Australian Journal of Basic and Applied Sciences, 3(2): 440-454, 2009
ISSN 1991-8178

A Review of Pneumatic Actuators (Modeling and Control)

Hazem I. Ali, Samsul Bahari B Mohd Noor, S. M. Bashi, M. H. Marhaban

Department of Electrical & Electronic Engineering, Faculty of Engineering,
University Putra Malaysia.

Abstract: The pneumatic actuator represents the main force control operator in many industrial applications, where its static and dynamic characteristics play an important role in the overall behavior of the control system. Therefore improving the dynamic behavior of the pneumatic actuator is of prime interest to control system designers. This paper is a review of literature that related of the pneumatic actuator systems. In particular, the innovations in different control strategies applied to pneumatic actuators along with the modeling, controlling and simulation techniques developed for different applications of pneumatic actuators are reviewed. The review concentrates also on the analysis, investigation, performance, practical constraints, nonlinearities, uncertainties and the new applications of the pneumatic actuators.

Key words: -Pneumatic actuators, Modeling, Nonlinear systems, Uncertain systems.

INTRODUCTION

Most of the earlier pneumatic control systems were used in the process control industries, where the low-pressure air of the order 7-bar was easily obtainable and give sufficiently fast response. Pneumatic systems are extensively used in the automation of production machinery and in the field of automatic controllers. For instance, pneumatic circuits that convert the energy of compressed air into mechanical energy enjoy wide usage, and various types of pneumatic controllers are found in industry. Certain performance characteristics such as fuel consumption, dynamic response and output stiffness can be compared for general types of pneumatic actuators, such as piston-cylinder and rotary types. Figure (1a) and (b) show the two types of pneumatic actuators (Sorli *et al.,* 1999). The final decision on the best type and design configuration for pneumatic actuator can be made only in relation to the requirements of a particular application. The pneumatic actuator has most often been of the piston cylinder type because of its low cost and simplicity (Tablin *et al.,* 1963). The pneumatic power is converted to straight line reciprocating and rotary motions by pneumatic cylinders and pneumatic motors. The pneumatic position servo systems are used in numerous applications because of their ability to position loads with high dynamic response and to augment the force required moving the loads. Pneumatic systems are also very reliable (Clements and Len, 1985).

The open literature surveyed showed a wide spectrum of new applications of pneumatic servos such as milling machines, robotics, and advanced train suspension. Therefore, the surveyed literature reported is subdivided into three main groups. The first group is concerned with various applications of pneumatic actuators. The second group includes the theoretical, experimental approaches for modeling the pneumatic actuator. The third group is related with the control strategies applied to pneumatic actuators.

Pneumatic Systems Attributes:

Pneumatic systems have many attributes that make them attractive for use in difficult environments: gases are not subjected to the temperature limitations of hydraulic fluids; the actuator exhaust gases need not be collected, so fluid return lines are unnecessary and long term storage is not a problem because pneumatic systems are virtually dry and no organic materials need be used. In addition, the pneumatic actuator has a lower specific weight and a higher power rate (torque-squred to inertia ratio) than an equivalent electromechanical actuator. In some cases, a pneumatic system may provide a significant weight advantage. In short duration missile applications, the weight of a self-contained solid propellant pneumatic servo may be half that of an equivalent self contained hydraulic system. Also the pneumatic actuators have many merits such as easy maintenance and handling, relatively simple technology and low cost, clean, safe and easy to installed (Tablin *et al.,* 1963).

Corresponding Author: Hazem I. Ali, Department of Electrical & Electronic Engineering, Faculty of Engineering, University Putra Malaysia.
E-mal: hazemcontrol2001@yahoo. com, samsul, {senan,hamiruce} @ eng. upm. edu.my

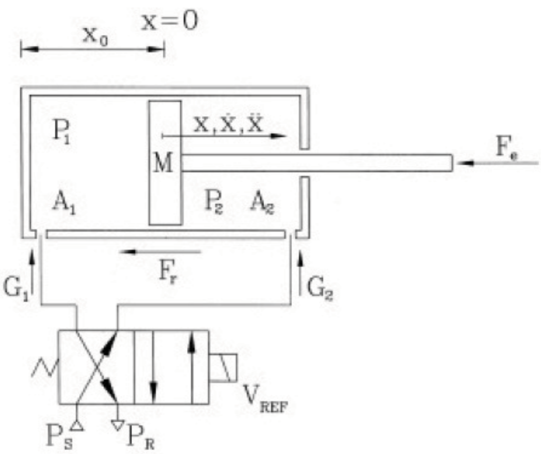

Fig. (1 a): Double acting linear pneumatic actuator.

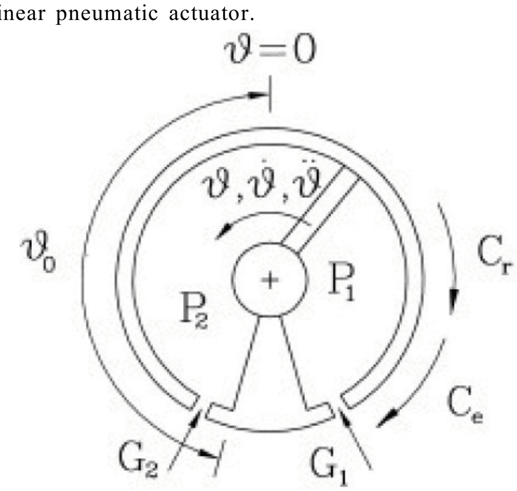

Fig. (1b): Vane rotary pneumatic actuator.

Pneumatic Actuators: Applications and Related Work:

Pneumatic servos have advantages over hydraulics in high temperature and nuclear environments. The actuator, rather than the servo valve, generally limits system response and stiffness. Where simplicity and cost are paramount, the piston cylinder is probably the best choice. But if minimum fuel consumption is desired rotary type of motor is indicated. (Taplin *et al.,* 1963). also have been shown the rotary servo has nearly twice the band pass of the piston cylinder servo. This result is typical for many applications. In short duration missile applications, the weight of a self-contained solid propellant pneumatic servo may be half that of an equivalent self contained hydraulic system. Where a pneumatic system is to replace a heavier hydraulic system, maximum dynamic response and output stiffness are essential. The outstanding difference between pneumatic and hydraulic systems arises from the low bulk modulus of the pneumatic working medium. The bulk modulus of a gas is p, where hh is the ratio of specific heats for the gas and p is the instantaneous pressure. This is the major obstacle in achieving a high response pneumatic system.

Several countries have been investigating and developing active suspension technologies in order to improve both vertical and lateral ride quality of fast train passenger cars. (Cho *et al.,* 1985). investigated the use of actively controlled pneumatic actuators in parallel with conventional passive suspension to improve vehicle dynamics. The use of pneumatic actuators for vehicle active suspension reduced the rms car body lateral suspension stroke by 34 percent with a power requirement of 5.7 KW per car.

(Singh *et al.,* 1985). described the design process by which the air brake control valves of heavy and medium duty trucks were centralized modulus. Truck air brake control systems were reviewed and a floor mounted pneumatic application valve acting on a centrally advanced design was developed using dash mounted electrical controls and a floor mounted pneumatic application valve acting on a centrally located electro pneumatic controller. The system performance was demonstrated on an operational truck and tested to the applicable system requirements of federal brake regulations.

Nearly all-modern process plants employ control valves, which use either pneumatic or electric actuators, the choice between the two being normally dictated by the size of the valve, the environment, media and availability of power source. (Clements *et al.,* 1985). have developed dedicated electro pneumatic positioner for a class of process valves. The position uses solid-state electronics to combine the functions of both the electric to pneumatic converter and valve positioner. Such are the savings in size and weight that have been achieved by the use of electronics that the resulting unit is housed in an enclosure small enough to be mounted directly on the actuator, which it is to operate.

(Virvalo *et al.,* 1988). showed that electropneumatic servo systems are viable alternatives to hydraulic systems for control of such machines as robots, but most of the research has been carried out on them using comparatively small cylinders. They have studied the problems involved in using heavier versions and have produced a satisfactory method of coping with the somewhat complex problems involved in designing such systems, since with a few simplifications a nonlinear model of a pneumatic servo system can be built and used to time the regulator.

An interesting pneumatic servomechanism, which employs pulse width modulation driving technique, was reported by (Sano *et al.,* 1988). A new electropneumatic on- off valve with a disk flapper driven by a pulse motor was developed. Experimental tests showed the positioning accuracy and the output power are tolerable but the speed of the response is comparatively less than those of other pneumatic servomechanisms.

The advantages and limitations of the conventional pneumatic cylinder were discussed by (Bird *et al.*, 1985). Recent developments in the design of pneumatic linear actuators have resulted in the production of more compact and better-guided actuators. The author worked on the development of special servo control system and its integration into complete control system. Typical applications of such systems are also given.

(Vincent et al., 1989). investigated an alternative approach to the design of controllers for positioning damping. To avoid conflicting requirements problem associated with traditional state variable feedback design, the design is based on energy methods and is not a full state variable feedback design. The method is illustrated using a low order spring mass example, and the results are compared with a linear quadratic design.

Electrohydraulic and electropneumatic servo drives can provide precise position control for a multitude of industries from textile manufacture to machine tools. A significant application of the latter type was in a universal rotary machining center where the primary requirement was for an increase in both productivity and flexibility. With the advantages of exact positioning at high speed and the ease of machine programming brought about by microprocessor control, complicated three dimensional work pieces can be simultaneously cut, milled, drilled and taped, all in one operation. Another interesting application to pneumatic actuators is that reported by (Ingold *et al.*, 1988). An electropneumatic design was developed and tested to meet the engine characteristics such as startability, load carrying ability, and engine dynamic performance.

As an application of micro-mechanical actuators a new concept for a micro- pneumatically driven actuator has been developed and realized. This actuation principle has several advantages: high energy density, large achievable displacement, high generated forces, excellent dynamic behavior, usage of various fluids as driving medium, usage as final controlling element with continuous action and high design flexibility (Sebastian *et al.,* 2002).

On the other hand, in intelligent soft arm control (ISAC) robot system the pneumatic actuator was used for the position control of a joint. A physical actuator model was designed and used as the basis for a subsidiary torque control. Experiments showed that the static hysteresis nonlinearity of the actuator is less important than the dynamic one. The research focused on the modification of a physical static model and the extension with a dynamic part. The quality of the model was verified by implementing it as a torque controller and running experiments on a testbed (Joachim *et al.,* 2003).

Also the pneumatic actuators are extensively used in conveying systems to transport granular materials. A methodology combining theoretical and experimental techniques for characterizing and predicting the friability of granules in a laboratory scale pneumatic conveying systems was developed by (Pavol *et al.*, 2008). Models of increasing mathematical complexity were used for analysis of experimental data. Firstly, a two dimensional (2-D) computational fluid dynamics (CFD) model of the gas–solid flow within the Malvern Mastersizer laser diffraction equipment was developed to simulate impact of different inlet jet pressures on the flow properties and to calculate average velocity and average volume fraction of particles in the equipment. Secondly, a simple maximum-gradient population balance (MG-PB) mathematical model of breakage was developed.

(Changhoon *et al.,* 2008). developed an efficient robotic deburring method based on a new active pneumatic tool. The developed method considered the interaction among the tool, the manipulator and the workpiece and couples the tool dynamics and a control design that explicitly considered deburring process information. The new active pneumatic tool was developed based on a single pneumatic actuator with a passive chamber to provide compliance and reduce the chatter caused by air compressibility. A coordination control method was developed for efficient control of the system, which adopts two-level hierarchical control structure based on a coordination scheme. Robust feedback linearization was utilized to minimize the undesirable effect of external disturbances such as static and Coulomb friction and nonlinear compliance of the pneumatic cylinder stemming from the compressibility of air. The developed coordination control method demonstrated its efficacy in terms of deburring accuracy and speed.

Pneumatic Actuators: Modeling:

Several approaches have been proposed for modeling the pneumatic actuators. One of the widely used methods for finding the mathematical model of the pneumatic actuator is a theoretical analysis. The analysis of pneumatic actuators requires a combination of thermodynamics, fluid dynamics and the dynamics of the motion. For constructing a mathematical model, three major considerations must be involved (French *et al.,* 1988): 1) the determination of the mass flow rates through the valve. 2) the determination of the pressure, volume and temperature of the air in cylinder. 3) the determination of the dynamics of the load. Identification techniques are also used for finding the mathematical model of the pneumatic actuators. Accurate model of pneumatic actuator is an important condition both for control design and for optimizing its operation. This section is concerned with the mathematical modeling, experimental testing and the software tools developed for pneumatic actuator systems.

(Sorli *et al.,*1999). presented two different formulations to model a pneumatic actuator, composed of an actuator and a digital valve. In the first one an air thermodynamic transformation was assumed and the simulation was carried out in the Matlab-Simulink environment, while in the second one also the energy equation was introduced, so that the thermic exchange between the chambers and the external ambient was considered.

A detailed mathematical model of dual action pneumatic actuators controlled with proportional spool valves was developed by (Edmond *et al.,* 2001). Effects of nonlinear flow through the valve, air compressibility in cylinder chambers, leakage between chambers, end of stroke inactive volume, and time delay and attenuation in the pneumatic lines were carefully considered. System identification, numerical simulation and model validation experiments were conducted for two types of air cylinders and different connecting tubes length, showing very good agreement. This mathematical model will be used in the development of high performance nonlinear force controllers, with applications in teleoperation, haptic interfaces, and robotics.

For modeling a pulse width modulation (PWM) based pneumatic systems a state space averaging approach was presented by (Eric *et al.,* 2002). This provided the analytic machinery necessary to remove the discontinuities associated with switching and results in a model tractable to standard nonlinear control design techniques. The control of a single degree of freedom pneumatic positioning system illustrated this technique experimentally.

(Arcangelo *et al.,* 2005). presented an extensive set of experiments and a related mathematical model investigating the dynamics of pneumatic actuators controlled by on-off solenoid valves, whose opening and closing time response is based on a pulse width modulation (PWM) technique. The experimental set-up consists of both commercial electronics and circuits appropriately realized where particular needs are required. As well as providing a highly repeatable set of measurements, valuable for future comparisons, the experimental investigation also provided an appropriate base aimed at testing the performances of the analytical model. The analytical- experimental comparisons showed the ability of the theoretical model to provide an accurate mean expectation of the position of the actuator less than about 2 mm. Such a capability of the model was tested for several operating and initial conditions during the first five cycles. The presented theoretical model dealing with non-linear dynamics phenomena whose behavior is highly transient should be considered an attempt aimed at providing a valuable tool for designing control strategies without the need for expensive physical models.

(Shu *et al.,* 2005). presented a methodology for deriving a nonlinear dynamic model for a pneumatic servo system. The model includes cylinder dynamics, payload motion, friction and valve characteristics. Methods for estimating the model parameters from simple experiments were also described. Experimental results demonstrating the ability of the model to predict the measured piston position and cylinder chamber pressure were included.

(Qinghua *et al.,* 2006). established the dynamic model of FPA (flexible pneumatic actuator), which is a new type of actuators, proposed in Zhejiang University of Technology. The primary factors, which affect the dynamic properties of FPA, are the mass flow of air and the volume of FPA chamber. Simulation results of inflating and deflating process of FPA indicated that the section area of air connector of FPA is proportional to the mass flow of air and affects the dynamic properties greatly. The dynamic response of FPA is rapid, completed within 15 milliseconds.

(Carducci *et al.,* 2006). validated a complete mathematical model of a pneumatic actuator driven by two on/off two ways valves (with Pulse Width Modulation technique) by tuning a number of geometric and functional characteristics and parameters by means of non-linear optimization algorithms. The experimental data were obtained driving the on/off valves with five different duty cycles: 10, 25, 50, 75 and 90% over a period of 20 ms and measuring the actuator position with a potentiometer. In particular experimental apparatus was realized in order to measure valve coefficients in all operative conditions.

(Xue *et al.,* 2007). presented a dynamic model and a design method for an accurate self-tuning pressure regulator for pneumatic pressure load systems that have some special characteristics such as being nonlinear and time varying. A mathematical model was derived, which consists of a chamber continuity equation, an orifice flow equation and a force balance equation of the spool. Based on a theoretical analysis of the system dynamics, a three order controlled auto regressive moving average (CARMA) model was used to describe the practical pressure load systems. Then a linear quadratic Gaussian self-tuning pressure regulator was designed to realize an adaptive control of pressure in the chamber. The Kalman filtering method and the recursive-forgetting factor least squares were adopted to estimate the system parameters and the system states. Experimental results show that the proposed self tuning pressure regulator can be adopted to parameters which vary with such factors as the volume of the chamber and the setting pressure and that better dynamic and static performances can be obtained.

(Nieto *et al.,* 2008). presented an analytical model of pneumatic (air spring) suspensions that is based on an experimental characterization. The suspension consists of three principal parts: the air spring, an auxiliary tank, and a pipe connecting the two. The solution of both the nonlinear model and its linearized version are well in agreement with our experimental measurements of the stiffness, damping factor, and transmissibility for a reasonable operation range of this suspension. It was shown that the dynamic behavior of the air suspension can be made more versatile by a convenient choice of the sizes of the elements, in particular of the air spring and reservoir volumes. On the other hand, reducing the air spring volume increases the stiffness and hence also the highest eigenfrequency. And on the other hand, increasing the reservoir volume reduces the stiffness and hence also the lowest eigenfrequency. The analysis allowed us to propose a practical strategy for the operation of the suspension.

(Burrows *et al.,* 1970). presented a comparison between experimental and theoretical transient and frequency response results for a low-pressure on-off pneumatic servomechanism comprising a polarized relay with dead zone and hysteresis operating a four-way flapper nozzle valve via a torque motor. The effect of dynamic conditions on the valve characteristics was discussed. Position, velocity, and quasi-transient pressure feedback are provided. The effect of dynamic conditions on the valve characteristics is discussed.

(Lee *et al.,* 1993). described an experimental method of determining sliding friction forces in pneumatic actuator. Several empirical and semi-empirical friction models were evaluated using measured friction force data.

(Chitty *et al.,* 1976). described experiments on a low-pressure pneumatic actuator and load. An impulse test was described, in which the transient behavior of a loaded actuator, operating in a particularly simple mode, was observed. The results were used to explain the nature of the expansion and compression process in the actuator and to aid understanding of the effects of position leakage and friction. Numerical values are obtained for the polytropic gas constant and for the friction and piston coefficients.

(Marumo *et al.,* 2004). presented an investigation into the modeling and control of the low speed of an air motor incorporating a pneumatic equivalent of the electric H-bridge. The pneumatic H-bridge had been devised for speed and direction control of the motor. The system was divided into three main regions of low, medium and high speed. The system was highly nonlinear in the low speed region and hence a controller with an ability of intelligence such as a neuro model and controller was proposed.

A digital simulation program to obtain the transient performance and stroking time of a pneumatic actuator and valve combination supplied from a constant pressure source is given by (Bowns *et al.,*1972). In the simulation, the flow characteristics of the valve were incorporated, and two modes of operation were investigated, one with the exhaust end of the actuator initially at supply pressure and the other with it pre-exhausted. Both modes of operation are in common use in pneumatic circuits. The simulation has been checked by careful experimental work, and it has been found that, provided the seal friction is known, the results give a high degree of agreement. Seal friction has been found to be the main indeterminate, and can vary widely between strokes of the same actuator. Lack of knowledge of this is the main obstacle to accurate.

A software tool developed for pneumatic actuator system computer aided simulation and design introduced by (Chen *et al.,* 2003). Pneumatic system components were initially organized into five major classes. Those components were considered as subsystems to a complete pneumatic system and the mathematical models for the individual components were derived which could be combined in different ways to form a complete pneumatic system model. A library was built up to accommodate the five classes of components. Users can pick up different components from the library to formulate a complete pneumatic system based on the design requirements. The complete system dynamic behaviors can then be simulated in different operating modes. The graphic user interface (GUI) and animation techniques were adopted in software design to create a user-friendly environment. Also (Djordje *et al.,* 2008). developed a program support, simulation and the animation of dual action pneumatic actuators controlled with proportional spool valves. Various factors were involved, such as time delay in the pneumatic lines, leakage between chambers, air compressibility in cylinder chambers as well as nonlinear flow through the valve. Taking into account the complexity of the model, and the fact that is described by partial differential equations, it is important to develop the program support based on numerical methods for solving this kind of problems. Simulation and program support in Maple and Matlab programming languages are conducted, and the efficiency of the results was shown from the engineering point of view.

Pneumatic Actuators: The Control Strategies:

The advantages of pneumatic systems are well known as clear, cheap, easily maintained, safe in operation, etc. But for their highly nonlinear properties such as compressibility of medium, friction effect and nonlinearity of valves, pneumatic actuators are seldom used in industrial servo applications. Moreover, some of their properties, e.g., poor damping, low stiffness, and limited bandwidth, are unfavorable in the servo control system design.

Some other difficulties in the control of pneumatic servo systems are the possible presence of unknown disturbances coming from leakage of valves, time-varying payloads, and external perturbations. Besides, uncertainties in system parameters make the controller design problem more challenging (Qiang and Fang, 2006). To cope with some of these problems, several advanced control algorithms have been proposed.

Recent trends within the process industry, and in particular the introduction of smaller and more efficient plant, have brought about increasing occurrences where the response characteristics of commercially available actuators are not able to meet the performance requirements of the plant. It is this latter observation which motivated (French *et al.,* 1988). to apply optimal regulator and sensitivity reduction methods to the design of a control scheme for an electropneumatic quarter-turn actuator which satisfies both the regulatory and the emergency slam shut/open requirements of the modern process application. The controller developed is of a novel structure incorporating a conditioned integrator whose performance depends on an adaptive feedforward element. The new system response time for a full 90 of rotation is about 0.1 seconds, which is extremely fast compared with the original unmodified system of 1.2 seconds.

Microprocessor based controls can be used to produce low cost pneumatic servo drives which could find wide application in manufacturing industries as reported by (Weston *et al.,* 1984). Incorporating digital compensation for system nonlinearities so that, when positioning loads in a point-to-point mode, it is possible to achieve a significant improvement in both the static and dynamic performance of the drive. For the compensation algorithms implemented a theoretical foundation was presented based on a lineraized model of pneumatic drives. Microprocessor based hardware and software were constructed to evaluate performance criteria. This test facility has allowed the software implementation of the compensation algorithms to be refined so that satisfactory performance can be achieved with both translational and rotational drives utilizing various forms of transmission. The test facility has also allowed various control system elements to be evaluated so that pneumatic drives suitable for industrial application, can be specified.

To improve the dynamic characteristic of pneumatic servo drives (Nagarajan *et al.,* 1985). described an approach based on an outer decision loop, which modifies the command issued to an existing closed loop drive. Experimental results are presented which show that the scheme can improve the quality of response in terms of overshoot and positioning time.

(Jihong *et al.,* 1999). proposed an accurate position control strategy for servo pneumatic actuator systems. This control strategy has been applied in combination with a modified PID controller to a pusher mechanism in the packaging of confectionery products. Both the positioning and the time accuracy required by the production task were achieved using such a control strategy.

An investigation into the real time control of an air motor using the concept of a pneumatic equivalent of the electric H-bridge was presented by (Takhi *et al.,* 2001). A radial piston air motor was considered. A pneumatic H-bridge was developed allowing speed and direction control of the motor. Also a PID control strategy was adopted to control the motor speed. Controlling the motor at high and low speeds tested the control strategy. Experimental results showed that a good level of speed control of the motor was achieved, and that the both speed and direction control of the motor is feasible in real time with the pneumatic H-bridge concept.

A robust control method using the dynamic impedance matching method was proposed by Shigeru *et al.,* 1995). This method was presented to make pneumatic actuator robust to load variation so that velocity (or force) output characteristics remain the same under load (or velocity) change. Complete robustness of actuator velocity output applied load requires actuator internal impedance to be strictly zero. Achievement of this condition is actually difficult, due to errors in actuator modeling and insufficient output measurements. However, actuator internal impedance can be made small by using proper feedbacks from two outputs, force and velocity and by supporting the existence of energy dissipating element in environment for system stability. To overcome the problems of the din and vibration that are resulted from the control valve in the pneumatic system, (Morioka *et al.,* 2000). proposed a simple controller structure shown in figure (2) using loop-shaping method. In this design scheme, the change of distance between the pneumatic actuator and the control valves are considered. As a result, the control valves, that are a source of a din and vibration, can be set apart from the pneumatic actuators. The proposed pneumatic servo systems, that can reduce a din and vibration, can be installed in the medical and welfare facilities. At the same time, the proposed control is very simple. Therefore it can be implemented on the cheap one board microcomputer. It also be noted that the proposed method admits the change of the plumbing route. The payload variation and external disturbance uncertainties are not taken in account.

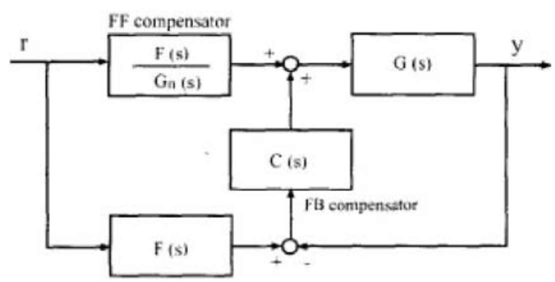

Fig. 2: Two degree of freedom control.

(Junbo *et al.,* 1997). introduced a new control scheme for a pneumatic servo system, which contain unknown parameters, possible nonlinear uncertainties and additive bounded disturbance. The proposed control scheme is essential to achieve robust stability and good performance for the pneumatic servo system. This control scheme not only guaranteed a robust stability, but also provided a control signal which is continuous and globally, uniformly bounded. The output tracking error could not be guaranteed to converge to zero but it was able to converge to globally and exponentially to a residue set whose radius is an arbitrary positive constant. The results of simulation examples and applying to a practical pneumatic servo system proved the effectiveness of this control scheme.

From the hardware point of view numerous researchers have sought to increase the bandwidth in pneumatic servo systems, which are relatively limited, to the maximum by changes to the hardware and the development of evolved control algorithms. (Guido *et al.,* 2004). tackled the problem of broadening the bandwidth of pneumatic servo systems with modulating digital valves. In general, good operation of these systems is determined by the high speed of the valve. In particular the system layout forecast the use of couples of valves in parallel; a valve was supposed to be characterized by low size and very short commutation time, while the other one's main characteristics were large size and long commutation time. The first valve was intended to ensure precision and high command signal update frequency, while the aim of the second valve was to ensure large flow rate when necessary. A control strategy was developed which makes it possible to synchronize operation of the envisaged valves, optimizing both the precision obtainable and the signal update frequency. The method is based on a deep experimental analysis of the valves performance in that kind of application. The final result makes it possible to significantly increase the dynamic performance of pneumatic servo systems with PWM piloted digital valves. Also a modified pulse width modulation (MPWM) valve pulsing algorithm was presented by (Kyoungkwan *et al.,* 2005). to allow on/off solenoid valves to be used in place of costly servo valves. A comparison between the system response of the standard PWM technique and that of the modified PWM technique showed that control performance was significantly increased. A state-feedback controller with position, velocity and acceleration feedback was successfully implemented as a continuous controller. A switching algorithm for control parameters using a learning vector quantization neural network (LVQNN) had newly proposed, which classified the external load of the pneumatic actuator. The effectiveness of this proposed control algorithm with smooth switching control had been demonstrated through experiments with various external loads. An effective and easy way to control the sequence of the pneumatic actuators movement and the states of pneumatic system using programmable controller was presented by (Swider *et al.,* 2005).

In the past few decades, neural network and fuzzy control have been widely used in many applications such as robot, motor, inverted pendulum, cargo ship steering and so on. It is known that the neural network has learning ability and is a good choice for modeling dynamic and complex process. On the other hand the fuzzy control has an important feature where it is a very effective and practical approach to the control of nonlinear, time varying and complex systems via the use a set of linguistic rules, which may come from a control engineer or an experienced operator for a particular system (Nagarajan *et al.,* 1985). So to obtain precise steady state response and good dynamic tracking of the pneumatic actuators, many neural, fuzzy and combination between them were used in literatures.

(Xuesong *et al.,* 2003). studied the modeling and motion control of manipulators driven by single rod pneumatic actuators. The dynamics model of pneumatic manipulator is analyzed profoundly at first. Then aim at the highly nonlinear, strong coupling, time various of pneumatic manipulator dynamics, a new internal model controller for pneumatic robot servo system is presented, which has a three layer feedforward neural network as controller (NNC) and a diagonal recurrent neural network (DRNN) as model predictor (NNM). Computer simulation results indicate that the system has strong robustness and significantly improves the control performance of pneumatic manipulator. As shown in figure (3) NNC and NNM represent neural network controller and neural network model predictor respectively.

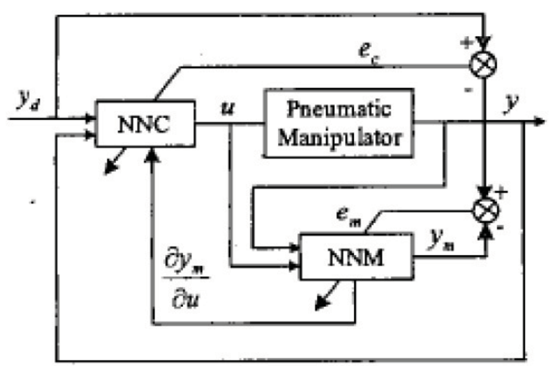

Fig. 3: Internal model controller with DRNN.

(Qiang *et al.,* 2006). presented the results on the modeling and control of a pneumatic system. With Levenberg-Marquardt method, a neural network model, from which a third-order ARX model was derived, has been developed for the pneumatic system. Based on the built ARX model, a direct digital controller was designed with Ragazzini method. To reject external noise, a disturbance observer (DOB) was constructed as shown in figure (4) to improve the control accuracy. The experimental results of the position control for the pneumatic system were given to demonstrate the performance of the DOB-based controller. The accuracy and response speed were satisfactory for both steady state and dynamic tracking.

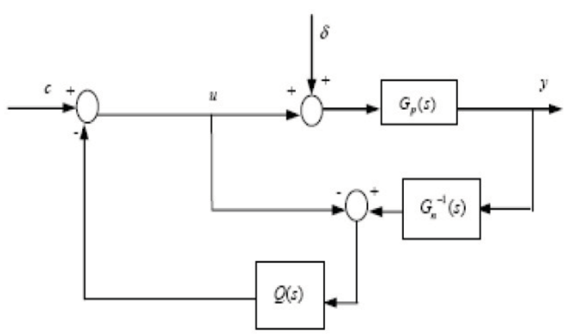

Fig. 4: Continuous time disturbance observer.

(Tu *et al.,* 2006). improved the control performance of 2 axes PAM (pneumatic actuator muscle) manipulator using a nonlinear PID controller. Superb mixture of conventional PID controller and the neural network, which has powerful capability of learning, adaptation and tackling nonlinearity, brings us a novel nonlinear PID controller using neural network. This proposed controller was appropriate for a kind of plants with nonlinearity uncertainties and disturbances. The experiments were carried out in practical 2 axes PAM manipulator and the effectiveness of the proposed control algorithm were demonstrated through the experiments, which suggests its superior performance and disturbance rejection.

(Qiang *et al.,* 2006). presented the favored results of fuzzy neural network (FNN) control for a pneumatic system based on extended Kalman filter (EKF). The back propagation (BP) algorithm was used to update the parameters of membership functions on-line. With the designed FNN controller for the pneumatic system, precise steady state response and good dynamic tracking were obtained.

(Kyoung *et al.,*2007). presented the solution for position control of a robot arm with slow motion driven by two pneumatic artificial muscles. However, some limitations still exist, such as a deterioration of the performance of transient response due to the changes in the external load. To overcome this problem, a switching algorithm of the control parameter using a learning vector quantization neural network (LVQNN) was proposed. The effectiveness of the proposed control algorithm was demonstrated through experiments with different external working loads.

(Mikio *et al.,* 2007). proposed an intelligent controller based on predictive fuzzy control using a control rule and a forward model. This model was designed using the current state and the input-output characteristics of the actuator. The effectiveness of the proposed intelligent controller was confirmed experimentally using a pneumatic servo system.

Genetic algorithms (GA) are general-purpose search procedures, optimization methods, or learning mechanisms based on Darwinian principles of biological evolution. When provided with a suitable objective function that evaluates the performance of the control systems, using genetic algorithms can readily optimize control parameters for fluid power servo systems. Applying genetic algorithms to optimize the control gains of a three-loop controller for a pneumatic servo cylinder drive was presented by (Yong *et al.,*1998). The three-loop controller has position, velocity, and acceleration feedback gain, all of which have formerly been manually tuned. A general procedure for optimizing the control parameters of fluid power systems by using genetic algorithms was presented. The optimized gains were confirmed by a plot of the fitness distribution defined in this study, which represented the control performance of the system in a given gain space.

Applying a feedback linearization technique was effective in many approaches to achieve more accurate tracking control for pneumatic servo systems. A tracking position control method was proposed by (Han *et al.,* 2002). for a linear positioning system. The positioning system was composed of a pneumatic actuator and 5-port proportional valve. A PID controller with feedback linearization was used in the pressure control loop to nullify the nonlinearity arising from the compressibility of air. The position controller was also a PID controller augmented with friction compensation using either neural network or nonlinear observer. In the former case, the nonlinearity due to friction was coded on the neural network in the training mode. The positioning system could then be regarded as a linear one, provided that the both nonlinearities in the inner loop and in the outer loop were completely compensated for. Experimental results indicated that the proposed controller significantly improves the tracking performance. On the other hand, a feedback linearization technique was applied by (Khayatic *et al.,* 2004). on the analytical nonlinear structure, dependently affined on parameter uncertainties that generically characterize the pneumatic systems and a constrained $H\infty$ minimization to perform the design objective. Also a two different cases were discussed by (Jihong *et al.,*2007). based on feedback linearization theory to achieve more accurate tracking control for servo pneumatic systems. The first one is that a single five port proportional valve drives the pneumatic cylinder and the second that the pneumatic cylinder is driven by a two three port proportional valves. At the initial stage, for the convenience of analysis, the static friction forces were ignored. They were treated as uncertainties addition to the system in the later sections. For on-line implementation, the controller was simplified to require only position and velocity state variables in its feedback. The simulation results show that the simplified controller can drive the system to achieve the required tracking accuracy. The feedback linearization design was also proposed by (Karim *et al.,* 2008). to cancel most of the resulting nonlinearities in pneumatic plant. Then the linear state feedback control and an additive nonlinear action were used to robustly bound the force error dynamics, devices which are required to handle the further parametric uncertainties and exogenous unbounded disturbances that arisen on the deduced structure. The design of the linear control gains was performed within robust closed loop pole clustering using a linear matrix inequality approach. Various experimental results illustrated the validity of the approach.

Many adaptive approaches are found to take care of uncertainties in the pneumatic systems. A common assumption for these adaptive schemes to be feasible is that all uncertain parameters should be time invariant. (Xiang *et al.,* 2005). presented a new adaptive fuzzy PD controller and researched the adaptability of the fuzzy PD controller for a pneumatic servo position control system, which has some typical characteristics of nonlinearity and time varying. A new control algorithm for friction compensation was introduced to enhance the accuracy of pneumatic servo position control systems by means of adjustment of a so-called adaptive controller parameter. Some experiments had been made to show that the adaptive fuzzy-PD controller could control the pneumatic servo system accurately.

(Mao *et al.,* 2005). investigated a novel large stroke and high precision pneumatic-piezoelectric hybrid positioning control system that contains a pneumatic servo cylinder and a piezoelectric servo actuator combined in cascade. The pneumatic servo cylinder serves to positioning with high speed and large stroke; the piezoelectric actuator positions in fine stroke for compensating the influence of friction force so as to achieve large stroke, high response and high positioning accuracy. The overall control systems have complex dual-input single-output (DISO). For that, the control strategies of the pneumatic controller and the piezoelectric controller were designed and verified in experiments, respectively, using adaptive discrete variable structure control (ADVSC) theorem. The ADVSC developed in this work combines self-tuning adaptive control and discrete variable structure control so that the control parameters can be adapted on-line for achieving an optimum sliding surface and reducing the chattering phenomenon of variable structure control. Subsequently, the pneumatic–piezoelectric hybrid positioning control was implemented, which test results clarified that the positioning accuracy of the novel pneumatic–piezoelectric hybrid positioning system can reach 0.1 lm, the resolution limit.

(Somyot *et al.,* 2005). proposed a hybrid adaptive neuro-fuzzy model reference to enhance the controller performance for the pneumatic system. Figure (5) showes the structure of the proposed hybrid controller. The concept of multimode switching was applied to activate either a bang-bang controller or an adaptive neuro-fuzzy model reference controller (ANFMRC). Bang-bang control was applied when the actual output is far away from set point, which results in high error value. Two types of controller; ANFMRC and hybrid ANFMRC were investigated. Simulation and experiment of a force controlled pneumatic system was investigated to evaluate the efficiency of the algorithm.

(Alexandru *et al.,* 2006). presented an adaptive neural control structure with application to a pneumatic servo system. The results were very promising and could be an alternative to the classical control. The results proved that the neural networks capable to cope with three main difficulties encountered in control: complexity, nonlinearity, and uncertainty.

(Qiang *et al.,* 2006). studied two effective algorithms for improving the performance of a pneumatic actuator. Without building the plant model, the proportional velocity acceleration (PVA) control with friction compensation was implemented to reduce the steady state error as shown in figure (6). To overcome the time delay problem unresolved by PVA, a CARIMA model referenced adaptive generalized predictive control (AGPC) was applied for the pneumatic actuator, whose parameters are updated by on-line recursive least square error (RLS) method with forgetting factor. The experimental results of AGPC for the position control of the pneumatic actuator were impressive for both the steady state and dynamic tracking.

(Yi *et al.,* 2008). proposed a function approximation technique (FAT) based adaptive controller for pneumatic servo systems with variable payload and uncertain disturbances. The system model was firstly described by a set of non-autonomous state equations with mismatched uncertainties. Since the uncertainties are time varying and their variation bounds are not available, most traditional robust designs or adaptive strategies are not directly applicable. The FAT based design was proposed here to estimate these uncertainties so that the closed loop stability can be proved by using the Lyapunov-like theory. Using the multiple-surface sliding control MSSC algorithm circumvented the problem in dealing with mismatched uncertainties. Experimental results justified that the proposed scheme can give good performance regardless of various uncertainties.

It is shown that the PI control law alone in a typical two degree of freedom control law alone cannot adequately satisfy the specified disturbance attenuation tolerance due to the presence of an under damped complex mode in the pneumatic transfer function. So the three-degree of freedom quantitative feedback theory (QFT) control was used to significantly improve the closed loop disturbance attenuation properties of the pneumatic actuator. Also the QFT control law was designed to give the best attenuation of the prescribed worst case persistent load disturbance in spite of practical limitations on the achievable closed loop performance and in the presence of other design constraints including closed loop tracking and stability. Figure (7) shows the block diagram of the two-degree of freedom QFT control structure (Mark *et al.,* 2004; Mark *et al.,* 2006).

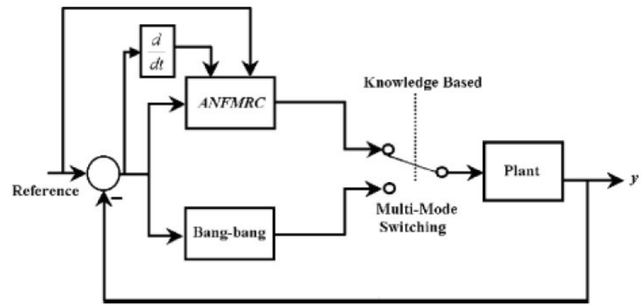

Fig. 5: Hybrid ANFMRC.

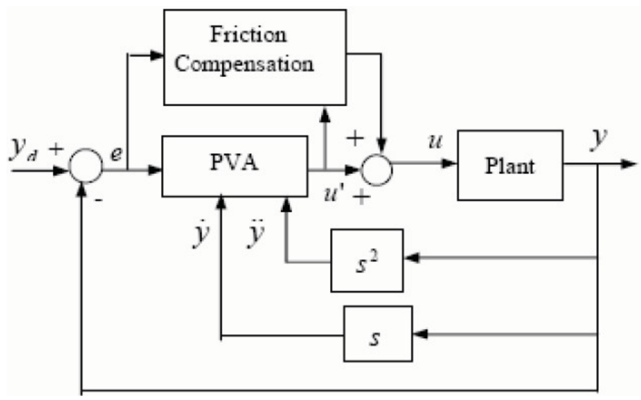

Fig. 6: PVA control with friction compensation.

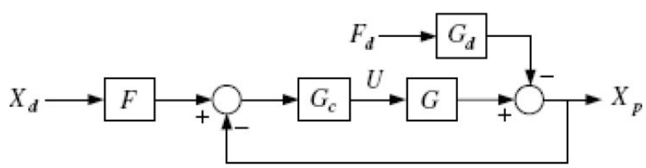

Fig. 7: Two degree of freedom QFT control structure.

In order to track the desired position and desired pressure in the pneumatic actuator chambers, a sliding mode control law was presented in different ways as stated in the following:

(Samaoui *et al.,* 2004) introduced a second order sliding mode control approach in the context of position control of an electropneumatic system. The main objective was to demonstrate through this approach the undesired chattering phenomenon can be avoided while retaining the same robustness of first order sliding mode control.

(Mohamed *et al.,* 2006). presented a synthesis of a nonlinear controller to an electropneumatic system. Nonlinear backstepping control and nonlinear sliding mode control laws were applied to the system under consideration. First, the nonlinear model of the electropneumatic system was presented. It was transformed to be a nonlinear affine model and a coordinate transformation was then made possible by the implementation of the nonlinear controller. Two kinds of nonlinear control laws were developed to track the desired position and desired pressure. Experimental results were also presented and discussed.

(Gary *et al.,* 2007). designed two control algorithms for the position-tracking problem and their experimental performance was compared for a pneumatic cylinder actuator. The first algorithm was sliding mode control based on a linearized plant model and the second was sliding mode control based on nonlinear plant model. Extensive experiments using different payloads, vertical and horizontal movements, and move sizes from 3 to 250 mm were conducted. The tracking performances of both the control algorithms were good.

(Yi *et al.,*2008). proposed a multiple surface-sliding controller (MS SC) for pneumatic servo systems with variable payload and mismatched uncertainties. The system is firstly modeled by a non-autonomous dynamic equation with consideration of the valve dynamics. Various nonlinearities and bounded uncertainties are then lumped into two bounded functions to represent the system equation into a formal form for the design of the MSSC so that the mismatched uncertainties can be properly compensated. The closed loop system was proved to have asymptotically stable performance by using the Lyapunov stability theory. Experimental results showed that the proposed algorithm is able to give good performance regardless of the uncertainties and time varying payload.

(Schulte *et al.,* 2004). described the design of a new motion controller for pneumatic actuators using local linear models with an application to a two-way servo pneumatic drive under a time variable vertical load. The dominant nonlinearities in the plant are the couplings between motion and pressure, pressure and flow rate, and the friction force. The control problem was to keep the accuracy of the position control independent of the payload and piston position. For each local linear model a state feedback controller was derived. The final controller of the system was designed as a fuzzy gain scheduler of the local state feedback controllers. It was shown by experimental results that this controller is capable to handle the dominant nonlinearities of the plant and different payloads, which were kept constant during each experiment.

(Navneet *et al.,* 2005). presented the development of two lyapunov based pressure observers for the pneumatic actuator system. The first method showed that an energy based stable pressure observer could be developed with the state equations. The other method incorporated the output error to control the convergence of the observed pressures. Simulation and experimental results were presented that demonstrate and validate effectiveness of the proposed observers.

(Takashi *et al.,* 2007). developed a pneumatic spool type servo valve having an air bearing and a high-resolution position sensor. It is attempted to achieve high frequency, high-accuracy flow rate control by digitization of the controller. Herein a control algorithm for digital control of this valve was presented. The characteristics of this valve were measured and the natural frequency of the valve was clarified to be up to 300 Hz. The spool position accuracy and the dynamic characteristics of the developed servo valve were greatly improved compared to existing valves.

(Xiangrong *et al.,* 2007). proposed a new approach to the design of a robot actuator with physically variable stiffness. The proposed approach leverages the dynamic characteristics inherent in a pneumatic actuator, which behaves in essence as a series elastic actuator. By replacing the four-way servo valve used to control a typical pneumatic actuator with a pair of three way valves, the stiffness of the series elastic component can be modulated independently of the actuator output force. Based on this notion, a control approach for the simultaneous control of actuator output force and stiffness was proposed. The general control and maximum/minimum stiffness approaches were experimentally demonstrated and shown to provide high fidelity control of force and stiffness, and additionally shown to provide a factor of 6 dynamics range in stiffness.

(Zhihong *et al.,* 2008). presented a new modeling approach and control law for pneumatic servo actuators. The nonlinear system model was developed using a combination of mechanistic and empirical methods. The use of novel bipolynomial functions to model the valve flow rate was shown to produce a more accurate solution than prior approaches. A novel multiple input single output nonlinear position control law was designed using the backstepping methodology. The stability analysis includes the effects of friction modeling error and valve modeling error. Experiments were conducted with 9.5-mm bore and 6.4-mm bore pneumatic cylinders, and four low cost two way proportional valves. In experiments with the 9.5-mm bore cylinder and a 1.5-kg moving mass, maximum tracking errors of ± 0.5 mm for a 1-Hz sine wave trajectory, and steady state errors within ± 0.05 mm for an S-curve trajectory were achieved.

Conclusion:

The pneumatic actuator represents the main force control operator in many industrial applications and its static and dynamic characteristics play an important role in the overall behavior of the control system. Therefore improving the dynamic behavior of the actuator is of prime interest to control system designers. The pneumatic actuators offer numerous advantages such as cleanliness, low cost, high ratio of power to weight, easy to maintain, safe, long anti explosion, working life and working overload. But on the other hand, the control accuracy is affected badly by its nonlinear characteristics.

The nonlinear characteristics, especially the nonlinear friction and the thermodynamics of the pressure air in the chambers of the cylinder have a bad influence on control accuracy of the displacement controlling of the cylinder. In addition, there are a series of nonlinear and time varying factors such as load force, temperature, position of the piston, staying time at still and wearing out during working procedure. Also the pneumatic actuators are uncertain systems.

A review of many researches that are conducted to study, model and design the accurate control algorithms for obtaining a high performance pneumatic actuator are presented in this paper. New applications of the pneumatic actuators are also reviewed.

REFERENCES

Alexandru, S., P. Gheorghe and C. Bogdan, 2006. Aspects regarding the neuroadaptive control structure properties application to the nonlinear pneumatic servo system benchmark, Electrotechnics, Electronics, Automatic Control, Informatics, 82-86.

Arcangelo, M., I.G. Nicola and G. Angelo, 2005. Experimenting and modeling the dynamics of pneumatic actuators controlled by the pulse width modulation (PWM) technique, Mechatronics, 15: 859-881.

Bird, P.J., 1985. Development in the design and control of pneumatic linear actuators, European Conference on Electrics versus Hydraulics versus Pneumatics, Inst. of Mechanical Engineers, London, In Mechanical Engineering, 77-83.

Bowns, D.E., and R.L. Ballard, 1972. Digital computational for the analysis of pneumatic actuator systems, Proc. Inst. Mech. Engrs, 186(73): 881-888.

Burrows, C.R. and C.R. Webb, 1970. Further study of a low pressure on-off pneumatic servomechanism, Proc. Inst. Mech. Engrs, 184(45): 849-859.

Canghoon, K., H.C. Jae and H. Daehie, 2008. Coordination control of an active pneumatic deburring tool, Robotics and Computer-Integrated Manufacturing, 24: 462-471.

Carducci, G., N.I. Giannoccaro, A. Messina and G. Rollo, 2006. Identification of viscous friction coefficients for a pneumatic system model using optimization methods, Mathematics and Computers Simulation, 71, 385-394

Clements and Len., 1985. Electro-pneumatic positioners get electronics, Journal of control and Instrumentation, 17: 54-56.

Chen, Y.Y., J. Wang and Q.H. Wu, 2003. A software tool development for pneumatic actuator system simulation and design, Computers in industry, 51: 73-88.

Chitty, A., and T.H. Lambert, 1976. Modeling a loaded two-way pneumatic actuator, ASME, Journal of Measurement and Control, 9, 19-24.

Cho, D. and J.K. Hedrick, 1985. Pneumatic actuators for vehicle active suspension on applications, Journal of Dynamic Systems, Measurement, and Control, 107: 67-72.

Djordje, D. and N. Novak, 2008. Simulation, animation and program suppot for a high performance pneumatic force actuator system, Mathematical and Computer Modelling.

Edmod, R. and H. Yildirim, 2001. A. high performance pneumatic force actuator system, ASME, Journal of Dynamic Systems, Measurement and Control, 122(3): 416-425.

Eric, J.B., Z. Jianlong and G. Michael, 2002. Sliding mode approach to PWM-controlled pneumatic systems, Proceedings of the American Control Conference, Anchorage, 2362-.

French, L.G. and C.S. Cox, 1988. The robust control of a modern electropneumatic actuator, IFAC, Automatic Control In Space.

Jihong,, W., P. Junsheng and M. Philip, 1999. Accurate position control of servo pneumatic actuator systems: an application to food packaging, Control Engineering Practice, 7: 699-706.

Jihong, W., K. Ulle and K. Jia, 2007. Tracking control of nonlinear pneumatic actuator systems using static state feedback linearization of the input-output map, Proceedings Estonian Academic Science of Physics and Mathematics, 56: 47-66.

Joachim, S. and E. Duygun, 2003. Dynamic pneumatic actuator model for a model-based torque controller, Proceedings IEEE International Symposium on Computational Intelligence in Robotics and Automation, Kobe, Japan, 342-347.

Junbo, S. and I. Yoshihisa, 1997. Robust tracking controller design for pneumatic servo system, International Journal of Engineering Science, 35(10/11): 905-920.

Han K.L., S.C. Gi and H.C. Gi, 2002. A study on tracking position control of pneumatic actuators, Mechatronics, 12: 813-831.

Ingold, J.B. and J.K. Tice, 1988. Development of an electro-pneumatic system for prestarified charge emission control, (PSC), Proceedings of Energy Source Technology Conference and Exhibition, USA.

Gary, M.B. and N. Shu, 2007. Experimental comparison of position tracking control algorithms for pneumatic cylinder actuators, IEEE/ASME Transactions on Mechatronics, 12(5): 557-561.

Guido, B., M. Stefano and M. Giuliana, 2004. A method for increasing the dynamic performance of pneumatic servosystems with digital valves, Mechatronics, 14: 1105-1120.

Karim, K., B. Pascal and A.D. Louis, 2008. Force control loop affected by bounded uncertainties and unbounded inputs for pneumatic actuator systems, ASME, Journal of Dynamic Systems, Measurement, and Control, 130: 1-9.

Khayati, K., 2004. A robust feedback linearization force control of a pneumatic actuator, IEEE International Conference on Systems, Man and cybernetics.

Kyoungkwang, A. and Y. Shinichi, 2005. Intelligent switching control of pneumatic actuator using on/off solenoid valves, Mechatronics, 15: 683-702.

Kyoung, K.A. and T.C. Huynh, 2007. Intelligent switching control of a pneumatic muscle robot arm using learning vector quantization neural network, Mechatronics, 17: 25 5-262.

Lee, E.S. and S. Rajendra, 1993. Experimental study of friction in a pneumatic actuator at constant velocity, Journal of Dynamic Systems, Measurement, and Control, 115: 575-577.

Marumo, R. and O.M. Tokhi, 2004. Intelligent modeling and control of a pneumatic motor, IEEE.

Mikio, Y. and Y. Seiji, 2007. An intelligent control for state-dependent nonlinear actuator and its application to pneumatic servo system, SICE Annual Conference, Kagawa University, Japan.

Mark, K. and K. Nariman, 2004. QFT design of a PI controller with dynamic pressure feedback for positioning a pneumatic actuator, Proceedings of the American Control Conference, Boston, Massachusetts, 5084-5089.

Mark, K. and K. Nariman, 2006. QFT synthesis of a position controller for a pneumatic actuator in the presence of worst-case persistent disturbances, Proceedings of the American Control Conference, Minneapolis, Minnesota, USA, 3158-3 163.

Mao, H.C., C.C. Chung and N.T. Tan, 2005. Large stroke and high precision pneumatic-piezoelectric hybrid positioning control using adaptive discrete variable structure control, Mechatronics, 15: 523-545.

Mohamed, S., B. Xavier and T. Daniel, 2006. Systematic control of an electropneumatic system: integrator backstepping and sliding mode control, IEEE. Transactions on Control Systems Technology, 14: 5.

Morioka, H., A. Nishiuchi, K. Kurahara, K. Tanaka and M. Oka, 2000. Practical robust control design of pneumatic servo systems, IEEE, 1755-1760.

Nagarajan, R. and R.H. Weston, 1985. Front end control schemes for pneumatic servo-driven modules, Proc. Inst. Mech. Engrs, 199(27): 1-280.

Nieto, A.J., A.L. Morales, A. Gonzalez, J.M. Chicharro and P. Pintado, 2008. An analytical model of pneumatic suspensions based on an experimental characterization, Journal of Sound and Vibration, 313: 290-307.

Navneet, G. and J.B. Eric, 2005. non-linear pressure observer design for pneumatic actuators, proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics Monterey, California, USA,

Pavol, R., D. Kumar, S. Csaba, M. Neil and C. Rey, 2008. Modeling and measurement of granule attrition during pneumatic conveying in a laboratory scale system, Powder Technology, 185: 202-210.

Qiang, S. and L. Fang, 2006. Neural network modeling and disturbance observer based control of a pneumatic system, IEEE.

Qiang, S. and L. Fang, 2006. Improved control of a pneumatic actuator pulsed with PWM, IEEE.

Qiang, S., L. Fang and D.F. Raymond, 2006. Improved fuzzy neural network control for a pneumatic system based on extended kalman filter, IEEE International Conference on Computational Intelligence for Modelling Control and Automation.

Qinghua, Y., B. Guanjum, Z. Libin and R. Jian, 2006. Analysis and simulation of dynamic characteristics of flexible pneumatic actuator FPA, Proceedings of the IEEE International Conference on Mechatronics and Automation, Luoyang, China.

Samaoui, M., X. Brun and D. Thomasset, 2004. Robust position control of an electropneumatic system using second order sliding mode, IEEE.

Sano, M. T. Fujita, H. Matsushima and H. Mumamoto, 1988. pneumatic servomechanism by electro-pneumatic on-off valve with disk flapper, Memories of the Faculty of Technology, Kanazawa University, Japan, 21(2): 45-51.

Schulte, H. and H. Hahn, 2004. Fuzzy state feedback gain scheduling control of servo- pneumatic actuators, Control Engineering Practice, 12: 639-650.

Sebastian, B., S. Volker and B. Stephanus, 2002. Novel micro-pneumatic actuator for MEMS, Sensors and Actuators, A 97-98: 638-645.

Shigeru, K., C. Michel and T. Toshi, 1995. Robust control of pneumatic actuators based on dynamic impedance matching, IEEE, 983-987.

Singh, H., P.R. Lang and J.T. Auman, 1985. Centralized electro-pneumatic system for truck air brakes, Truck and Bus Meeting and Exposition, SAE, Warrendale.

Shu, N. and M.B. Gary, 2005. Development of a nonlinear dynamic model for a servo pneumatic positioning system, Proceedings of the IEEE International Conference on Mechatronics and Automation, Niagara falls, Canada, 43-48.

Sorli, M., L. Gastaldi, E. Codina and S. Heras, 1999. Dynamic analysis of pneumatic actuators, Simulation Practice and Theory, 7: 589-602.

Somyot, K. and P. Manukid, 2005. Force control in a pneumatic system using hybrid adaptive neuro-fuzzy model reference control, Mechatronics, 15: 23-41.

Swider, J., G. Wszolek and W. Carvalho, 2005. Programmable controller designed for electro-pneumatic systems, Journal of Materials Processing Technology, (164-165): 1459- 1465.

Tablin, L.B. and A.J. Gregory, 1963. Rotary pneumatic actuators, Journal of Control Engineering, 58-63.

Takashi, M., F. Toshinori, S. Kazutoshi, K. Kenj and K. Toshiharu, 2007. Development of a digital control system for high-performance pneumatic servo valve, Precision Engineering, 31: 156-161.

Tokhi, M.O., M. Al-Miskiry and M. Brisland, 2001. Real-time control of air motors using a pneumatic H-bridge, Control Engineering Practice, 9: 449-457.

Tu, D.C. and K.A. Kyoung, 2006. Nonlinear PID control to improve the control performance of 2 axes pneumatic artificial muscle manipulator using neural network, Mechatronics, 16: 577-587.

Vincent, T.L., S.P. Joshi and Yeong Ching Lin, 1989. Position and active damping of spring mass systems, Journal of Dynamic Systems, Measurement, and Control, 111: 592-599.

Virvalo, T. and H. Koskinen, 1988. Electro-pneumatic servo system design, power International, 34(402): 272-275.

Weston, R.H., P.R. Moore and G. Morgan, 1984. Computer controlled pneumatic servo drives, Proc. Inst. Mech. Engrs, 198(14): 275-281.

Xiang, G. and J.F. Zheng, 2005. Design study of an adaptive fuzzy-PD controller for pneumatic servo system, Control Engineering Practice, 13: 55-65.

Xiangrong, S. and G. Michael, 2007. Simultaneous force and stiffness control of a pneumatic actuator, ASME, Journal of Dynamic Systems, Measurement, and Control, 129: 425-434.

Xue, S.W., H.C. Yu and Z.P. Guang, 2007. Modeling and self-tuning pressure regulator design for pneumatic-pressure-load systems, Control Engineering Practice, 15: 1161-1168.

Xuesong, W. and P. Guangzheng, 2003. Modeling and control for pneumatic manipulator based on dynamic neural network, IEEE, 223 1-2236.

Yi, C.T. and C.H. An, 2008. Multiple-surface sliding controller design for pneumatic servo systems, Mechatronics.

Yi, C.T. and C.H. An, 2008. FAT-based adaptive control for pneumatic servo systems with mismatched uncertainties, Mechanical Systems and Signal Processing, 22: 1263-1273.

Yong, S.J., O.L. Chung and S.H. Ye, 1998. Optimization of the control parameters of a pneumatic servo cylinder drive using genetic algorithms, Control Engineering Practice, 6: 847-853.

Zhihong, R. and B. Gary, 2008. Nonlinear modeling and control of servo pneumatic actuators, IEEE Transactions on Control Systems Technology, 16(3): 562-569.