hitrosti v; mazivo - mast;* $T_0 = 20\ ^oC$.
Fig. 2. *The friction force F in the pneumatic cylinder without pressures versus velocity v; the lubricant-grease;* $T_0 = 20\ ^oC$.



Sl. 3. *Povečani levi del krivulje sile trenja F v področju majhnih hitrosti v do 2 mm/s.*
Fig. 3. *Enlarged left part of the friction force F curve in the range of low velocities v under 2 mm/s.*

Levi del krivulje na sliki 2, v področju majhnih hitrosti med nič in 2 mm/s, je posebej zanimiv in za boljše razumevanje problematike trenja v pnevmatičnem valju izredno pomemben. Povečani

The left part of the curve in Fig. 2 in the range of small velocities between zero and 2 mm/s is particularly interesting and is very important for a better understanding of friction levi del krivulje je prikazan na sliki 3. Sila trenja se z naraščajočo hitrostjo bata najprej poveča do določene vrednosti in nato zopet zmanjša, dokler ne doseže najmanjše vrednosti. Z naraščajočo hitrostjo se potem sila trenja zopet zvečuje.

Takšen potek krivulje sile trenja v odvisnosti od hitrosti je značilen za viskoelastično trenje elastomerov in dokazuje, da obstaja v pnevmatičnem valju problem viskoelastičnega trenja tesnil, kjer pri majhnih hitrostih prevladuje predvsem adhezijski, pri velikih hitrostih pa histerezni delež sile trenja. Obe sestavini sile trenja sta tipična viskoelastična pojava, ki se pojavita na mikro- ali makronivoju v elastomeru med drsenjem [8], [9], [10]. Na sliki 3 je izrazito viden adhezijski delež sile trenja pri majhnih hitrostih do 2 mm/s. Adhezija je površinski pojav in je posledica vzpostavljanja oziroma rušenja vezi med atomi in molekulami obeh mejnih površin ter pomeni molekularno-kinetično trzavo drsenje [10]. Pri večjih hitrostih začne prevladovati histerezna sestavina sile trenja, ki se z naraščajočo hitrostjo zvečuje (sl. 2). Histereza je prostorninski pojav in nastane zaradi periodičnega deformiranja in povrnitve elastomera v prvotno lego ob drsenju po izboklinah osnovne površine. Ta komponenta je enaka sili deformacije elastomera [10].

2.2 Vpliv mazanja na silo trenja

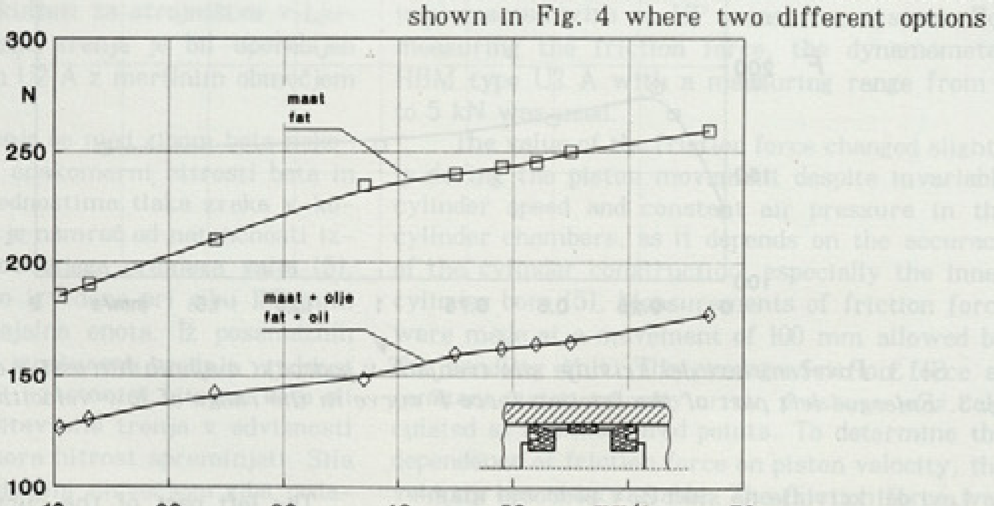
Dodatno mazanje tesnil z oljem in naoljenim zrakom ima za posledico zmanjšanje sile trenja v pnevmatičnem valju predvsem zaradi vpliva mehanizma dodatne »podpore obremenitve«, ki se razvije pri relativnem gibanju tesnila (elastomera) po mazani hrapavi površini [8]. Slika 4, prikazuje rezultate meritev sile trenja v primeru, ko sta

problems in the pneumatic cylinder. The enlarged left part of the curve is shown in Fig. 3. The friction force increases to a certain value in accordance with the increasing piston velocity at the beginning and then decreases again until it reaches its least possible value. With increasing velocity the friction force increases again.

Such variations of the friction force curve in dependence on velocity are characteristic for viscoelastic friction of elastomers, proving a problem of viscoelastic friction of the seals in the pneumatic cylinder. The adhesion component of friction force predominates at low velocities and the hysteresis component at higher velocities. Both components of friction force are typical viscoelastic phenomena which occur on the micro- or macro-levels within the elastomer during sliding [8], [9], [10]. The adhesion component of friction force in Fig. 3 is very distinct at low velocities under 2 mm/s. Adhesion is a surface effect resulting from the forming and collapsing of bonds between atoms and molecules of both contact surfaces and represents the molecular kinetic stick-slip effect [10]. The hysteresis component of the friction force begins to predominate at higher velocities. It increases according to increasing velocity as shown in fig. 2. Hysteresis is a bulk phenomenon and is a result of periodic deformation and relaxation of an elastomer during sliding over the bulges of the base surface. This component is equal to the deformation force of the elastomer [10].

2.2 The influence of lubrication on friction force

Additional lubrication of piston seals with oil and oiled air results in reduction of friction force in the pneumatic cylinder. This is due to the influence of the mechanism of additional »load support«, generated at relative movement of the seal (elastomer) over the rough surface [8]. The results of measurements of the friction force are shown in Fig. 4 where two different options of



Sl. 4. *Sila trenja F v odvisnosti od hitrosti v pri različnih mazivih.*
Fig. 4. *The friction force F versus velocity v of different lubricants.*

uporabljena različna načina mazanja valja. V primeru, ko je razen masti uporabljen tudi naoljen zrak in olje na tesnilih, je sila trenja manjša kakor v primeru, če je za mazanje uporabljena samo mast. Rezultati so prikazani za območje hitrosti od 10 do 70 mm/s, medtem ko so relativni tlaki v komorah enaki nič. Uporabljena je mast INT 436 in olje INA HIDRAOL DVC 22 s kinematično viskoznostjo 22 mm²/s, temperatura okolice pa je 21 °C.

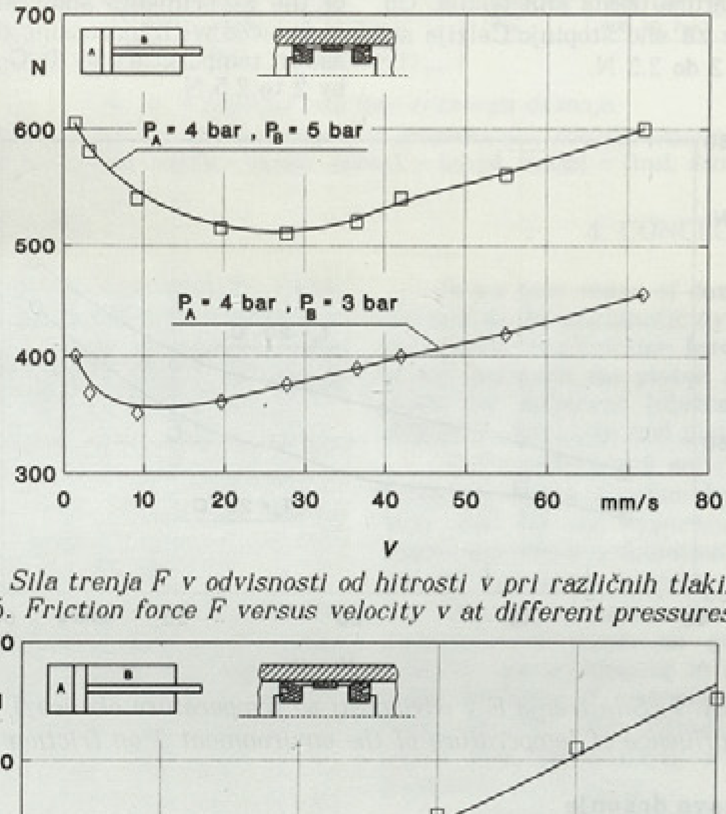
2.3 Vpliv tlaka in hitrosti na silo trenja

V skladu s teorijo viskoelastičnega trenja elastomerov [10] se tudi sila trenja v pnevmatičnem valju, v odvisnosti od hitrosti, zvečuje s povečanjem tlaka v komorah valja. Na sliki 5 so prikazani rezultati meritev sile trenja v odvisnosti od hitrosti pri različnih tlakih v komorah valja.

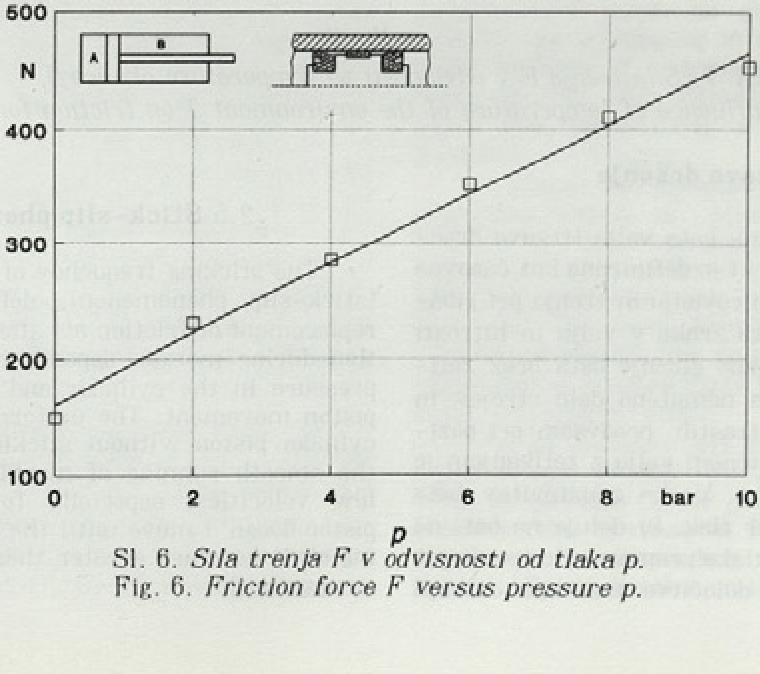
lubrication in the cylinder were used. The friction force is smaller in the case when not only grease but also oiled air and oil in the seals are used. The results are shown for the range of velocity from 10 to 70 mm/s, while relative pressures of air in the chambers vanish. Grease INT 436 and oil INA HIDRAOL DVC 22 with kinematic viscosity 22 mm²/s were used. The temperature of the environment was 21 °C.

2.3 Influence of pressure and velocity on friction force

In accordance with the theory of viscoelastic friction of elastomers [10], friction force in the pneumatic cylinder grows with increasing pressure in the cylinder chambers with respect to the piston velocity. Results of the measurements of friction force versus velocity at different pressures in the cylinder chambers are shown in fig. 5.



Sl. 5. *Sila trenja F v odvisnosti od hitrosti v pri različnih tlakih p.*
Fig. 5. *Friction force F versus velocity v at different pressures p.*



Sl. 6. *Sila trenja F v odvisnosti od tlaka p.*
Fig. 6. *Friction force F versus pressure p.*

Uporabljeno mazivo je, tako kakor v prejšnjem primeru, mast in olje, temperatura okolice pa je 22 °C. Povečanje tlaka oziroma obremenitve na tesnilo povzroči zvečanje sile trenja, bolj pa je izražen tudi adhezijski delež sile trenja, kar je lepo vidno ob primerjavi krivulj na sliki 5. Neposredna odvisnost sile trenja od tlaka v komorah valja je prikazana na sliki 6. Tlak na obeh straneh bata je enak ($p_A = p_B = p$) in se spreminja od relativne vrednosti 0 do 5 bar. Uporabljeno mazivo je mast in olje, temperatura okolice je 22 °C. Meritve so bile izvedene pri nespremenljivi hitrosti bata 30 mm/s.

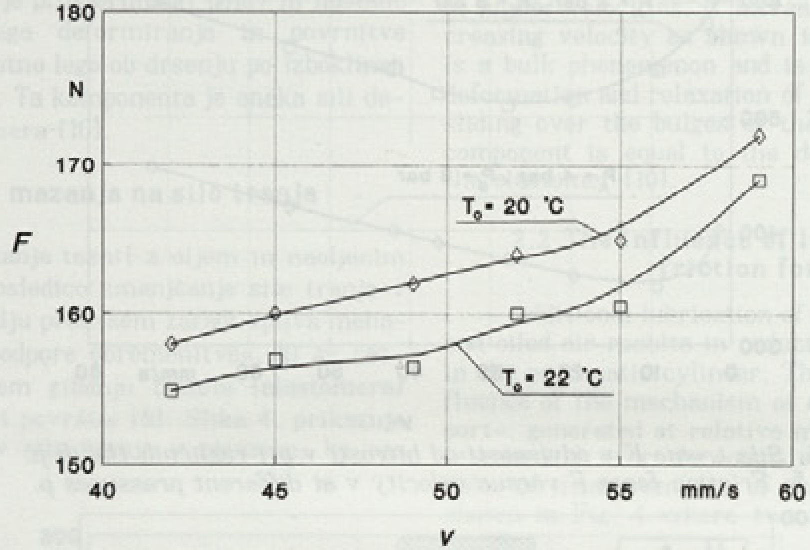
2.4 Vpliv temperature okolice na silo trenja

Na silo trenja vpliva tudi temperatura okolice, kar je razvidno s slike 7. Rezultati meritev kažejo, da z zvišanjem temperature upada sila trenja. Ob povečanju temperature za eno stopinjo Celzija se sila trenja zmanjša za 2 do 2,5 N.

The same lubricants, grease and oil, are used as before and the temperature of the environment is 22 °C. The increase in pressure or the load on the seal causes the increase in friction force. The adhesion component of friction force also predominates as can be seen by comparison of curves in fig. 5. The direct dependence of friction force on pressure in cylinder chambers is presented in Fig. 6. The pressure on both piston sides is equal ($p_A = p_B = p$) and changes from relative value zero to 5 bar. The lubricant used is grease and oil and the temperature of the environment is 22 °C. During the experiments, the piston velocity was constant, 30 mm/s.

2.4 Influence of temperature of the environment on friction force

The temperature of the environment influences friction force as presented in Fig. 7. Results of the experiments show that the friction force is reduced with increasing temperature. An increase in temperature by 1° C reduces friction force by 2 to 2.5 N.



Sl. 7. *Sila trenja F v odvisnosti od temperature okolice T.*

Fig. 7. *Influence of temperature of the environment T on friction force F.*

2.5 Trzavo drsenje

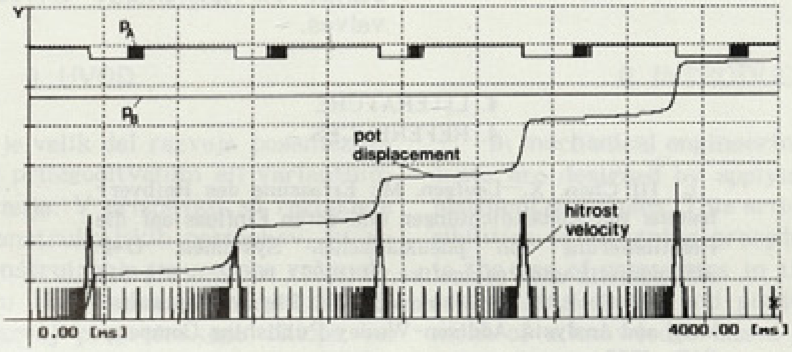
Frekvenca zatikanja bata valja (trzavo drsenje – stick slip efect), ki je definirana kot časovna zamenjava trenja pri mirovanju in trenja pri gibanju, je odvisna od tlaka zraka v valju in hitrosti gibanja bata. Enakomerno gibanje bata brez zatikanja je pomembno za nemoteno delo strojev in naprav pri majhnih hitrostih, predvsem pri pozicioniranju. V pnevmatičnem valju z zatikanjem je pot bata neenakomerna. Vsaka zaustavitev bata traja tako dolgo, dokler tlak, ki deluje na bat, ne naraste toliko, da sila tlaka premaga silo trenja pri mirovanju. Preizkusi določitve trzavega drsenja

2.5 Stick-slip phenomenon

The sticking frequency of the cylinder piston (stick-slip phenomenon), defined as the time replacement of friction at standstill and of friction during motion, depends on the level of air pressure in the cylinder and on the velocity of piston movement. The uniform movement of the cylinder piston without sticking is important for the smooth running of machines and devices at low velocities, especially for positioning. The piston doesn' t move until the pressure force acting on it becomes greater than the friction force at standstill.

so izpeljani na preizkuševališču z enim pnevmatičnim valjem s premerom 100 in z gibljajem 200 mm. Komora B je odprta in v njej je atmosferski tlak, medtem ko je v komori A napajalni tlak 1,05 bar. Rezultati meritev so prikazani na sliki 8.

Experiments to determine the stick-slip phenomenon are made with a setup of one pneumatic cylinder with a cylinder bore of 100 and stroke of 200 mm. Chamber B is open and has an atmospheric pressure, while the feeding pressure in chamber A is 1.05 bar. The results of the experiments are shown in Fig. 8.



MERILA:Y	Začetni	Končni	Delitev
Tlak	0.00	1.20	0.15 [bar]
Pot	0.00	20.00	2.50 [mm]
Hitrost	0.00	0.20	0.03 [m/sek]

MERILA:X	Delitev
Čas	400.00 [ms]

Sl. 8. *Rezultati meritev trzavega drsenja.*

Fig. 8. *Results of the stick-slip phenomenon measurements.*

tlak – pressure, čas – time, merila – scales, začetni – initial, končni – final, delitev – partition

3. SKLEP

V tem članku so podani nekateri novi načini obravnavanja problematike trenja v pnevmatičnem valju. Sila trenja je bila raziskana predvsem med tesnili bata in plaščem valja z različnimi mazivi tesnil in pri različnih tlakih ter hitrostih bata.

Pri tem je bilo uporabljeno preizkuševališče s štirimi pnevmatičnimi valji in pnevmo-hidravlično podajalno enoto. Krmiljenje in odjem merjenih parametrov, ter obdelava podatkov so bili opravljeni z merilnim sistemom HP.

Pokazalo se je, da je sila trenja močno odvisna od hitrosti bata valja in se v vseh primerih spreminja v skladu z zakoni trenja elastomerov s poudarjenimi viskoelastičnimi lastnostmi [8], [9], [10]. To dokazujejo rezultati meritev, predvsem v primeru odvisnosti sile trenja od hitrosti.

Poudariti je treba, da je sedaj raziskano tudi področje majhnih hitrosti pod 1 mm/s, ki je bilo do sedaj v številnih raziskavah zanemarjeno. Tudi tu rezultati glede na vir [10] dokazujejo, da gre v pnevmatičnem valju za viskoelastično trenje elastomerov. Hitrosti bata so v pnevmatičnem valju veliko premajhne, da bi histerezni delež sile trenja dosegel značilni viskoelastični vrh.

Na silo trenja močno vpliva tudi tlak zraka in temperatura okolice. S porastom tlaka v komorah valja je povečanje sile trenja izredno veliko, kar ustreza tudi teoretičnim enačbam. Minimum krivulje in celotna vrednost sile trenja se pomakneta proti višjim vrednostim sile trenja in hitrosti bata.

4. CONCLUSION

Some new ways of dealing with problems of friction in the pneumatic cylinder are presented in this paper. The friction force was analysed, first of all, between the piston seals and the cylinder walls for different lubricants of the seals and different pressures and piston velocities.

The experimental setup with four pneumatic cylinders and a pneumo-hydraulic handling unit was used for the experiments. Remote control, signal and data manipulation were performed using the HP measuring system.

The experiments show that friction force depends very much on piston velocity of the cylinder and is changing in all cases in accordance with the laws of viscoelastic friction of elastomers [8], [9], [10]. Results of the experiments prove this, particularly when friction force is dependent on velocity.

It should be stressed that the previously neglected range of small velocities under 1 mm/s has now been analysed. According to the source [10], the results of the experiments prove that viscoelastic friction of elastomers exists in this case. The piston velocities in the pneumatic cylinder are much too small for the hysteresis component of friction force to reach the characteristic viscoelastic peak.

The air pressure and the temperature of the surroundings greatly influence friction force. With an increase in air pressure in the cylinder chamber, the increase in friction force becomes significant, corresponding to equations of the theory. Minimum value on the curve and the total

Dodatno mazanje tesnil je povzročilo zmanjšanje sile trenja, kar ustreza teoriji.

Rezultati raziskav dogajanj v pnevmatičnem valju in krmilnih ventilih bodo kasneje lahko koristno uporabljeni pri razvoju natančnih servopnevmatičnih pogonov in tudi pri razvoju proporcionalnih mernostnih ventilov.

value of friction force shifts to higher values of friction force and piston velocity. Additional lubrication of seals results in a reduction of friction force in accordance with theory.

The results of research on problems of the pneumatic cylinder and control valves will become applicable in the future with development of accurate servopneumatic drives and proportional valves.

4. LITERATURE
4. REFERENCES

[1] Chen, X.—Leufgen, M.: Erfassung des Reibverhaltens von Kolbendichtungen und deren Einfluss auf die Positionierung von pneumatischen Systemen. O+P »Ölhydraulik und Pneumatik«. 31 (1987). Nr.12. S. 914–917.

[2] Cook. N.H.–Rabinowicz, E.: Physical Measurement and Analysis. Addison-Wesley Publishing Company. INC., 1963.

[3] Csulits, A.: Reibverhalten und Gebrauchsdauer von Kolben und Stangendichtungen in Pneumatikzylindern. O+P »Ölhydraulik«. 25 (1981). Nr. 6. S. 523–528.

[4] Denker. K.: Anwendungs-Evolution der Pneumatik. 10. Aachener Fluidtechnisches Kolloquium, Bd. 3 (1992). S. 189–209.

[5] Eschmann, R.: Reibkräfte an pneumatischen Zylinderantrieben. O+P »Ölhydraulik und Pneumatik«, 34 (1990). Nr. 6. S. 416–419.

[6] Herakovič. N.: Modeliranje in simulacija pnevmatičnega pogonskega sklopa. Magisterij. Fakulteta za strojništvo v Ljubljani, 1991.

[7] Köhnlechner. R.: Schmierfilmdicken und Reibkräfte bei pneumatischen Zylindern. O+P »Olhdraulik und Pneumatik«, 25 (1981). Nr. 8. S. 656–663.

[8] Moore. D.F.: Principles and Application of Tribology. Pergamon Press, 1975.

[9] Moore, D.F.: The Friction of Pneumatic Tyres. Elsevier Scientific Publishing Company, 1975.

[10] Moore, D.F.: The Friction and Lubrication of Elastomers. Pregamon Press, 1972.

[11] Kagawa, T.–Ohligschläger, O.: Simulationsmodell für pneumatische Zylinderantriebe. O+P »Ölhydraulik und Pneumatik«. 34 (1990). Nr. 2. S. 115–120.

[12] Saffe. P.: Moderne Technik und neue Ideen für marktgerechte Pneumatikgeräte. 10. Aachener Fluidtechnisches Kolloquium, Bd. 3 (1992). 11–32.

[13] Sholz. D.–Mostert. E.: Geschwindigkeitsgeregelte servopneumatische Zylinderantriebe. O+P »Ölhydraulik und Pneumatik«. 32 (1988). Nr. 1. S. 45–52.

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