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Experimental analysis of tribological behaviour of advanced composite spools used in commercial pneumatic spool valves

Marko Simic *, Niko Herakovic [1]

Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, 1000 Ljubljana, Slovenia

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ABSTRACT

In this paper, we present the study of the tribological conditions inside a pneumatic valve. The main goal is to analyse the friction behaviour of new pneumatic valve spools made of advanced composite materials in detail by using the experimental approach. The spools are intended to be used without any lubricant in the valve, therefore experimental tests are carried out in dry working conditions. On the basis of the measured force curves the static and dynamic friction forces are determined as well as the friction forces depended on the spool velocity. Finally, the spool with the best friction characteristics, the minimal friction forces, is defined. Also, the machinability of the composite spools is considered.

1. Introduction

The performance of pneumatic components depends on the quality and type of their parts, materials, surface quality and surface texture, machining tolerances, etc. In newer high performance industry applications such as pneumatic servo position cylinders and pneumatic muscles used in robots to perform the accurate position control, new advanced pneumatic components with better characteristics are required. Here, the step response of the pneumatic valve (PV) has a major impact on the improvement of the non-linear behaviour of the servo pneumatic system. The new systems also require low energy consumption components. These valve characteristics can be improved by using new materials and new sophisticated valve actuators [1]. In many environments, neither grease nor oil particles are permissible. Therefore, a thorough knowledge of the interaction between the seal and the sliding counterface is required when designing pneumatic components.

Author in [2] describe the methodology how to design an air-lubricated seals for pneumatic cylinders. The study shows that a proper seal and pneumatic cylinder design (air-lubricated seal) can reduce the friction forces. In this way the pressurised air is used as lubricant instead of conventional lubricant. Authors in [3] investigated proper control algorithm with pulsation signal in order to reduce the static friction inside the pneumatic valve. The stick–slip effect between the spool and the seals is reduced significantly. The importance of seal geometry, material, and roughness of the counterpart (cylinder bore) was investigated in [4,5] by means of experimental friction measurements on pneumatic piston seals. In [6,7,8], friction force measurements were carried out on commercial pneumatic cylinders and seals by means of experimental tests and numerical approach; the findings made it possible to develop pneumatic cylinder friction laws and new low-friction seal geometries as well as new numerical models describing the friction behaviour. A detailed analysis of the seal–counterface contact provided information on seal behaviour in terms of sealing capability, friction, and wear [9–12]. In these studies, experimental tests on pneumatic and hydraulic piston seals were performed using photoelastic methods [9], pressure-sensitive films [10,11], and interferometric techniques [12]. Surface treatment of elastomers and surface texturing as a means of improving tribological properties by reducing friction, wear, and the noise of sliding sealing systems were addressed in [13–17], where elastomer surface conditioning with thin-film or thick-film coating and solid lubricant embedded in thermoplastic polyurethane seals and flat samples was investigated. In [18–20], the cross-section of hydraulic and pneumatic elastomer seals was redesigned and optimised on the basis of a numerical analysis and experimental tests, reducing friction to improve performance. These studies were carried out in nominal mounting conditions without considering the effects of machining tolerances which are dependent on the machinability of the products.

* Corresponding author. Tel.: +386 14771727.
E-mail addresses: marko.simic@fs.uni-lj.si (M. Simic), niko.herakovic@fs.uni-lj.si (N. Herakovic).
[1] Tel.: +386 1 4771 726.

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Nomenclature

A_{sum}	the size of all seal contact areas [m^2]
A_i	the size of an individual seal contact area [m^2]
d	the diameter of the spool hole [m]
D	the diameter of the pneumatic spool [m]
D_{p1}	the spool diameter of prototype 1 [m]
D_{p2}	the spool diameter of prototype 2 [m]
D_{ref}	the reference spool diameter [m]
F_{tr}	the overall friction force [N]
$F_{tr,i}$	the friction force at local contact [N]
$F_{n,i}$	the normal component of the friction force at local contact [N]
$F_{tr}(t)$	the friction force curve as a function of time [N]
$F_{tr,m}(t)$	the measured friction force curve as a function of time [N]
$F_{stat,i}$	the static friction force [N]
$F_{dyn,avg,i}$	the average dynamic friction force [N]
$F_{dyn,min,i}$	the minimal dynamic friction force [N]
$F_{stat,Al}$	the static friction force of aluminium spool [N]
$F_{dyn,avg,Al}$	the average friction force of aluminium spool [N]
$F_{dyn,min,Al}$	the minimal friction force of aluminium spool [N]
Sol_1, Sol_2	the solenoid actuators of pilot stage pneumatic on/off valves
R_a	the surface roughness [m]
U_1, U_2	the control signals of solenoid actuators [V]
x_p	the spool stroke [m]
$x_p(t)$	the spool stroke as a function of time [m]
$\dot{x}_p$	the spool velocity [m/s]
t	time [s]

Greek symbols

μ_i	the friction force coefficient at local contact [/]

Acronyms

ABS	acrylonitrile butadiene styrene
Al	aluminium
BDMA	benzyl dimethylamine
ET	engineering thermoplastics
Fcycle	friction force for one measuring cycle
FEA	finite element analysis
FWC	filament-wound composites
HNBR	hydrogenated nitrile butadiene rubber
LC	laminated composites
NBR	nitrile butadiene rubber
NI	National Instruments
PC	Polycarbonate
PES	Polyester
PV	pneumatic valve
3D	three-dimensional (model)

On the basis of the above cited literature it can be seen that most studies are focused on the development of new sealing components in pneumatic actuators (cylinders). Some of the authors analysed the friction behaviour of pneumatic valves, but again, the seals represent the main focus of the studies. There is no paper describing the spools made of different materials and their characteristics which might also influence the friction behaviour inside the pneumatic valves. Therefore, the study presented in this paper focuses on the much more important role of the pneumatic valve spool in order to understand the friction behaviour inside the pneumatic valves. Several spools in a pneumatic valve made of new advanced materials are studied to improve the tribological characteristics of the valve, which influences the stability of the behaviour of the pneumatic valve, the dynamic characteristics and the electrical energy consumption.

2. Pneumatic valve and tribological conditions

2.1. Pneumatic valve

The pneumatic valve treated in this study is shown in the photo of Fig. 1. It is a directional spool valve of the ISO 3 5/3 BCC (5 ports, 3 stages) type which is controlled by two on/off pilot stage valves activated with solenoid actuators (Sol_1 and Sol_2).

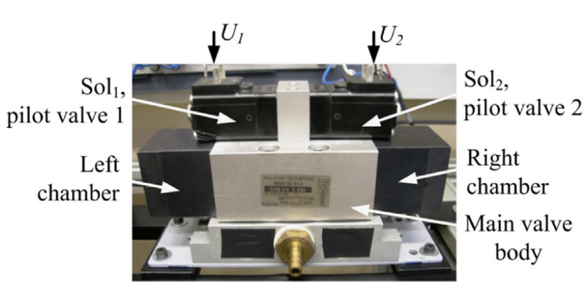

Fig. 1. Pneumatic valve ISO 3 5/3 BCC.

The pneumatic valve has two main parts which have to be analysed and have major effects on the tribological behaviour: the cartridge assembly inserted into the main pneumatic valve body and the valve spool (Fig. 2a). The detailed view of the cartridge assembly with the spool inside is shown in Fig. 2b. The cartridge assembly consists of six NBR (Nitrile Butadiene Rubber) seals, five spacers made of trademark material Lexan 3262R (Polycarbonate-PC with 20% of glass fibres) and two end aluminium covers (Al cover). The spacers assure the exact position of the seals along the valve body to achieve the valve functionality and to prevent the valve internal leakage between control valve chambers. Arrows, shown in Fig. 2b from 1 to 5, presents the valve ports: 1-inlet, 2-working port, 3-exaust, 4-working port and 5-exaust.

The functionality of the valve without air leakage is assured with the proper dimensions and tolerances of the seals and the pneumatic spool. The manufacturer provides the inner and outer diameter tolerance for the NBR seals shown in Fig. 3a. Material characteristics and the type of the seal are: hardness of 80 Shore, tensile strength of 25 MPa, type PNA 28-2 80NBR878. Pneumatic spools should be manufactured within the tolerances presented in Fig. 3b.

2.2. Composite spools

The spools analysed in the experimental study are presented in Table 1. A conventional spool, made of aluminium (Al), is treated as the reference spool while the other spools can be divided into three main groups [21,22]:

- *FWC* - filament-wound composites (spools number 3, 4, 9 and 10),
- *ET* - engineering thermoplastics (spools number 6 and 8) and
- *LC* - laminated composites (spools number 1, 2, 5 and 7).