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Trajectory Tracking Controller of Air Bellow

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Abstract The paper deals with describing of air bellow and designing of control system for its trajectory tracking. A lot of research works were done in the past concerning to pneumatic cylinders and their control systems based on servovalves. This paper investigates unconventional pneumatic actuator – air bellow, which is controlled by two two-way normally closed valves in consideration of expensive servovalves. In the paper air bellow is described as mass-damper-spring mechanical system of 2nd order. The paper also introduces the control system for purposes of trajectory tracking of air bellow top platform. Derived algorithm was experimentally tested on measuring stand while control system consists of PLC B&R X20 in collaboration with input / output measuring card MF634 working through the software Matlab / Simulink. The results show that used methodology is suitable for certain applications, where it is not necessary to achieve high precise of positioning and also there is requirement to stiffness of mechanical system.

Keywords: *air bellow, controller, PLC, pneumatic system, stiffness, trajectory tracking*

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1. Introduction

One of the first work concerning pneumatic servo control system is described by Shearer in [1], which became the base for many other researches in this area. Nowadays, pneumatic servo control systems use servovalves to control airflow into and out to pneumatic actuator. The works like [2] or [3] dealt with servocontrol via spool-type four-way servovalves, [4] dealt with control by flapper or jet-pipe servovalves. These researches showed that utilization of servovalves in pneumatic servo systems is good solution for precise positioning. However, using of this solutions can be difficult from the view of economy.

Consider kinematically redundant mechanism which uses pneumatic actuators. In general, kinematically redundant mechanism is mechanism which has more degrees of freedom as necessary to perform their required task. In order to control of this kinematically redundant mechanism it would be necessary to have a large amount of servovalves those price is not low. For high number of DOF it would not effective solution.

From this reason we have investigated different way of control of pneumatic actuator. Instead of servovalves we use two-way normally closed On / Off valves SX11F-DH from the company SMC. These valves work with frequency 350 Hz what is sufficient frequency for our purposes. These valves will be uses to control of unconventional pneumatic actuator – air bellow, which works like single-acting pneumatic cylinder.

The paper is divided as follows. The section 2 describes air bellow as mass-damper-spring system as mechanical system of 2nd order. Third section introduces control system for trajectory tracking task or air bellow top platform. Fourth section deals with experimental verification of designed control system and show results of the experiments. In the last section the results are discussed as well as future work is mentioned.

2. Air Bellow

In many researches were described control systems for pneumatic cylinders. Our research deals unconventional pneumatic actuator – air bellow also known as air spring. Within this paper the position of air bellow top platform will be controlled by two On / Off, 2/2 NC (normally closed) valves. Air bellows were investigated in several works describing the active suspension, for example [5,6,7,8]. The air bellow working with reservoir are modelled in [9,10]. The results of these researches, which investigated the behaviour of air bellows show that air bellow can be modelled as mass-damper-spring mechanical system what is a system of 2nd order.

The air bellow works like single-acting pneumatic cylinder. It has only one input which serves for supply as well as exhaust orifice. Consider extension or shortening of air bellow from its steady state by external forces. When these forces are canceled the bellow tries to obtain its steady state like single-acting pneumatic cylinder.

In this research we have used air bellow Dunlop 2 ¾ x 3 which works with pressure up to 10 bar. Diameter of the bellow is 78 mm, static height 119 mm and maximum height is 145 mm. Mentioned air bellow has top and bottom platform made from aluminum, see Figure 1.

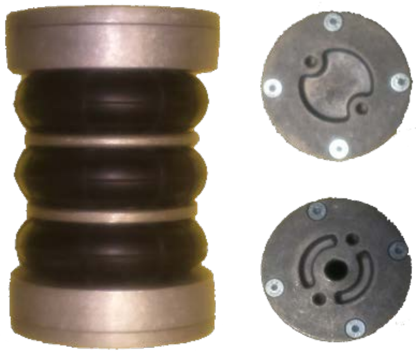

Figure 1. Air bellow with aluminum platforms

2.1. Identification of Air bellow Parameters

To derivate the control system of air bellow for precise positioning of the top platform there should be known the basic constants of the investigated system. Since we consider air bellow as mass-damper-spring mechanical system, we have to know stiffness coefficient k and damping coefficient b .

In general, the stiffness of a spring can be measured by static loading of the spring. So, the air bellow will be loaded while extension of the bellow is measured.

The great advantage of air bellow in comparison with standard steel spring is that air bellow can change its stiffness by changing of inner pressure in the bellow. In other words, by increasing pressure in the air bellow the stiffness of the bellow increases as well. From this reason the measurements of air bellow stiffness will be performed not only with changing load but also with changing inner pressure. The pressure to the bellow will be supplied from the compressor.

During the experiments, the load was changed from 0 to 7 kg and pressure supplied to the bellow was changed from 0 to 6 bar. The measurements were done in steady state. For each changing condition (load, pressure) were done 10 measurements and the average value was computed.

The results of air bellow extension during changing conditions can be seen in the Figure 2.

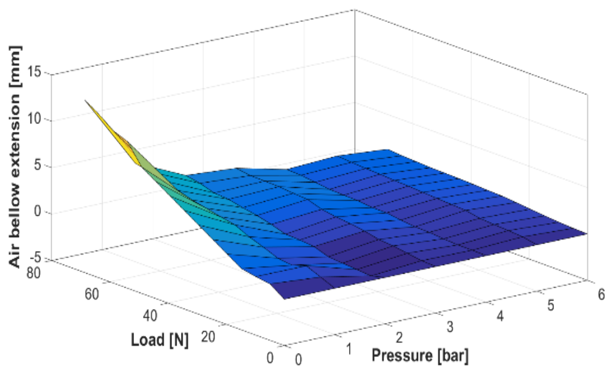

Figure 2. Measured air bellow extension with changing external load and inner pressure in the bellow

From the Figure 2 is obvious that maximal bellow extension is in the case when there is not air supplied to the bellow from the compressor. In other cases when there is 1 – 6 bar in the bellow the extensions are roughly the same despite of increasing load. This is significant property of bellow as actuator. By this way can be changed stiffness of the bellow. [13]

The air bellows can be used as pneumatic actuators in mechanical systems. By changing of inner pressure in the bellow can be changed the stiffness of entire mechanical system. Sometimes it is necessary to have mechanical system more or less springy, what can be achieved by suitable control of inner pressure in the air bellow. From the Figure 2 is obvious that the highest influence to the air bellow extension has supply pressure between 0 – 2 bar.

Considering the steady state, from the equation of motion of mass-damper-spring mechanical system can be determined the stiffness.

$$k = \rho \frac{F}{x} \tag{1}$$

where x is an extension of the bellow, F is load and ρ represents coefficient which considers the pressure in the air bellow. This coefficient is dependent on properties of air bellow (material, dimensions, etc.).

Next parameter which have to be determined is damping coefficient b. This coefficient can be derived from the equation of motion of mass-damper-spring mechanical system.

$$b = \frac{-m\ddot{x} - kx - G}{\dot{x}} \tag{2}$$

where G is force due to gravity which affects the air bellow platform. To measure the damping coefficient b , the bellow will be displaced from its steady state and the kinematic variables $\ddot{x}, \dot{x}, x$ will be measured. According to equation (2) the average value of damping coefficient b can determined.

The experiments were performed by input / output multifunction measuring card MF634 which cooperates with software Matlab / Simulink. For measuring kinematic variables was used ultrasonic sensor.

3. Experimental Model

The position of top platform of air bellow will be controlled by 2 two-way normally closed valves with frequency 350 Hz. These valves are electromagnetic solenoid valves which are activated by voltage 24 VDC.

In the Figure 3 is shown the way of control of air bellow. The extension and shortening of the bellow works as follows. By turning supply valve on, the air flows from compressor to the air bellow while exhaust valve is turned off. By this way the bellow extends. Shortening of the bellow starts when supply valve is turned off while exhaust valve is turned on and the air flows from the bellow to the environment.

For experiments was used PLC B&R X20 cp1584 with analog input card X20 AI4622 and digital output X20 DOF322. The ultrasonic sensor has analog output which is connected to AI4622. Electromagnetic valves are connected to DOF322.

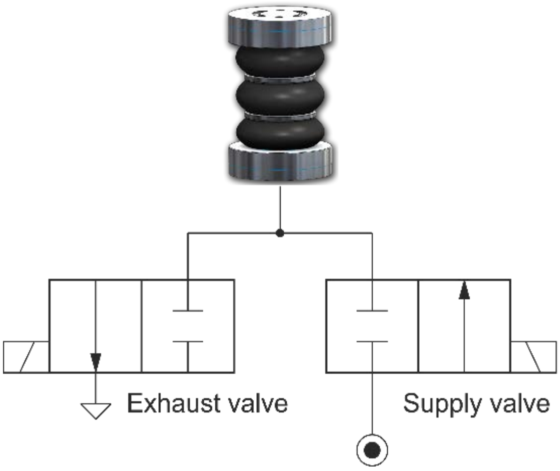

Figure 3. Control of pressure in air bellow by two 2/2 NC valves

For trajectory tracking measurement has been done the measuring stand, see Figure 4. One side of the bellow is fixed to the frame (bottom) while second side can performs linear motion upward. On the top platform of measuring stand is placed ultrasonic sensor. Output signal from the sensor is measured with frequency 100 Hz.

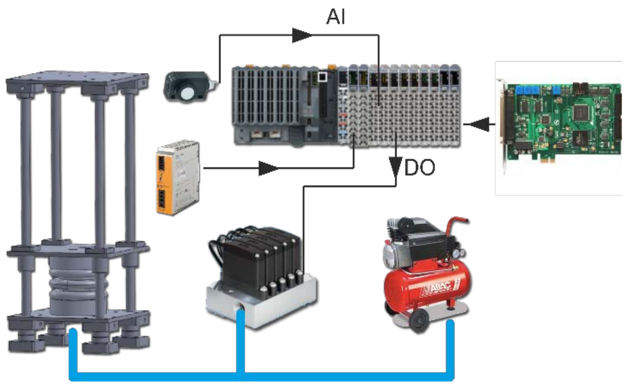

Figure 4. Hardware of control system

The reference trajectory (acceleration, velocity and position) is generated by Matlab / Simulink and transfer to the PLC by measuring card MF634.

For electromagnetic valves has been done special manifold base in order to air can flow to the valves according to requirements of this application.

4. Trajectory Tracking Control System

The main task of our control system is to achieve the motion of air bellow top platform according to changing reference signal. Our system can be described as mass-damper-spring system by following equation.

$$m\ddot{x} + b\dot{x} + kx = p_C S_B - G \tag{3}$$

where p_C is controlled pressure in air bellow and S_B is cross-section of air bellow on which the pressure acts. The aim of this control system is to change the position of air bellow top platform according to required trajectory matrix $\mathbf{X}_d$, which consists of required acceleration, velocity and position.

The control system is based on inverse model [11,14] described by following equation.

$$f' = \ddot{x}_d + K_v \dot{e} + K_p e \tag{4}$$

where

$$f' = \ddot{x} \tag{5}$$

In equation (4) e represents control error and K_p and K_v are constants of the designed controller.

In our case, the precision of trajectory tracking control will dependent on choosing of suitable controller constants and also on knowledge of investigated mechanical system (constants *m*, *b*, *k*). Using the inverse model method should be determination of air bellow constants done responsibly.

Based on above mentioned equations, the trajectory tracking control system can be described following scheme.

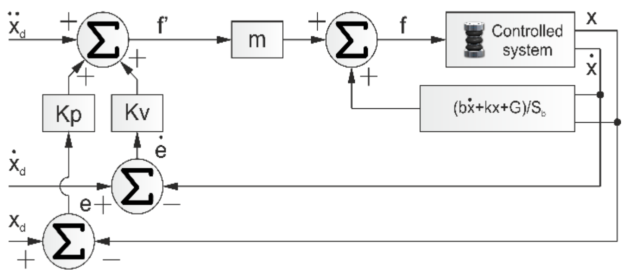

Figure 5. Control system of trajectory tracking

Constants K_P, K_v which are constants of controller were determined experimentally. By sum of the term $f' x$ and term $(b\dot{x} + kx + G) / S_B$ one obtain control input the controlled system.

Next point of control system design is consideration that air bellow will behaves like single-acting pneumatic cylinder. Based on this consideration we can write equation [1].

$$\dot{p} = \frac{Rkt\dot{m}}{V} - \frac{pk\dot{V}}{V} \tag{6}$$

where p is pressure in the bellow, V is volume of air in the bellow and $\dot{p}$ and $\dot{V}$ are their derivatives, R is gas constant, k is specific heat ratio of air, T is temperature of compressed air and $\dot{m}$ is mass airflow.

The pressure in air bellow is controlled by two 2/2 NC valves which work in On / Off regime. From this reason, for pressure control have to be used PWM control. By considering the properties of an air described by equation (6), the duty cycle can be expressed as [12,15]

$$d = \begin{cases} G\dfrac{T}{p\gamma_1} \leftarrow G \geq 0 \\ G\dfrac{T}{p\gamma_2} \leftarrow G < 0 \end{cases} \tag{7}$$

where d is duty cycle, T is period of PWM signal. Parameters γ_1 and γ_2 are experimentally determined parameters for supply and exhaust state.

The energy flow G can be expressed as.

$$G = kRT\dot{m} = K_V \dot{e}V + K_p eV + pk\dot{V} \quad (8)$$

Duty of PWM signal changes from 0% to 100%. In other words, by duty of PWM signal the time of electromagnetic valve in regime – On is determined.

5. Experiments

The control system derived in previous section is now implemented to PLC B&R X20 cp1584. The loop for ultrasonic sensor evaluates analog signal from sensor as well as determine control error and its first derivative. The second loop running in PLC evaluates necessary control signal to the mechanical system and also converts it to the PWM signal. This loop works with frequency 250 Hz.

In the Figure 6 the measuring stand is shown.

Figure 6. Measuring stand for air bellow with ultrasonic sensor, fixed bottom platform, moving top platform

The distance between ultrasonic sensor and top platform on air bellow in steady state is 207 mm. The reference position changes according to function *sin* from value 207 mm up to 225 mm.

In the Figure 7 is shown the result from the experiment.

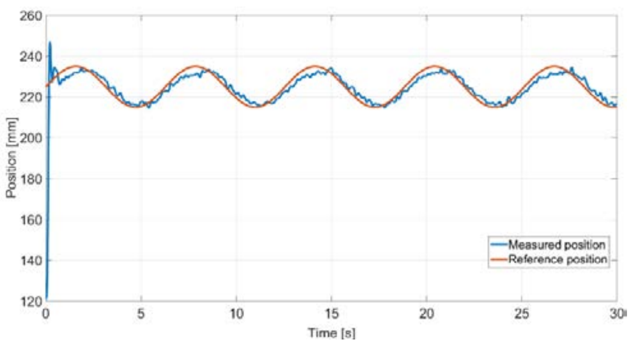

Figure 7. Experimentally measured position of air bellow top platform compared with reference signal

From the several experiments was obvious that trajectory tracking in downward direction has more smoothly course in comparison with upward direction.

6. Conclusion

Conventional approach to position control of pneumatic actuator is by using servovalves. This paper deals with control of nonconventional pneumatic actuator – air bellow which is controlled by two 2/2 NC On / Off electromagnetic valves with frequency 350 Hz. To design appropriate control system there should be known basic parameters of air bellow. Air bellow can be described as mass-damper-spring mechanical system of 2^{nd} order. In the paper the basic parameters of bellow are determined experimentally. From the measurement of air bellow stiffness is obvious that stiffness changes significantly especially in the case when there is any or small inner pressure in the bellow. By supplying the inner pressure from value 2 – 6 bar the extension of the bellow increases slightly.

In the next section the control system for trajectory tracking is derived. The control model is based on inverse model. Applied pneumatic electromagnetic valves work in regime On / Off and therefore PWM control is used.

Derived control system was experimentally verified on measuring stand. The results show that error during trajectory tracking is roughly 2 mm.

Acknowledgements

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