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UŠTEDA ENERGIJE SA ZATVORENIM PNEUMATSKIM SUSTAVOM
ENERGY SAVING WITH CLOSE CIRCUIT PNEUMATIC SYSTEM

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Sažetak**:** *U ovome se članku analiziraju dosadašnje spoznaje o zatvorenom pneumatskom sustavu i mogućnost njegove izvedbe. Sve činjenice govore da zatvoreni sustav ima mogućnosti uštedjeti energiju. Eksperimentalna istraživanja i teorijske analize pokazuju da se uporabom zatvorenoga pneumatskog sustava u kombinaciji sa servo-sustavima ne mijenja način rada aktuatora u odnosu na njegov rad u otvorenom sustavu. Nadalje, takav pristup ima prednosti zbog uklanjanja onečišćenja okoliša uljem, smanjuje se moguća kontaminacija pogona vlagom te se smanjuje emisija buke kao posljedica ispuštanja zraka u atmosferu.*

Ključne riječi: – zatvoreni pneumatski sustav
– ušteda energije

Abstract:*The article analyses the possibility of performance and knowledge up to this time about close circuit pneumatic systems. All facts declare that the closed circuit has the possibility for energy saving. Experimental research and theoretical analysis shows that using the closed pneumatic system combined with a servo-system does not change the performance of the actuator in relation to its performance in an open system. Furthermore, the close circuit approach offers the advantage of elimination of oil contamination from the surroundings, reduction of the effects of moisture contamination and reduction of noise emission from exhaust flows to the atmosphere.*

Keywords: – close pneumatic circuit
– energy saving

1. UVOD

Komprimirani zrak ima važnu ulogu u industriji. Ako se komprimirani zrak ispravno koristi, vrlo je prikladan izvor energije. Analiza provedena na industrijskim postrojenjima pokazuje da dvije trećine ukupnih troškova potrebnih za posluživanje postrojenja s komprimiranim zrakom odlazi na gubitke. Uzroci te neučinkovitosti su propuštanja, pretjerani gubitak tlaka u cjevovodima, rad s nepotrebno visokim tlakovima, nekontrolirano odzračivanje itd. Kada bi se umjesto da se odzračuje, zrak iz pogona mogao koristiti ili spremiti, učinkovitost sustava komprimiranog zraka mogla bi se povećati.

Jedna metoda za poboljšanje učinkovitosti pneumatskih sustava razmatra mogućnost da se zrak koji ostaje u komori cilindra na kraju njegova hoda koristi za pokretanje u suprotnom smjeru tj. za povratni hod. Metoda je poznata kao "energija reklamacije" ili "interkomorno strujanje" [1]. Ta je metoda pokazala da se potrošnja zraka može smanjiti za oko 50 %.

Drugi prijedlog za uštedu energije u pneumatskim sustavima je korištenje koncepta dvostrukog tlaka [2]. Vrlo često operacija zahtijeva da se teret pomiče samo u jednom smjeru, a da povratni hod bude bez opterećenja, pri čemu se može koristiti niži tlak.

1. INTRODUCTION

Compressed air plays an important role in the industry. If compressed air is used properly, it is a very convenient source of energy. Analysis carried out in industrial plants showed that two thirds of the total costs required serving the plant with compressed air going to losses. The source of this inefficiency is due to leakage, excessive pressure loss in transmission lines, operating at higher pressures than required, uncontrolled venting, etc. If, instead of venting, the air from the plant could be used or stored, the efficiency of the compressed air system would improve.

One method for improving the efficiency of pneumatic systems is considering the possibility of using air which remains in the cylinder chamber at the end of its stroke, for operation in the opposite direction, i.e. for the return stroke. This method is known as “energy reclamation” or “inter-chamber cross-flow” [1]**.** This method has been shown to produce about 50 % reduction in air consumption.

Another proposal for energy savings in pneumatic systems is the use of the concept of double pressure [2]. Frequently, an operation requires a load to be moved in only one direction and the return stroke is done under no

Treći način uštede energije je koncept zatvorenog pneumatskog kruga. Uobičajeno je da se kod pneumatskih sustava za pozicioniranja koristi otvoreni krug: priključak za kompresor i odzračivanje aktuatora spojeni su s atmosferom. Taj je pristup jednostavan i lako provediv. U cilju poboljšanja učinkovitosti sustava komprimiranog zraka predložen je zatvoreni krug. U zatvorenom sustavu kompresor usisava zrak iz niskotlačnog spremnika, a iz aktuatora zrak odlazi u taj isti spremnik, kao što je to slučaj u hidrauličkom krugu. Takav su sustav predložili Sanville [3] i Bachmann [4].

load conditions, therefore lower pressure can be used.
A third way of saving energy is the concept of the closed pneumatic circuit. The pneumatic positioning system usually uses an open circuit: the compressor and the exhaust from the actuator are connected with the atmosphere. This approach is simple and easy to implement. In order to improve the efficiency of the compressed air system, the closed circuit concept is proposed. In a closed system, the compressor draws from a low pressure receiver and the actuator exhausts to the same receiver, as in a hydraulic circuit. This system was proposed by Sanville [3] and [4].

2. ZATVORENI PNEUMATSKI KRUG

Jedan je od glavnih razloga istraživanja koncepta zatvorenoga kruga (slika 1) ušteda energije. Ako iz aktuatora istječe prigušena struja zraka, tada uvijek postoji mogućnost uštede energije. Struja zraka odvodi se, umjesto u atmosferu, u spremnik pod tlakom $P_e > P_{atm}$, a da pri tome izlazna struja i dalje ostane prigušena. Jednadžba (1) pokazuje da sve dok je izlazna struja zraka prigušena, maseni protok ne ovisi o tlaku na izlazu:

2. CLOSED CIRCUIT PNEUMATICS

One of the main reasons for investigating the closed circuit concept (Figure 1) is due to energy savings. If the exit flow from an actuator is in the choked region, the potential for saving energy exists. Rather than having an actuator exhaust to the atmosphere, it could exhaust to a receiver at a pressure $P_e > P_{atm}$ such that the exit flow still remains choked. Equation (1) shows that as long as the exit flow remains choked, the exhaust mass flow does not depend on the downstream pressure:

$$\dot{m}_b = -\frac{C_d\, C_{mb}\, A_v\, P_b}{\sqrt{T}} z\,. \tag{1}$$

U stacionarnom stanju, maksimalna brzina klipa cilindra iznosi:

In steady state, the maximum cylinder piston speed is:

$$\dot{y}^{ss} = \frac{C_d\, C_{mb}\, R\, A_v\, z \sqrt{T}}{A}\,, \tag{2}$$

gdje je $\dot{m}_b$ maseni protok u izlaznoj komori „b", C_d koeficijent istjecanja proporcionalnog razvodnika, C_{mb} koeficijent masenog protoka, A_v površina poprečnog presjeka izlaznog otvora razvodnika, P_b tlak u komori "b", z normalizirani regulacijski signal, T temperatura, R univerzalna plinska konstanta i A površina poprečnog presjeka klipa cilindra.
Kompresor bi za opskrbljivanje sustava usisavao zrak iz spremnika niskog tlaka. Kako je tlak u spremniku viši od atmosferskoga, snaga potrebna za sabijanje zraka na tlak P_2 reducirana je u odnosu na otvoreni pneumatski sustav. Pu i Weston [5] ustanovili su da je tlak u stacionarnom stanju u aktivnoj komori cilindra funkcija dobavnog tlaka i temperature zraka u komori, a reguliran je servoventilom. Za takav je sustav tlak u stacionarnom stanju dan s:

where $\dot{m}_b$ is the mass flow rate in exhaust chamber "b", C_d the proportional valve discharge coefficient, C_{mb} the mass flow coefficient, A_v the valve port area, P_b upstream pressure, z the normalized control signal, T temperature, R the universal gas constant, and A is the cylinder bore area.
The compressor would then draw from the low pressure receiver to supply air to the system. As the pressure in the receiver is higher than the atmospheric pressure, the power required for compression of the air to pressure P_2 in relation to the open pneumatic system is reduced. Pu and Weston [5] point out the fact that the steady state pressure is the function of pressure and temperature in the active chamber of the cylinder, and that it is regulated by the servo-valve. For such a system, pressure in the steady state is given by:

$$P_{high}^{ss} = 0{,}8075\, P_s\,, \tag{3}$$

gdje su dobavni tlak P_s i tlak u stacionarnom stanju

with supply P_s and steady state P_{high}^{ss} pressures taken in

P_{high}^{ss} uzeti u apsolutnim iznosima. Pod pretpostavkom da pogon ima konstantnu brzinu, te da nema vanjskog opterećenja, vodeća jednadžba gibanja postaje:

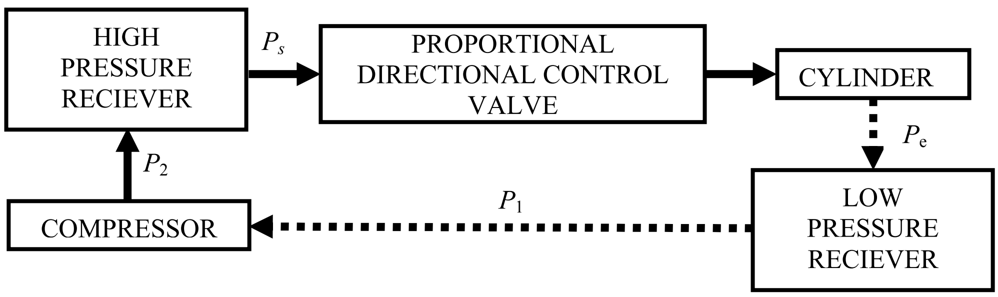
absolute terms. Assuming that the system has a constant speed, and that there was no external load, the leading equation of motion becomes:

$$A\left(P_a - \mathrm{P_b}\right) = f_v\,\dot{y} - \mathrm{F_{cd}}\,sign\left(\dot{y}\right). \tag{4}$$

Iz jednadžbe je vidljivo da tlak u komori koja se odzračuje (P_b) u stacionarnom stanju ovisi o viskoznom f_v i dinamičkom Coulombovu F_{cd} trenju u cilindru. Razina dobavnog tlaka i vrijednosti trenja u kombinaciji s karakteristikama ostalih uređaja određuju hoće li odzračivanje biti prigušeno. Kod većine industrijskih pneumatskih uređaja, ako je dobavni tlak 7 bara, tlak stacionarnog stanja iznosi približno 5,5 bara, a za razumne uvjete trenja tlak odzračivanja je prigušen (tj. $P_b > P_{atm} / 0{,}528$).
Prema tome, tlak odzračivanja (tj. P_e) nema utjecaja na brzinu aktuatora sve dok je izlazni protok prigušen. Dovedena snaga aktuatoru kao umnožak sile i brzine ostaje ista, pa će prema tome istu snagu dati i aktuator. Ušteđena energija je ona potrebna za pogon kompresora. Ako se uporabi zatvoreni strujni krug, maseni protok potreban sustavu isti je onome za otvoreni krug, samo se umjesto kompresije zraka od P_{atm} na P_2 zrak komprimira od P_1 na P_2 (gdje je P_1=P_e, pri čemu je $P_{e>} P_{atm}$), što će uštedjeti snagu na kompresoru, a snaga odaslana aktuatoru ostaje ista.

From the equation it is evident that the pressure in the vented chamber (P_b) in the steady state depends on viscous and dynamic Coulomb friction in the cylinder. The level of the supply pressure and values of friction in combination with other characteristics of the device determines if the exhaust is chocked. In the majority of industrial pneumatic equipment, if the delivery pressure is 7 bars, the pressure of the steady state is approximately 5.5 bars and with the reasonable requirements of friction, the exhaust would be chocked (i.e., $P_b > P_{atm} / 0.528$).
Thus, exhaust pressure (i.e., P_e) has no effect on the rate of the actuator until the exit flow remains choked. The power delivered to the actuator as a product of the applied force and velocity remains the same, therefore the same work can be performed by the actuator. Saved energy is that required to drive the compressor. If the closed circuit system is utilized, the mass flow rate required by the system is the same as that for the open system, but instead of compressing air from P_{atm} to P_2, it is compressed from P_1 to P_2 (where P_1=P_e with $P_{e>} P_{atm}$). This would be an energy savings for the compressor without sacrificing the power delivered to the actuator.

$$\dot{W}_{cyl} = F_{app}\, v = \left(A_a\, P_a - A_b\, P_b\right)\dot{y}. \tag{5}$$



Slika 1. Koncept zatvorenog pneumatskog kruga
Figure 1. Concept of the close circuit pneumatic system

2.1. Stupanj iskoristivosti sustava

Druga je mogućnost analize ušteđene energije u zatvorenom pneumatskom sustavu utvrđivanje njegove učinkovitosti. Da bi se usporedio stupanj iskoristivosti otvorenoga nasuprot zatvorenome sustavu, polazi se od sljedeće definicije:

2.1. System efficiency

Another possibility for analysis of saved energy in a closed pneumatic system is to determine its effectiveness. To compare the efficiency of open versus closed system, we start from the following definition:

$$\eta_{sys} = \frac{\dot{W}_{cyl}}{\dot{W}_{comp}}. \tag{6}$$

Ako se snaga, potrebna za kompresiju $\dot{W}_{comp}$, temelji na

If the power required for compression $\dot{W}_{comp}$ is based on politropi, prema Brownu [5], a obzirom na pozitivni regulirajući signal, jednadžba (6) postaje:

the polytrophic compression that is given by Brown [5], and considering a positive control signal, the equation (6) becomes:

$$\eta_{sys} = \frac{\left(1 - \frac{A_b}{A_a}\frac{P_b}{P_a}\right)T_a}{\frac{n}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]T_1}, \tag{7}$$

pri čemu se uzima da je stupanj iskoristivosti kompresora 100 %, a $P_{a,b}$ su tlakovi u komorama cilindra, $A_{a,b}$ površine poprečnih presjeka klipa, n koeficijent politrope, a $T_{1,a}$ odgovarajuće apsolutne temperature. Sve dok je izlazni protok prigušen, brojnik jednadžbe (7) ostaje isti. No, ako sustav djeluje kao zatvoren, tlak usisa P_1 se povećava. Stoga se nazivnik jednadžbe (7) smanjuje, a stupanj iskoristivosti sustava raste.

where the compressor efficiency is taken as 100 %, and $P_{a,b}$ are pressures in cylinder chambers, $A_{a,b}$ the cylinder bore areas, n the polytrophic coefficient and $T_{1,a}$ the appropriate absolute temperature. As long as choked exit flow conditions exist, the numerator of the equation (7) remains the same. But, by operating as a closed system, the intake pressure P_1 is increased. Therefore the denominator of equation (7) is reduced and the overall system efficiency is greater.

2.2. Potencijalni stupanj iskoristivosti

2.2. Potential efficiency

Sanville [3] je definirao potencijalnu energiju komprimiranog zraka kao rad koji se može dobiti u idealnom pogonu:

Sanville [3] defines the available energy in compressed air as the work that can be obtained from an ideal actuator:

$$W = (P_2 - P_1)V_s, \tag{8}$$

gdje su P_1 i P_2 tlakovi na objema stranama cilindra, a V_s je odgovarajući volumen komore cilindra. Srednja snaga za jedan ciklus je:

where P_2 and P_1 are the pressures on either side of the cylinder and V_s is the volume swept by the piston. The average power for one cycle is:

$$\dot{W}_{pot} = (P_2 - P_1)Q. \tag{9}$$

Koristeći umjesto volumnog protoka maseni protok, jednadžba (9) može se napisati kao:

Using mass flow instead of volumetric flow, the equation (9) can be written as:

$$\dot{W}_{pot} = \left(1 - \frac{1}{r}\right)R T_2 \dot{m}, \tag{10}$$

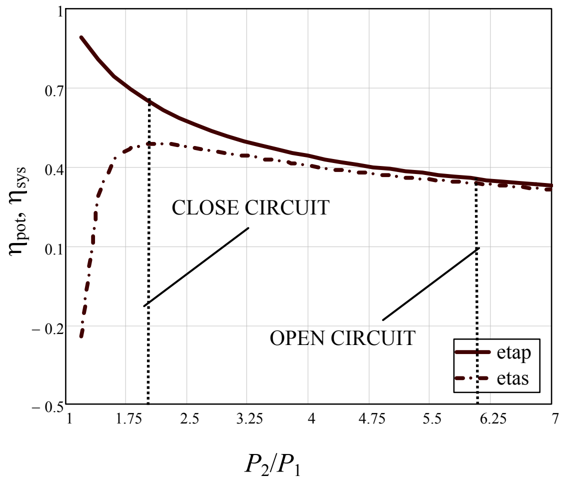
gdje je r omjer tlakova P_2/P_1. Ako se kvocijent potencijalne energije i snage potrebne za kompresiju definira kao potencijalni stupanj iskoristivosti, tada je:

where r is the pressure ratio P_2/P_1. If the quotient of the potential energy and power required for compression defines potential efficiency, then:

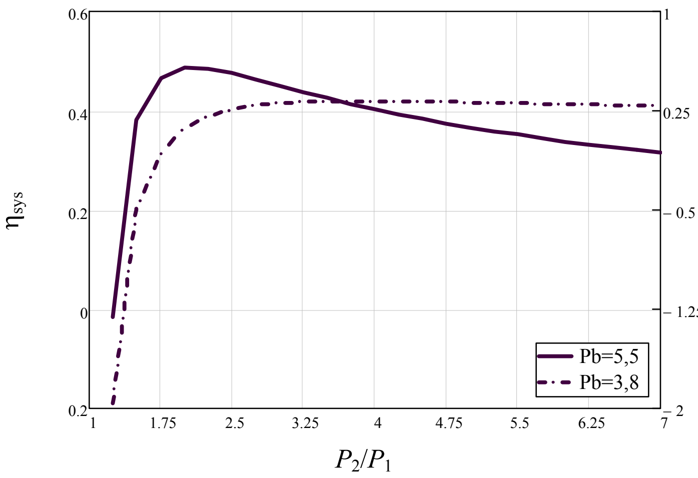
$$\eta_{pot} = \frac{n-1}{n}\frac{1 - \frac{1}{r}}{r^{\frac{n-1}{n}} - 1}\frac{T_2}{T_1}. \tag{11}$$

To predstavlja mjeru termodinamičke sposobnosti kompresora. Sanville je objavio da je postigao potencijalni stupanj iskoristivosti (za $n = 1{,}25$ i $T_1 = T_2$) od 39 % za otvoreni i 71 % za zatvoreni pneumatski krug.

This represents the measure of the thermodynamic performance of a compressor. Sanville reported potential efficiencies (with $n = 1.25$ and $T_1 = T_2$) of 39 % and 71 % for the open and closed circuits respectively.



a)



b)

Slika 2. a) Potencijalni stupanj iskoristivosti sustava, b) Stupanj iskoristivosti sustava za visoki i niski tlak u stacionarnom stanju

Figure 2. a) Potential and system efficiency, b) System efficiency for high and low steady state pressures

Za dijagrame prikazane na slici 2a korišteni su rezultati eksperimentalnih istraživanja u [4] i jednadžbe (7) i (11). Vidljivo je da otvoreni pneumatski sustav ima stupanj iskoristivosti sustava oko 30 %, dok se za zatvoreni krug potencijalni stupanj iskoristivosti povećava na 60 %, a za cijeli sustav na 50 %. Ti rezultati vrijede za visoki tlak u stacionarnom stanju od 5,5 bara. Slika 2b prikazuje usporedbu stupnja iskoristivosti sustava za visoki tlak u stacionarnom stanju od 5,5 bara i za niski tlak od 3,8 bara. Tlak usisa kompresora (tlak u niskotlačnom spremniku) je P1 a izlazni tlak iz kompresora je P_2, koeficijent politrope je n = 1,4 a $T_1 = T_2$. Uz to je vidljivo da je kod nižeg tlaka u stacionarnom stanju, počev od omjera tlakova P2/P1 = 2,5, stupanj iskoristivosti sustava konstantan, dok kod višega stacionarnog tlaka stupanj iskoristivosti naglo opada.

3. ZAKLJUČAK

Mnoge analize pokazuju da sustav zatvorenoga pneumatskog kruga omogućuje povećanje stupnja iskoristivosti sustava, a posebno uz primjenu servosustava, bez narušavanja dinamičke stabilnosti u domeni tlakova u stacionarnom stanju. Ta činjenica zasjenjuje problem specijalnog tipa kompresora, dodatnog spremnika zraka te dodatnih vodova i elemenata. Prednosti su, uz veću učinkovitost, smanjenje buke prilikom odzračivanja i smanjenje učinka onečišćenja vodom i uljem. Dodatni troškovi mogu se smanjiti jer kompresor može biti manjeg kapaciteta, a najvažnije je da se troškovi za utrošenu energiju smanjuju. Uz to zatvoreni sustav, kao i hidraulički, može biti neovisan što je vrlo značajno za male korisnike kao što su roboti i manipulatori.

For the diagrams shown in Figure 2a., the results of experimental research in [4] and equations (7) and (11) were used. It is clear that the open pneumatic system has an efficiency of about 30 %, while for the closed circuit potential efficiency increases to 60 % and system efficiency to 50 %. These result are valid for a high steady state pressure of 5.5 bar. Figure 2b. shows a comparison of the efficiency for high pressure in the steady state of 5.5 bar and a low pressure of 3.8 bar. The intake pressure for the compressor (the pressure in low pressure receiver) is P_1 and the outgoing pressure from the compressor is P_2, the polytrophic coefficient n = 1.4 and $T_1 = T_2$. In addition, it is evident that at a lower steady state pressure starting from the pressure ratio P_2/P_1 = 2.5 the system efficiency is constant, while at a higher steady pressure the efficiency rapidly decreases.

3. CONCLUSION

Many analyses show that the closed circuit pneumatic system enables an increase in the system efficiency, especially with the use of servo-systems, without impairing dynamic stability in the steady state domain of pressures. That fact overshadows the problem of the special construction of the compressors, and the additional receiver and extra lines and fittings. The advantages, besides the greater efficiency, are reduction of the noise emerging from the exhaust flow to the surroundings, and reduction of the effect of water and oil contamination. The additional costs can be reduced because the main compressor can be smaller, and energy costs are reduced. In addition, a closed circuit system, like a hydraulic system, can be independent, which is important for end users such as robots and manipulators.

4. POPIS OZNAKA / 4. LIST OF SIMBOLS

površina poprečnog presjeka klipa cilindra	A -	m^2	cylinder bore area
površina poprečnog presjeka izlaznog otvora razvodnika	A_v -	m^2	valve port area
koeficijent istjecanja proporcionalnog razvodnika	C_d -	$m^3/(sN^{1/2})$	proportional valve discharge coefficient
koeficijent masenog protoka	C_{mb} -	$N^{1/2}K^{1/2}s^2/m^4$	mass flow coefficient
dinamičko Coulombovo trenje	F_{cd} -	N	dynamic Coulomb friction
viskozno trenje	F_v -	N	viscous friction
koeficijent viskoznog trenja	f_v -	$N/(ms^{-1})$	viscous friction coefficient
maseni protok	$\dot{m}$ -	kg/s	mass flow
koeficijent politrope	n -		polytrophic coefficient
tlak na ulazu u aktuator	P_b -	Pa	upstream pressure
tlak u stacionarnom stanju	P_{high}^{ss} -	Pa	steady state pressure
dobavni tlak	P_s -	Pa	supply pressure
volumni protok	Q -	m^3/s	volumetric flow
omjer tlakova	r -		pressure ratio
univerzalna plinska konstanta	R -	J/ (kgK)	universal gas constantans
temperatura	T -	^oK	temperature
potencijalna energija, rad	W -	Nm	potential energy, work
snaga	$\dot{W}$ -	W	power
brzina gibanja klipa	$\dot{y}$ -	m/s	piston velocity
normalizirani regulacijski signal	z -		normalized control signal
stupanj iskoristivosti	η -		efficiency

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