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ENERGY EFFICIENCY IMPROVEMENT OF PNEUMATIC ACTUATOR BY TURBO EXPANDER AND BYPASS VALVE

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ABSTRACT

Energy wasting is major issue in major engineering industries The issue of energy saving nowadays is very crucial. Pneumatic systems, constituting an important segment of almost every industry, represent large energy consumers. pneumatic systems have wide application industry. The major disadvantage is their lower efficiency in energy utilization. in order to improve their efficiency , in this paper a new hybrid pneumatic electrical system with by pass valve and a turbo expander is used to utilize the energy of exhaust air. the turbo expander is used to drive a electric generator which will produce electrical energy . Thus the proposed system is kind of "pneumatic-electrical" system. A closed-loop coordinate control system using a micro controller is used to control the whole system including DCV control.

Index Terms—by pass valve, turbo expander, pneumatic system, exhaust air, control system.

1. INTRODUCTION

Increase of energy efficiency during positioning of cylinders is very important, and this primarily depends on the type of actuator and on the applied control of position. The problem is particularly pronounced in large cylinders. Reduction of compressed air consumption of cylinders is possible when different levels of pressure in the extending and retracting stroke are used. Another problem is that when the piston reverses its movement, all the compressed air from one chamber is released into the atmosphere. This is a great compressed air loss because the air still has substantial potential energy, which could be used for something else. There are many papers dealing with the issue of reduction of compressed air consumption in pneumatic systems. Sanville (1986) added a secondary reservoir in the system collecting air, which would be otherwise released into the atmosphere, and uses it as a secondary reservoir. Quaglia & Gastaldi (1995) proposed a pneumatic cylinder which contains multiple chambers within one actuator for recycling of exhaust compressed air. Wang *et al* (2000) showed that some velocity profiles of servo pneumatic actuator can increase energy efficiency. Al-Dakkan *et al* (2003) proposed that instead of one proportional valve 5/3, two proportional valves 3/3 were used in order to independently control pressures in cylinder chambers and in this way reduce consumption of compressed air. Yang *et al* (2009) proposed retaining of proportional valve 5/3, but add a 3/2 valve for bypassing the cylinder chambers. For such realization, it is necessary to drill the actuator and install additional ports, which is not appropriate when using standard industrial components. Apart from that, this by-passing is accomplished at the moments when the air pressure in the driving chamber becomes lower than the used-up one, so the by-passing is performed multiple times during one extending or retraction stroke. In this way, the by-passing valve is under great workload and its service life is severely reduced. To increase the efficiency of pneumatic system, a new way is introduced using by-pass control scheme combined with turbo expander.

In this paper, a hybrid system is introduced in the conventional pneumatic system by using a bypass valve and turbo expander to increase the efficiency. The bypass valve is used to bypass the exhaust compressed air for the return purpose. After expansion the exhaust compressed air from the system is collected in a collecting tank. This exhaust air stored in the tank is supplied to a turbo expander which is coupled to a electric generator. Exhaust air get expanded in the turbo expander and expanded power is fed to generator ot produce electricity, thus the system gives combined mechanical and electrical output simultaneously. The diagrammatic representation of the whole system is illustrated in the fig 1.1.

The proposed system comprises of three sections 1) upstream part - It includes the air supply, pneumatic actuator(s) and the main load(s). In this paper, an ac generator with its load is employed for simulating the upstream load driven by pneumatic actuators. 2) Downstream part- it consists of an intermediate air tank, a turbo expander, a dc generator, and its electric load. The air tank is used to buffer the downstream impact imposed onto the upstream. 3) Control system- for managing the system operation, a proper control strategy is developed for maintaining upstream actuators' operations and supporting exhaust energy recovery.

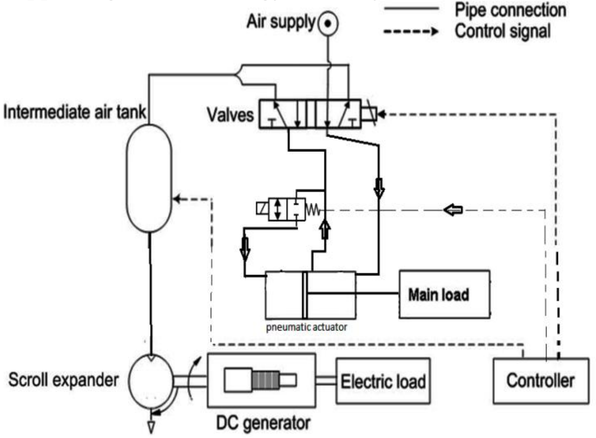

Fig. 1.1. Schematic arrangement of the designed system

2. DESCRIPTION OF THE ARRANGEMENT

Two types of pneumatic actuators—cylinders and air motors are used to mimic the real industrial scenario. The mathematical models of two corresponding actuators, double acting cylinders and vane-type air motors are presented, and then the whole system is modeled in the later subsections

Pneumatic Cylinders

The coordinate system of a typical double acting rod less cylinder is illustrated in Fig. 2.

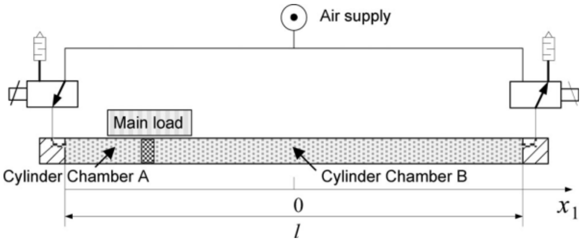

Fig. 2.1 pneumatic actuator with coordinate system

Vane-type Air Motors

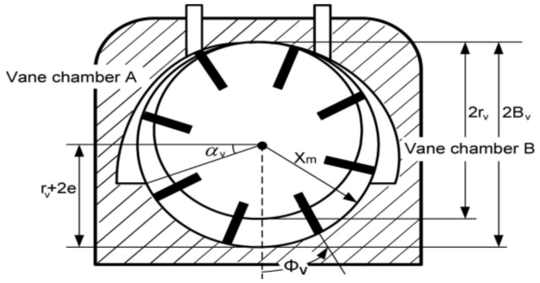

Fig. 2.2 diagram of vane compressor which consists of eight vanes

The structure of a vane-type air motor with eight vanes is shown in Fig. 2.2

Turbo Scroll Expanders

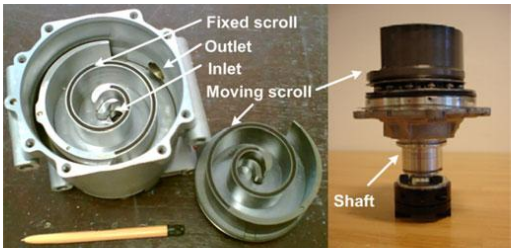

Fig. 2.3 structure of turbo expander

The turbo expander is a key component for the proposed system, and its high-energy efficiency characteristic is resulted from its smart mechanical structure as shown in Fig. 2.3. It consists of two identical spirals, i.e., the fixed and the moving scrolls. One scroll is mirrored with respect to another and each scroll is fitted with a back plate. The crankshaft connects to the moving scroll back plate through a bearing mechanism.

High efficiency characteristics of scroll expanders were studied in [10] and [11]. The compressed air power consists of the transmission air power and the expansion air power [17]. Pneumatic actuators, pneumatic cylinders and vane air motors, mainly employ the transmission air power, that is, the power carried by compressed air to push the pistons or to drive the vanes to motion, and the expansion air power is not effectively employed [17], [18]. From the scroll's structure, the scroll expander can utilize not only the transmission air power, but also the expansion air power. Thus, the scroll expander can deliver high-energy efficiency [11], [17], [18]. The working principle of scroll expanders is: the moving scroll pushed by compressed air always wobbles along with its inherent orbit, and the fixed scroll is the envelop of the family of the moving scroll curves. The compressed air flows through the inlet port (see Fig. 4); then, the air expands with the increase in size of the scroll chambers; the exhaust air with the relatively low pressure is finally discharged from the outlet.

The working process can be considered to have three phases: charging, expansion, and discharging, which are associated with the central, side, and exhaust chambers

By pass valve

The by-pass valve activation occurs when the piston is moving, and when the position error is higher than the adopted value it means ON–OFF activation of the actuator by-pass valve in appropriate intervals

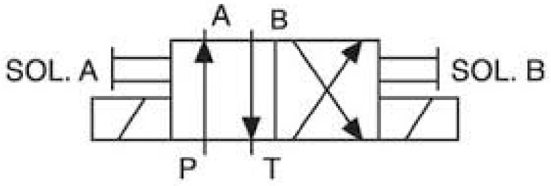

Fig. 2.4 solenoid valve

Intermediate Air Tank

The structure of intermediate air tank is shown in Fig. 5. The inlet(s) of the tank is (are) connected to the exhaust port(s) of the upstream actuator(s). In the tank, a part of the exhaust air directly goes to the atmosphere through the controlled valve; the rest part of the air enters into the scroll expander.

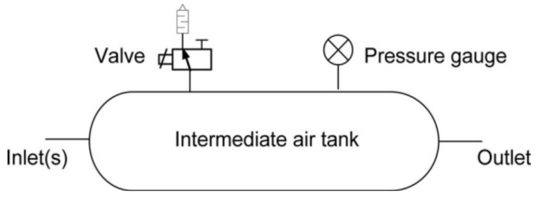

Fig 2.5. Diagrammatic arrangement of intermediate air tank.

AC Generator

A permanent magnet synchronous generator (PMSG) is used as the upstream load

DC Generator

The permanent magnet dc generator has many outstanding characteristics, such as simplicity in structure and relative easiness in modeling. Thus, it has been employed as the driven machine for the scroll expander in the simulation study and the laboratory test

3. CONTROL STRATEGY STUDY

This section investigates the role of a control strategy for the proposed energy recovering system. The section starts from simulation study of the system without involving coordinate control, and the parameters of system are listed in Table I. Figs. 6 and 7 show the typical dynamic responses of the pneumatic-electrical system without applying any additional control. In this simulation study, the upstream system consists of a pneumatic cylinder and a vane-type air motor, respectively.

The supply pressures to the upstream actuators are both at 6.0 × 105 Pa. The simulation has been conducted by engaging the downstream scroll expander at 1.5 s from the time at which the upstream pneumatic actuators are in operation. From Figs. 6 and 7, it is clearly seen that the exhaust chamber pressures at the upstream increase and the speeds of the pneumatic actuators decrease. Thus the working conditions of the upstream cannot be maintained due to its connection with the downstream scroll expander. Fig. 7 shows the simulation results with different air tank sizes. It can be seen that, at the initial stage of engaging the downstream system, the bigger the tank volume is, the smaller the actuator speed changes are. After the Initial stage, the speed changes will be settled at a steady state level no matter what the size of the air tank is. The aforementioned simulation study indicates that the upstream working condition cannot be maintained without extra control applied.

A combined control strategy is proposed in this paper, that is, the high-gain control is used to achieve accurate positioning for upstream actuators [23], [24], and the PID control is applied for the downstream, which is shown in Fig. 8. Also for achieving rapid responses, a feed forward function has been added to the upstream control.

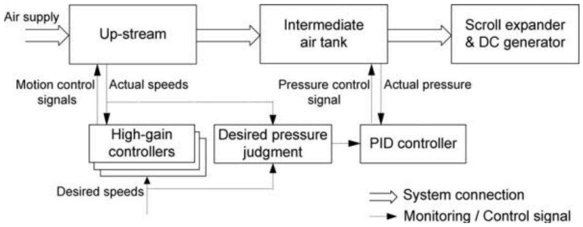

Fig. 3.1 Schematic layout of the control system.

To the downstream operation, the air pressure inside the intermediate air tank has been monitored and regulated, which can be considered as the compressed air supply to the scroll expander. This pressure is a key factor in propagating the down stream's influences back to the upstream operation.

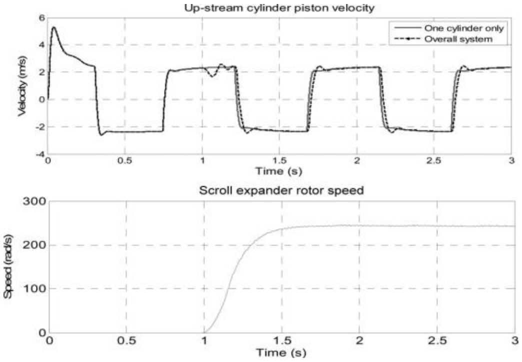

Fig. 3.2 Dynamic responses of the overall system with controllers connected (connecting to a cylinder exhaust).

One PID controller is employed to keep the air pressure inside the tank at the appropriate level, which is determined by the performance requirement to the upstream actuator speed control, for example, to have the steady speed no less than 95% of its stand-alone operation speed. For both simulation study and real-time laboratory tests, the intermediate air tank pressure is maintained through a look-up table method.

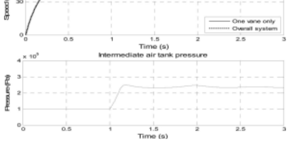

Fig. 3.3 Dynamic responses of the overall system with controllers connected (connecting to a vane type of air motor exhaust).

The simulation results are shown in Fig. 9 for the case that the controlled energy recovery system is connected to the exhaust of one pneumatic cylinder actuator. The figure shows the piston velocity and the scroll expander rotating speed. The supply pressure to the cylinder is at 4.0 × 105 Pa. The energy recovery scroll expander system is engaged at the moment of 1 s after the cylinder is in its operation. In order to maintain the upstream cylinder piston velocity, the desired air pressure in the air tank is set to be not higher than 2.5 × 105 Pa. From Fig. 9, it can be seen that the cylinder piston movement can be maintained near to the desired speed level, and the scroll expander can operate properly for energy recovery. Correspondingly, the simulation results of dynamic responses of the controlled overall system for the case of a vane-type air motor operating at the upstream are shown in Fig. 10. The supply pressure to the vane-type air motor is at 4.0 × 105Pa. The upstream vane-type air motor load is a 3-phase permanent magnet synchronous generator with its resistive load. The desired pressure inside the air tank is set to be 2.3 × 105 Pa, which is derived through repeating multi cycle simulation studies and the experimental tests. The simulation has shown that, after the co-ordinate control system is in operation, the working performances of the upstream vane-type air motor can be properly maintained.

The simulation study for multiple upstream pneumatic actuators is conducted. There are three upstream actuators, i.e., two cylinders and one vane air motor, which will work with different supply pressures at: 3.5 × 105 Pa, 4.0 × 105 Pa, and 4.5 × 105 Pa. During the 6-s simulation time interval, each actuator operates at different time intervals as shown in Fig. 11. The energy recovery system is engaged at the moment of 1 s after the upstream actuators are in operation. During the overall system working with the proposed controllers, if any of these three upstream pneumatic actuator average speeds cannot be maintained above 90% of their desired speeds, the limitation of the air pressure inside the air tank will be adjusted accordingly. In the associated simulation study, the exhaust air is controlled to flow in one direction only, i.e., from the exhausts of three pneumatic actuators to the intermediate air tank. Fig. 12 shows the simulation results of the dynamic responses of the controlled overall system for the case of the multiple upstream pneumatic actuators' operation. From the figure, the second cylinder velocity can be maintained properly. And it is noticed that, at the moment when the supply pressure to the first cylinder is shut and the second cylinder started to work simultaneously, the tank pressure dropped during the period from 2 to 2.3 s. Also it can be seen that, from 4 to 5-s period, due to the vane-type air motor average speed cannot be maintained above 90% of its desired speed, the pressure inside the air tank dropped from 2.6 × 105 Pa to 2.3 × 105 Pa around the fifth second. Then, the vane air motor rotating speed recovers until it approaches to the desired level due to regulation of the downstream pressure

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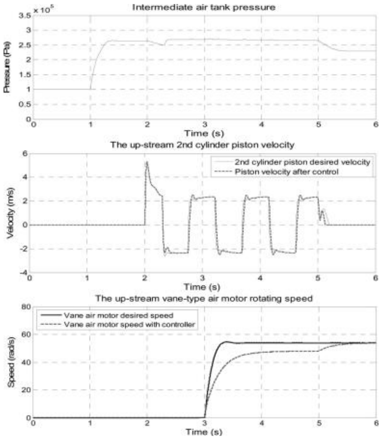

Fig. 3.4 Dynamic responses of the overall system with controllers connected (connecting to the exhausts of two cylinders and a vane air motor).

4. ENERGY EFFICIENCY ANALYSIS

From Fig. 1, the energy transmission and conversion can be schematically illustrated shown in Fig. 16. The system energy efficiency can be analyzed by calculating the ratio between the useful output power and the whole system input air power. Thus, it is necessary to find how much air power/energy contained in the compressed air inputs to the system. And the standard temperature and pressure (STP, with 0 ◦C at 1 atm) is normally employed as the reference state [20], [27]. From the fundamental theory of the applied thermodynamics,

the air power flowing into the pneumatic actuator $\dot{Q}_{airin}$ referred to STP can be obtained by [19], [20], and [27]

$$\dot{Q}_{\mathrm{airin}} = \dot{m}_{\mathrm{in}}(\tilde{h}_{\mathrm{in}} - \tilde{h}_{\mathrm{atm}}) - T_{\mathrm{atm}}\dot{m}_{\mathrm{in}}(\tilde{s}_{\mathrm{in}} - \tilde{s}_{\mathrm{atm}})$$

Where $\tilde{h}$ stands for the enthalpy per unit mass of the air, $\tilde{s}$ is the entropy per unit mass of the air, $\dot{m}$ refers to the mass flow rate, the subscripts in and atmstand for the inlet thermodynamic state and the atmospheric state, respectively. Although the air power is a function of air enthalpy and entropy, in practice, it is not easy to measure or calculate these two variables directly. So an alternative simplified approach is required for calculating the input air power $\dot{Q}_{airin}$ referred to STP [17], [19], [20] which is:

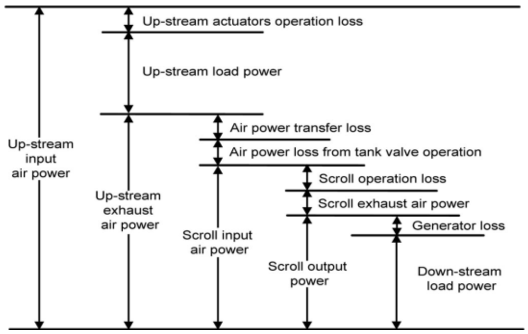

Fig. 3.5 factors need to consider during process.

where *R*air is the gas constant of air, *P* is the air pressure, and *k* is the specific heat ratio. Thus, from the actuator pressure, temperature, and the flow rate at the intake port, the air power into the actuator can be derived. To the proposed pneumatic-electrical system, when the upstream pneumatic actuators are in operation and the downstream energy recovery subsystem is not engaged, the upstream energy efficiency is obtained from the following:

$$\eta_{\text{actuators}} = \frac{\sum_{i=1,2,\ldots} \dot{Q}_{\text{up\_power}}(i)}{\sum_{i=1,2,..} \dot{Q}_{\text{airin}}(i)}$$

Where ˙*Q*up power (*i*) is the obtained load power from the ith upstream pneumatic actuator and ˙*Q*airin(*i*) is the corresponding air power flowing into the ith actuator. When the combined pneumatic-electrical system is in operation, the overall system energy efficiency is calculated by

$$\eta_{\text{overall}} = \frac{\dot{Q}_{\text{scroll\_power}} + \sum_{i=1,2,\ldots} \dot{Q}_{\text{up\_power}}(i)}{\sum_{i=1,2,..} \dot{Q}_{\text{airin}}(i)}$$

Where ˙*Q* scrollp ower is the useful power output from the scroll work, which refers to the electrical resistance load power obtained from the dc generator. Thus, the energy efficiency difference relative to the efficiency of the original pneumatic actuator system can be calculated by

$$\eta_{\text{diff}} = \frac{(\eta_{\text{overall}} - \eta_{\text{actuators}})}{\eta_{\text{actuators}}} \times 100\%.$$

From (18), *η*diff stands for the percentage of energy efficiency changes with respect to the original actuator system operation. With the test rig shown in Fig. 13, Figs. 17 and 18 present the test results of the energy efficiency improvement for the cases at different air supply conditions. At the upstream, a three phase electric load is connected (PMSG supplies to 8 Ω in each phase). At the downstream, the electric resistance load for the dc generator has been set at 12 Ω. In the tests, the desired air pressures in the intermediate air tank had been set at the level of 2.0 × 105*Pa* and 2.3 × 105*Pa*, respectively. Due to the laboratory safety regulations and other experimental limitations, the system was not set to operate at the full load power rate. The air supply pressures at *AS*1 and *AS*2 points in Figs. 17 and 18 are the minimum workable pressures at which the downstream scroll expander can be engaged. The pressures at the two points are obtained through multiple experimental tests and they are 2.5 × 105 Pa and 2.9 × 105 Pa, respectively. From Figs. 17 and 18, it can be seen that, different desired pressure settings for the intermediate air tank will result in different overall system energy efficiency improvement. Fig. 18 shows that, for the full test range, the overall system energy efficiency improvement increased up to 16.7%. Fig. 18 shows that the maximum energy efficiency improvement reaches 18.1%. The experimental test confirmed that the overall pneumatic actuator system energy efficiency is improved indeed and the new strategy for improving energy efficiency is feasible. Fig. 19 demonstrates the corresponding simulated results of the energy efficiency improvement from the pneumatic- electrical system at different air supply pressures. The desired air pressure in the intermediate air tank was limited to 2.3 × 105 Pa.

Compared with the percentages of the energy efficiency improvement obtained from experimental data (see Fig. 20), it can be seen that the experimental and simulation results have the same trend at the corresponding air supply pressure conditions. However, the energy efficiency improvement of the simulation results is higher than the experimental results under the same operating conditions. This may be caused by the air energy transmission loss in the pipe, air leakages during the operation, no-uniform mechanical friction energy losses, the heat transfer and other assumptions/approximations made for modeling. It is observed that energy efficiency has been improved from both simulation and experimental results.

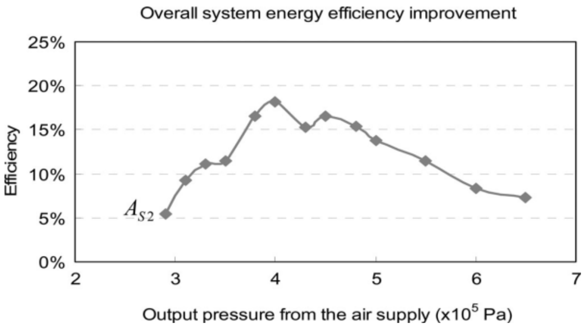

Fig.3.6 test result of energy efficiency improvement

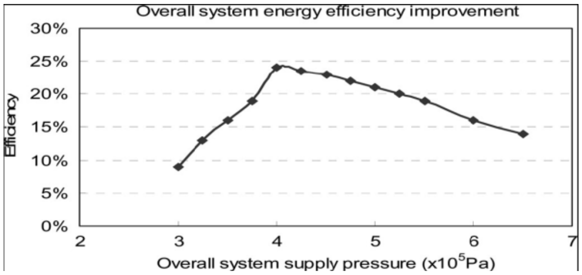

Fig.3.7 schematic showing result of energy efficiency improvement

5. CONCLUSION

This paper reports the recent achievement in developing a new strategy for improving pneumatic actuator system energy efficiency by connecting a scroll expander for recovering exhaust compressed air energy. The proposed system structure and operation process are described in this paper. A complete system mathematical model is derived. Then, a test rig is built for hosting the experimental investigation. Both simulation and experimental studies have shown that the proposed strategy is feasible for improving pneumatic actuator system energy efficiency.

A suitable control for coordinating the upstream and downstream actuator operation is essential. With a suitable coordinate control strategy, the energy efficiency improvement can reach 18.1% from the tests. Considering wide applications of pneumatic actuators in the world, overall energy saving can potentially be significant.

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