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Energy optimisation of pneumatic actuator systems in manufacturing

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ABSTRACT

Compressed air systems account for a significant proportion of industrial energy usage in the European Union and the United States. Improving the energy efficiency of final air consumers is an essential aspect of overall system optimisation. This paper investigates and compares the minimisation of air consumption in linear pneumatic actuator systems using two approaches: dual pressures and the utilisation of expansion energy in compressed air. In order to simplify the implementation of energy saving circuits for industrial end-users, a software program has been developed based on a combination of genetic algorithms and dynamic simulations. The developed program, described in this paper, automates the selection process of optimal design parameters and control input variables for pneumatic cylinders. The robustness of the optimisation software has been experimentally validated. The results from a vertical lifting application case study indicate that the proposed optimisation approaches can reduce compressed air usage by up to 29% per cycle, whilst simultaneously satisfying other common automation design objectives or constraints. The paper concludes with a discussion on methods to increase the application of such energy efficiency measures in pneumatic production machinery.

1. Introduction

Improving the energy efficiency of manufacturing processes is one of the top priorities in the sustainable energy hierarchy and is a widely adopted strategy by industry to reduce energy usage, emissions and costs (Bunse et al., 2011; Despeisse et al., 2013). Within industrial manufacturing facilities air compressors are major consumers of energy, supplying compressed air to pneumatic actuators, air motors, vacuum ejectors and other key enabling devices in production machines. In particular, pneumatic actuators are a preferred choice of automation solution for industrial production and handling tasks due to their low cost, long lifetime, and high power density. However, recently they have been critically reviewed from an energy efficiency point of view, particularly for high frequency/cycling applications (Cai et al., 2002). Since a large percentage of compressed air demand in factories is due to pneumatic actuator usage, it is an important area for efficiency improvements. Additionally from an automation technology perspective, the energy costs over the lifetime of a pneumatic device are significant. The low efficiency of pneumatic actuators negatively impacts on life cycle cost comparisons with electric linear actuators of comparable force output. It has been shown in (Bader and Kissock, 2000) that a combined approach of reducing compressed air demand, and subsequently downsizing compressor capacity to match the reduced demand, can result in significant improvements to system exergy efficiency and electrical energy savings. In fact, a major factor in the widely reported low efficiency of compressed air systems is the poor efficiency of end-use pneumatic devices e.g. linear cylinders.

There has therefore been considerable effort in the research community to improve the energy efficiency of servo-pneumatic positioning systems, and more recently of open-loop single and multi-axis point-to-point positioning systems, see (Harris et al., 2012a) for a comprehensive review of the state-of art. Specifically with regard to pneumatic actuators, there are a number of methods used to maximise drive efficiency (Fig. 1). For example, many manufacturers offer model selection software which helps avoid the over-sizing of cylinder and circuit dimensions. Hepke and Weber have shown that optimising the design parameters of a pneumatic drive, such as cylinder bore, supply pressure, tubing length and circuit flow capacity can allow for energy savings of up to 44% without effecting the motion profile (Hepke and Weber, 2013).

Once preventable energy losses have been eliminated, alternative designs to the standard pneumatic actuator circuit with meter out control, are necessary for improved energy efficiency. In particular, one of the most promising approaches for significantly increasing the efficiency of pneumatic devices is to utilise the

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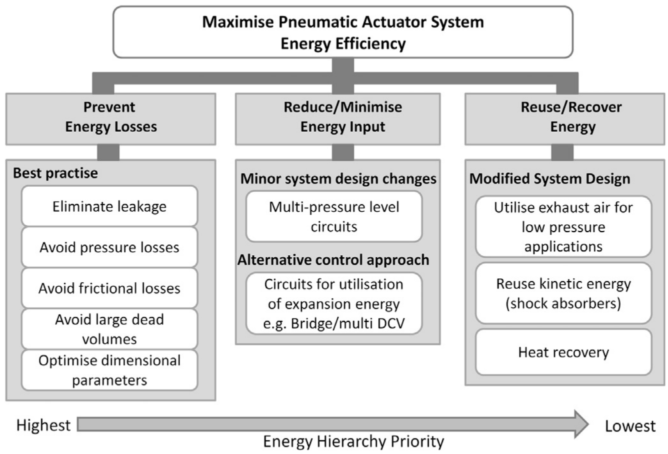

Fig. 1. Decomposition of EEM's for pneumatic actuator system, adapted from (Hepke and Weber, 2013; Zein et al., 2011).

expansion energy of compressed air. Doll et al. (2011) have demonstrated up to 80% compressed air savings over a conventional actuator circuit using a five valve bridge configuration for a horizontally mounted cylinder, albeit with reduced savings for higher final pressure and zero impact velocity constraints. A key advantage of the approach in (Doll et al., 2011) is that the expansion energy of air can be utilised with only limited valve switching, which prolongs the device's lifetime. In addition, the bridge circuit configuration allows for the elimination of shock absorber(s) and their associated cost.

Another energy saving method involving two supply pressures for dissimilar extend and retract payload or stroke time requirements is described in (Fleischer, 1995). This method also offers considerable air consumption reductions of up to 50%, though only for certain applications. A further benefit of the dual pressure approach is that a pressure reduction on one side of a pneumatic cylinder may also allow for a subsequent pressure reduction in the alternate side, due to the decreased backpressure load to overcome (Fleischer, 1995).

The energy saving potential in pneumatic circuits has therefore been well documented in the literature, and concepts widely disseminated e.g. by OEM's in industry trade articles. Furthermore, the financial merit of such approaches has also been demonstrated (Hepke and Weber, 2013) with payback times typically less than 2–3 years – the usual industrial requirement. Yet based on observations from recent case studies conducted by the authors in industrial facilities, the widespread adoption of such technology by industry appears to be progressing slowly. While general barriers to energy efficiency such as limited access/availability of capital for investment and organisational inertia play a role, there are still also technical challenges which hamper the industrial uptake of energy saving measures. Specifically with respect to pneumatic systems, energy saving circuits are comparatively more difficult to implement and the system performance (e.g. cycle time) is sensitive to parameter selection. In contrast, a meter out actuator system can be rapidly assembled and tuned to meet cycle time requirements, though typically with little concern for energy efficiency. Hence, there is a requirement for a robust method or tool to aid in the selection of design and control parameters for alternative pneumatic circuits and control methods. In addition, there is scope for further investigation of the reductions in air consumption that are achievable for multi-objective automation design problems. Finally, the application of optimisation techniques such as genetic algorithms for the design of pneumatic positioning systems is also underdeveloped (Doll and Sawodny, 2010; Jeon et al., 1998).

This paper presents an approach for the identification of pneumatic actuator, circuit and control parameters that optimises energy efficiency whilst fulfilling typical automation design objectives such as cycle time, holding force and impact energy.

2. Minimisation of energy input for pneumatic actuator systems

2.1. Energy efficiency approaches

The traditional meter out pneumatic circuit, along with the dual pressure and expansion utilisation circuit designs are shown in Fig. 2. It can be seen from the figure, that the dual pressure approach is a straightforward and cost effective option to implement, since only an additional pressure regulator is needed for the circuit and no changes to existing actuator control are required e.g. PLC program. Many manufacturers also offer pressure regulators, sometimes coupled with quick exhaust valve, for mounting directly on a pneumatic cylinder. Such an approach is particularly suited for applications with a payload that moves in only one direction or with gravity assisted loads. To ensure the piston moves smoothly/uniformly the dual pressure approach may require the addition of one or two flow controls (Fleischer, 1995). Note the pilot air for the control valve must be supplied from the higher pressure regulator in order to avoid adversely affecting valve switching time. Also, in order to implement dual pressures with valve manifolds, which are common in industrial installations, the valve assembly must have three ports (single supply, two exhausts).

The expansion utilisation circuit requires an additional directional control valve, though a pressure regulator is not necessary, resulting in a small extra investment cost. In the setup described in (Doll et al., 2011) five valves with 2 ports and 2 positions (i.e. 2/2) are utilised, with the fifth valve used as a bypass for recovering lower pressure exhaust air. However, since most of the reported energy savings are attributed to the use of the expansion energy of compressed air, the bypass valve is not considered in this paper. This simplifies the circuit setup and control (Fig. 2). Ideally two 3/3 valves would be used but since such valves are not commonly available commercially, an alternative approach is to use two 5/3 valves and block the second working ports on each valve. This approach is labelled the 'Dual DCV' approach for the remainder of the paper, to differentiate it from previous work. The drawback of using a 5/3 spool valve instead of 3/2 or 2/2 poppet valves is the slower comparative response time of the valve, and subsequent allowable switching frequency e.g. a typical response time with DC solenoid is 20 ms–30 ms. In contrast to the meter out and dual pressure circuits, the utilisation of expansion energy requires more sophisticated control logic, see Fig. 3 for an example of the PLC code necessary for a simple extend movement of a linear cylinder. Nevertheless, the scale of the energy savings justifies the extra once-off effort and time required for PLC programming.

2.2. Classification of energy savings

In terms of energy savings, both the dual pressure and expansion energy approach ultimately reduce the electrical energy usage of air compressors by reducing the air consumption of pneumatic actuators. Assuming the compressor capacity or pressure setpoint are not reduced to meet the new demand/pressure requirements, then the reduced consumption allows the compressor to stay in idle mode or automatic shutdown for a longer period of time (scenario A, Table 1). In addition, reducing actuator pressure also reduces leakage losses in the circuit, and could therefore significantly reduce overall air demand if the pneumatic circuit contains seal-less components, such as lapped spool valves or ultra-low friction cylinders. However,