Research article

Applicability of bridge-type pneumatic energy-saving systems and its experimental validation

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ARTICLE INFO

Keywords:
Mechanical engineering
Dynamical system
Mathematical optimization
Energy conservation
Fluid mechanics
Compressed air
Bridge-type pneumatic system
Energy-saving
Dynamic optimization
Applicability range

ABSTRACT

The bridge-type pneumatic system is to control the intake and exhaust time sequences of an air cylinder with four switch valves by applying the expansion energy of air for work to save energy. However, the system is often sensitive, and thus, the control accuracy can be rather poor. Therefore, the applicability of this system remains to be further tested. A nonlinear dynamic optimization model with the air consumption as the objective function was established. A simultaneous collocation method was used to obtain the on–off time sequences. The concept of optimization performance rating to evaluate the system's energy-saving performance and the stability was introduced. Experiments were done to validate the applicability of the circuit. The results showed that the bridge circuit was applicable to a certain range of working conditions under each given action system and that instability, such as rebound or impact, could occur outside this range.

1. Introduction

With the development of the global economy, industrial demand for energy is increasing rapidly, accounting for half of the world's energy consumption. Additionally, demand for industrial energy is increasing at a rate of nearly 1% per year (Hassan Khattak et al., 2018). The direct and indirect emissions of carbon dioxide by the manufacturing sector currently account for more than 50% of all emissions (May et al., 2017). Therefore, energy efficiency has become a key factor in industrial development. Improving energy efficiency can help enterprises reduce costs and remain competitive. Significant research has been conducted to improve energy efficiency through technological improvement (Solnordal and Foss, 2018).

As one of the most important energy sources for industrial use, compressed air is widely used in the manufacturing industry because of its cleanness, availability, and usability. For manufacturing companies, however, the cost of compressed air is very high, because the energy conversion efficiency of compressed air is only 5–10% (Saidur et al., 2010). The energy consumed by compressed air is mainly reflected in the following three aspects: (1) the annual life-cycle cost of the air compressor and related equipment; (2) operation and maintenance costs of the equipment; and (3) the air consumption cost. Because of the low energy efficiency and long operating cycle of the compressed air system, air consumption cost accounts for 75% of all three costs (Yang, 2009). Thus, improving the energy efficiency of air compressors is a rather challenging task.

Earlier studies on the pneumatic energy-saving system mainly focused on the design of the drive circuit (Kaya et al., 2002). Subsequent research primarily emphasized two aspects: the electrical energy consumed in producing and processing compressed air, and the consumption of compressed air in the terminal equipment (Parkkinen and Zenger, 2008). In recent years, research on the conservation of compressed air focused mainly on improving and controlling pneumatic components and circuits (Harris et al., 2012; Sesiila et al., 2016). Such a mode of energy-saving is realized in two main ways: (1) the expansion energy of air can be used because of the compressibility of air; and (2) the exhaust air can be recycled.

As for using the expansion energy to do work, the dual-pressure control circuit has been proven to be effective in energy-saving. The pneumatic action system mainly involves extension and retraction of the pneumatic actuator with loads, but the processes of reciprocating motion are different. The basic idea of dual-pressure control is to drive with different air pressures during pneumatic reciprocating motion. One way to achieve dual-pressure control is to add a pressure-reducing valve to the exhaust circuit in which case the piston rod uses different pressures for air supply during the process of extension and retraction. This type of exhaust circuit can save 25% of the compressed air (Beater, 2007).
There are two approaches to recycle the exhaust air: (1) adding an air storage device in the exhaust circuit as a supplementary air source, and (2) adding a by-pass valve to directly use the exhaust air. Shi (2011) first proposed a method to store part of the high pressure air on the exhaust side in a container during the exhaust process. When the actuator moved in the opposite direction, this part of the air would enter the charging side as pressurized air, thereby saving energy. This principle now is being used to develop energy-saving cylinders. On the basis of the idea of a by-pass valve and digital-sliding mode, Blagojević et al. (2013) controlled the position of the pneumatic actuator system using all or part of the air in the previous chamber, and the system showed good accuracy and robustness, with an energy-saving rate of 29.5%. Likewise, to improve the energy efficiency of a servo-pneumatic-drive system, Yang et al. (2009) made full use of the exhaust air using a by-pass valve, and the energy-saving rate reached 12–52% under different working conditions. Other researchers have explored the pneumatic accumulator as another approach to recycle the air exhausted by the pneumatic system, including designing and manufacturing the accumulator as well as controlling the intake and exhaust of the air to save the energy (Pfeffer et al., 2015; Cummins et al., 2017).

To fully and simultaneously consider the expansion energy applied for work and the reuse of exhaust air, Doll et al. (2011) proposed a new type of bridge circuit. Figure 1 shows the principle of its pneumatic basic circuit.

The basic idea was to apply the expansion energy for work and to recycle the exhaust air on the base of air compressibility. The expansion energy was applied for work by controlling the pressure of the intake and exhaust cavities, and the exhaust air was recycled by the by-pass valve. Then the aim of the system were transformed into solving the on–off time sequences of the four switch valves. Doll et al. (2011) solved the on–off time sequences of the four switch valves (not considering the by-pass valve) based on nonlinear dynamic optimization. In their work, considering energy as the optimization goal, system operating state equations (e.g., the mass flow equation, pressure differential equation, and piston kinematics equation) as the constraints, and the time sequences of the valves as the state control variables, programming was conducted in the optimized modeling language AMPL, and the time sequences were solved by calling the interior point method. According to the experimental results, the energy-saving rate was up to 85% compared with the traditional system. Following this idea, Harris et al. (2014) and Du et al. (2018, 2020) also solved the time sequences for the four switch valves according to the idea of optimization. Harris et al. (2014) used the genetic algorithm to compute the time sequences, which verified that an energy-saving rate of 27–29% could be achieved by the dual-pressure control of the bridge-type pneumatic action system and the expansion energy could be applied for work. Du et al. (2018, 2020) used the finite element method to discretize the system and further applied the interior point method to solve the time sequences. This method ensured better computational stability and tested the energy-saving and stability of the bridge circuits controlled the four switch valves under different working conditions, with an energy-saving rate of 50–70%. In addition, it was proposed that by controlling the bridge circuit, a certain adaptive buffer could be realized, which could avoid impact and crawl to some extent. Using the idea of a bridge circuit, many researchers carried out research on trajectory tracking control to achieve high precision trajectory tracking control of the cylinder while also saving energy (Pfeffer et al., 2016, 2018; Gluck, 2012). The air flow equation of the valve port of the reversing valve was established, and the pulse width modulation (PWM) signal was generated according to the pulse signal modulation method, thereby controlling the duty ratio of the high-speed switch valve. On this...
basis, the control model to track the pressure and trajectory of the pneumatic cylinder was established by different controllers (pneumatic PWM pressure control or feed forward pressure control), and the proposed air pressure and trajectory tracking control methods were numerically simulated and experimentally validated. The results of these studies verified the accuracy and feasibility of the control model and scheme, and provided an effective means to realize high-precision trajectory tracking control of the bridge circuit.

To summarize the previous researches on applying the expansion energy for work or recycling the exhaust air, the bridge-type pneumatic energy-saving circuit is an effective and unified method in the field of pneumatic energy-saving systems. Doll et al. (2011) and Du et al. (2018, 2020) both proved the energy-saving characteristics of the bridge circuit. However, on-off sequence accuracy of the former was insufficient and only a single condition was considered; the latter algorithm was not quite steady. Based on these two research, a method in this study to explore and experimentally test the applicability of the bridge-type pneumatic energy-saving system was proposed with an improved algorithm and multiple-variable experiments. The energy-saving effects were performed with different system operating state and the sensitivity of the pneumatic system.

The structure of this paper is as follows: In the second section, conclusions were presented.

### 2. Modeling and optimization

On the basis of a study conducted by Du et al. (2018, 2020), to compute the time sequence control of the four valves (with the role of the by-pass valve temporarily not considered), the following mathematical model was conducted.

argmin \( V_w = C \int_{t_0}^{t_f} |u_1(t) \cdot \phi(P_0, x_1(t), b) + u_2(t) \cdot \phi(P_0, x_2(t), b)| dt, \quad t(t) \in [0, 1]^4 \)

subject to

\[
\begin{align*}
x_1(t) &= x_1(t) \\
x_2(t) &= \frac{1}{m} (A_{h1} x_1(t) - A_{h2} x_2(t) - A_{h0} - F_l(t)) \\
m_i &= u_i \cdot C_v \cdot \rho_b \cdot \phi(P_0, x_i(t), b) \cdot P_0, i = 1, 2, 3, 4 \\
x_1(t) &= \frac{n}{V_a(t) + V_m} (RT_0 m_2(t) - x_1(t) \cdot V_a(t)), m_2 = m_1 - m_3 \\
x_2(t) &= \frac{n}{V_a(t) + V_m} (RT_0 m_2(t) - x_2(t) \cdot V_a(t)), m_3 = m_2 - m_4 \\
\end{align*}
\]

and

\[
\begin{align*}
x_1(t) &\in [x_{l1}, x_{r1}], \quad x_2(t) \in [x_{l2}, x_{r2}] \\
x_1(t) &\in [p_{l1}, p_{r1}], \quad x_2(t) \in [p_{l2}, p_{r2}] \\
\end{align*}
\]

and

\[
\begin{align*}
\{ x_1(t), x_2(t), x_3(t), x_4(t) \}_{L_1} &= [x_{1L}, x_{2L}, x_{3L}, x_{4L}] \\
\{ x_1(t), x_2(t), x_3(t), x_4(t) \}_{G} &= [x_{1G}, x_{2G}, x_{3G}, x_{4G}] \\
\end{align*}
\]

where,

\[
\phi(P_0, x_1(t), b) = \begin{cases} 
1 & \frac{p_0}{x_1(t)} < b \\
1 - \left( \frac{p_0}{x_1(t)} - b \right)^2 & \frac{p_0}{x_1(t)} \geq b 
\end{cases}
\]

The definitions and descriptions of parameters in the above equation are shown in Table 1.

To solve the above optimization problem, the finite element orthogonal collocation method and the interior point method to compute the optimized time sequences was used (see the algorithm flow chart in Figure 2).

In this study, the fourth level of the Lobatto orthogonal configuration method was chosen, and the pseudo-code of the discretization program is the following Figure 3. After discretization, the dynamic optimization problem became a large scale NLP problem. The search was determined by the number of collocation points. Then, this paper proposed an improved interior point method to solve the NLP problem. This method could easily

### Table 1. Parameters used in modeling.

| Parameter symbol | Meaning |
|------------------|---------|
| \( V_w/mL \)    | System air consumption |
| \( C_v/dm^3/(S.bar) \) | Corresponding sonic conductance |
| \( P_0/Mpa \)  | Air supply pressure |
| \( \iota_i, \tau_i/s \) | The starting and ending times of system operation |
| \( u_i \in \{0, 1\} \) | On-off position of \( i \)th valve |
| \( \phi() \) | Stream function |
| \( b, m/kg \) | Critical pressure ratio and load mass |
| \( x_i/mm, x_i/m/s, x_i/Mpa, x_i/Mpa \) | Displacement, speed, and pressure of chamber a and b |
| \( m_i \) | The \( i \)th valve’s mass flow (i = 1,2,3,4) |
| \( m_a \) | Mass flow through the chamber a |
| \( m_b \) | Mass flow through the chamber b |
| \( A_p/m^2 \) | Piston area |
| \( A_r/m^2 \) | Piston rod area |
| \( F_f/N \) | Friction |
| \( V_a(x)/ml, V_a/mL \) | Volume and of the \( i \)th chamber |
| \( V_r(x) \) | Chamber volume gradient |
| \( R, k \) | Air constant and air polytrophic index |
| \( T_0/K \) | Air temperature |
| \( \rho_a/Mpa, \rho_r/Mpa \) | Upstream and downstream air pressure |
| \( D \) | The cylinder diameter |
| \( l_c \) | The cylinder stroke |
| \( m \) | Load |

![Figure 2](image)

**Figure 2.** Flow chart of the algorithm solving the on-off time sequences of the switch valves.
deal with equality or inequality constraint. The boundary constraint could be considered as an obstacle part of the objective function, which could avoid to calculate the constraint set during the solving process. Through this idea, only a series of sub-problems needed be done. More details can be found in Wächter and Biegler (2006). The algorithm routine was implemented in the AMPL programming environment (Fourer et al., 2002).

3. Applicability of the bridge-type pneumatic energy-saving system

The applicable range of the bridge-type pneumatic energy-saving system can be different under different working conditions. In this study, to analyze the applicability of the bridge-type pneumatic energy-saving system, the applicable range of the bridge-type pneumatic energy-saving system was obtained by fully optimizing and simulating the working conditions under different cylinder diameters, air pressures, and loads. Note that the research done in this study was based on the process of extension of the piston rod when the cylinder was installed horizontally.

To describe the optimization result more intuitively, the optimization results was divided into four levels: level 4 indicated the best optimization result, and the time sequence solved by the optimization method (Figure 4a) could be applied directly to the experiment; level 3 denoted the second-best optimization result, and the time sequence obtained (Figure 4b) needed to be properly adjusted before being used for implementation.
experiments; level 2 indicated that the time sequence obtained appeared in a waveform (Figure 4c), which was difficult to adjust; and level 1 denoted the worst optimization result. The time sequence obtained at level 1 is shown in Figure 4d, which indicated that switch valve 1 controlling the intake was not opened from the starting moment, but after a period of time, which was inconsistent with actual application. Therefore, the on–off time sequences obtained at level 1 could not be used in this experiment.

3.1. Applicable range under different cylinder diameters

Different types of cylinders with a cylinder diameter of 16–63 mm as research objects were selected. For different cylinder diameters, such parameters as switch valve, load mass, and cylinder stroke were also different. According to the actual application and data of the samples, the selected parameters are shown in Table 2.

According to the system parameters provided in Table 2, the optimization results under different cylinder diameters were divided into four levels based on the optimization result. Three-dimensional maps of the optimization results under different cylinder diameters were drawn in MATLAB (Figure 5).

As shown in the figure,

(1) When the cylinder diameter ranged from 16 mm to 63 mm, the travel time varied from 0.3 s to 0.9 s; if the travel time was too short, the displacement would mutate during the optimization process, but if the travel time was too long, switch valve 1 controlling the intake would be opened after a period of time rather than from the starting moment, which was inconsistent with actual application. Thus, the on–off time sequences obtained at this time could not be used in this experiment.

(2) In the case of a short full-stroke time, the optimization result got worse as the cylinder diameter and stroke increased. As shown in Table 2, the load rates were similar under different cylinder diameters. The larger the cylinder diameter and stroke, the longer it took for the piston to arrive at the stroke end. In the case of a long stroke time, as the cylinder diameter and stroke decreased, the optimization result worsened.

(3) When the cylinder diameter and stroke were small, the travel time range was relatively small and the travel time range increased as the cylinder diameter and stroke increased.

3.2. Applicable range under different air pressures

According to the applicable range of the bridge-type pneumatic energy-saving system under different cylinder diameters analyzed in Section 3.1, when D was small, the travel time range also was small, whereas when D was large, the travel time range as relatively large as well. Therefore, in this section, the applicable range of the bridge-type pneumatic energy-saving system under different air pressures were analyzed when D was between 16 mm and 63 mm.

The CDA2L63-600N-M9BW model produced by SMC for the cylinder with a diameter of 63 mm was selected. According to the sample data, the selected air pressure range was 0.2–0.7 MPa. Under different air pressures, the theoretical output force of the cylinder was different, and the load that could be driven also was different. On the basis of the selected air pressure, an appropriate load mass was selected (Table 3).

According to the system parameters provided in Table 3, the on–off time sequences of the switch valves was optimized under different air pressures and divided the optimization results into four levels (Figure 6). To more intuitively reflect the travel time range under different supply pressures, the x-axis was reversed.

As shown in the figure:

(1) When D = 63 mm and \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the travel time varied from 0.5 s to 0.85 s;

(2) When the air pressure was 0.2 MPa, the time sequence was obtained with the form a waveform, which was difficult to adjust;

(3) In the case of a short stroke time, the optimization result got worse as the pressure decreased; when the pressure was small, the volume flow of the air was small as well and the piston motion time naturally became longer when the load, cylinder diameter, and other external conditions were determined.

The AND-16-300-A-P-A model produced by FESTO for the cylinder with a diameter of 16 mm was selected. According to the sample data, the

| No. | Air pressure [MPa] | Load [kg] |
|-----|-------------------|-----------|
| 1   | 0.2               | 28.5      |
| 2   | 0.3               | 38.5      |
| 3   | 0.4               | 58.5      |
| 4   | 0.5               | 78.5      |
| 5   | 0.6               | 98.5      |
| 6   | 0.7               | 108.5     |

Table 2. Parameters under different cylinder diameters.

| No. | Cylinder diameter \( D \) [mm]| Distance of travel \( L \) [mm] | Air pressure \( P_0 \) [MPa] | Load m [kg] | Value of electromagnetic valve C [dm³/s*bar] | Critical pressure ratio b |
|-----|--------------------------------|-------------------------------|----------------------------|-------------|---------------------------------------------|---------------------------|
| 1   | 16                             | 300                           | 0.6                        | 7.2         | 0.3                                         | 0.45                      |
| 2   | 25                             | 300                           | 0.6                        | 18.5        | 0.58                                        | 0.45                      |
| 3   | 32                             | 400                           | 0.6                        | 28.5        | 1.1                                         | 0.38                      |
| 4   | 40                             | 400                           | 0.6                        | 48.5        | 1.1                                         | 0.38                      |
| 5   | 50                             | 500                           | 0.6                        | 68.5        | 1.96                                        | 0.55                      |
| 6   | 63                             | 600                           | 0.6                        | 98.5        | 1.96                                        | 0.55                      |
The selected air pressure range was 0.2–0.7 MPa. The specific parameters are shown in Table 4.

On the basis of the system parameters provided in Table 4, the optimization result was obtained (Figure 7).

As shown in the figure:

1. When \( D = 16 \text{ mm} \) and \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the travel time ranged from 0.35 s to 0.55 s;
2. When the air pressure was 0.2 MPa, the time sequence was obtained in the form a waveform, which was difficult to adjust.

By analyzing the optimization results under different air pressures with \( D = 63 \text{ mm} \) and 16 mm, it was evident that the optimization result was rather poor when the supply pressure was 0.2 MPa. The bridge-type pneumatic energy-saving system was applicable within an air pressure range of 0.3 MPa–0.7 MPa under the two different cylinder diameters.

### 3.3. Applicable range under different loads

According to the applicable range of the bridge-type pneumatic energy-saving system under different air pressures in Section 3.2, when

| No. | Air pressure \( P_0 \) [MPa] | Load m [kg] |
|-----|----------------|-------------|
| 1   | 0.2            | 2.2         |
| 2   | 0.3            | 4.2         |
| 3   | 0.4            | 5.2         |
| 4   | 0.5            | 6.2         |
| 5   | 0.6            | 7.2         |
| 6   | 0.7            | 8.2         |

the supply pressure was 0.2 MPa, the optimization results were not ideal. Therefore, in this section, the applicable range of the bridge-type pneumatic energy-saving system was explored under different loads only when the air pressure was 0.3 MPa, 0.5 MPa, or 0.7 MPa.

When \( D = 63 \text{ mm} \), the selected load parameters are shown in Table 5.

According to the system parameters provided in Table 5, the optimization results were obtained (Figure 8).

As shown in the figure:

1. When \( D = 63 \text{ mm} \), the travel time ranged from 0.5 s to 0.9 s;
2. When \( D = 63 \text{ mm} \) and \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the load mass varied from 28.5 kg to 118.5 kg.

When \( D = 16 \text{ mm} \), the selected load parameters are shown in Table 6.

According to the system parameters provided in Table 6, the optimization results were obtained (Figure 9).

As shown in the figure:

1. When \( D = 16 \text{ mm} \), the travel time ranged from 0.3 s to 0.55 s;
2. When \( D = 16 \text{ mm} \) and \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the load mass varied from 3.2 kg to 9.2 kg.

By analyzing the optimization results under different loads with a cylinder diameter of 63 mm and 16 mm, under the same air pressure, it was found that the travel time increased with an increase in the load. When \( D = 63 \text{ mm} \) and \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the load mass was applicable within the range of 28.5 kg–118.5 kg. When \( D = 16 \text{ mm} \) and \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the load mass was applicable within the range of 3.2 kg–9.2 kg.

### 4. Experimental validation

On the basis of the applicable range of the bridge circuit explored in the third section, the bridge circuit was applicable when the cylinder
diameter ranged from 16 mm to 63 mm, the air pressure varied from 0.3 MPa to 0.7 MPa, and the load ranged from 3.2 kg to 118.5 kg. To further test the applicable range of the bridge circuit, on the basis of the built test benches (i.e., the composition of the test benches and parameters of their components were set according to the study conducted by Du et al. [18]), a experiment test rig was established on the base of the on–off time sequences of the four switch valves obtained by the optimization method. The experimental test bench was shown in Figure 10, which was mainly composed of four 2/2 directional control valve, a dual acting cylinder, two flow meters, a displacement sensor and two pressure sensors. By monitoring the displacement of the piston motion and the displacement error allowed by the system, the applicable range of the bridge circuit was determined.

For bridge circuits with a cylinder diameter of 16 mm and 63 mm, when different full stroke times were set in the optimization, the piston's displacements were measured (Table 7). The error rate refers to the deviation of the actual displacement from the cylinder stroke.

As shown in Table 7, for a bridge circuit with a cylinder diameter of 16 mm and a stroke of 300 mm, when the air pressure was 0.6 MPa and the load mass was 7.2 kg, the following was observed:

1. When the travel time set in the optimization was 0.55 s, the piston could reach the end stroke;
2. The full travel time range available in the experiment was significantly smaller than the full travel time range available for optimization;
3. The shorter the travel time, the greater the rebounded displacement after the piston arrived at the end stroke.

When the travel time set in the optimization was relatively short, switch valve 1 opened for a long time. That is, more compressed air will enter the air intake chamber, so that the piston will experience a large impact and rebound.

For the bridge circuit with a cylinder diameter of 63 mm and a stroke of 600 mm, when the air pressure was 0.6 MPa and the load mass was 98.5 kg, the following was observed:

1. When the travel time set in the optimization was 0.7 s–0.8 s, the piston could reach the end stroke;
2. The full travel time range available in the experiment was significantly smaller than the full travel time range available for optimization;
3. When the travel time set in the optimization was relatively short, switch valve 1 was opened for a long time, resulting in large impact and rebound;
4. When the travel time set in the optimization was relatively long, switch valve 1 opened for a short time, whereas it took a long time to open switch valve 4. Because of the opening pressure of the pipeline and check valve in the circuit, less compressed air entered the air intake chamber, preventing the piston from reaching the end of the stroke.

As discussed in Section 3.2, when \( D = 16 \text{ mm} \) and \( L = 300 \text{ mm} \), the bridge circuit achieved a good optimization result within the air pressure range of 0.3–0.7 MPa. According to the parameters in Table 4, when the travel time was set differently in the optimization, the displacements of the piston were measured (Table 8).

As shown in Table 8, for the bridge circuit with \( D = 16 \text{ mm} \) and \( L = 300 \text{ mm} \), when the air pressure varied from 0.3 MPa to 0.7 MPa, the following was observed:

1. For each working condition, there was an on–off time sequence of the switch valve that made the piston reach the end stroke;
2. The full travel time range available in the experiment was significantly smaller than the full travel time range available for optimization;
3. If the travel time set was too short or too long, the piston would experience different degrees of impact and rebound;
4. As noted in the previous section, when \( D = 63 \text{ mm} \) and \( L = 600 \text{ mm} \), the bridge circuit achieved a relatively good optimization result within the air pressure range of 0.3–0.7 MPa. According to the parameters in Table 5, when the travel time was set differently in the optimization, the displacements of the piston were measured (Table 9).

As shown in Table 9, for the bridge circuit with \( D = 63 \text{ mm} \), when \( P_0 \) ranged from 0.3 MPa to 0.7 MPa, the following was observed:

1. When the travel time set in the optimization was 0.55 s, the piston could reach the end stroke;
2. The full travel time range available in the experiment was significantly smaller than the full travel time range available for optimization;
3. When the travel time set in the optimization was relatively short, switch valve 1 was opened for a long time, and the piston would experience different degrees of impact and rebound;
4. When the travel time set in the optimization was relatively long, switch valve 1 opened for a short time, whereas it took a long time to open switch valve 4. Because of the opening pressure of the pipeline and check valve in the circuit, less compressed air entered the air intake chamber, preventing the piston from reaching the end of the stroke.
### Table 7. Applicable range under different cylinder diameters.

| Load [kg] | Air pressure [MPa] | Time range obtained by dynamic optimization [s] | Full stroke time set in the optimization [s] | Displacement of the piston in the bridge circuit experiment [cm] | Error rate |
|-----------|---------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------------------------|------------|
| 7.2       | 0.6                 | 0.45–0.6                                      | 0.45                                        | 20.1                                                           | 33%        |
|           |                     |                                               | 0.5                                         | 29.1                                                           | 3%         |
|           |                     |                                               | 0.55                                        | 30                                                            | 0          |
|           |                     |                                               | 0.6                                         | 16.2                                                           | 46%        |
| 98.5      | 0.6                 | 0.6–0.85                                      | 0.6                                         | 58.5                                                           | 2.5%       |
|           |                     |                                               | 0.65                                        | 58.9                                                           | 1.8%       |
|           |                     |                                               | 0.7                                         | 60                                                            | 0          |
|           |                     |                                               | 0.75                                        | 60                                                            | 0          |
|           |                     |                                               | 0.8                                         | 60                                                            | 0          |
|           |                     |                                               | 0.85                                        | 57.1                                                           | 4.8%       |

### Table 8. Applicable range under different air pressures with D = 16 mm.

| Load [kg] | Air pressure [MPa] | Time range obtained by dynamic optimization [s] | Full stroke time set in the optimization [s] | Displacement of the piston in the bridge circuit experiment [cm] | Error rate |
|-----------|---------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------------------------|------------|
| 4.2       | 0.3                 | 0.5–0.55                                      | 0.5                                         | 25.8                                                           | 14%        |
|           |                     |                                               | 0.55                                        | 30                                                            | 0          |
| 5.2       | 0.4                 | 0.4–0.55                                      | 0.4                                         | 8.7                                                           | 71%        |
|           |                     |                                               | 0.45                                        | 22.1                                                           | 26.3%      |
|           |                     |                                               | 0.5                                         | 30                                                            | 0          |
|           |                     |                                               | 0.55                                        | 25.7                                                           | 14.3%      |
| 6.2       | 0.5                 | 0.4–0.55                                      | 0.4                                         | 12.2                                                           | 59.3%      |
|           |                     |                                               | 0.45                                        | 18.4                                                           | 38.7%      |
|           |                     |                                               | 0.5                                         | 25.5                                                           | 15%        |
|           |                     |                                               | 0.55                                        | 30                                                            | 0          |
| 8.2       | 0.7                 | 0.4–0.55                                      | 0.4                                         | 15.5                                                           | 48.3%      |
|           |                     |                                               | 0.45                                        | 21.2                                                           | 29.3%      |
|           |                     |                                               | 0.5                                         | 30                                                            | 0          |
|           |                     |                                               | 0.55                                        | 24.8                                                           | 17.3%      |

### Table 9. Applicable range under different air pressures with D = 63 mm.

| Load [kg] | Air pressure [MPa] | Time range obtained by dynamic optimization [s] | Full stroke time set in the optimization [s] | Displacement of the piston in the bridge circuit experiment [cm] | Error rate |
|-----------|---------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------------------------|------------|
| 38.5      | 0.3                 | 0.65–0.8                                      | 0.65                                        | 57.8                                                           | 3.7%       |
|           |                     |                                               | 0.7                                         | 60                                                            | 0          |
|           |                     |                                               | 0.75                                        | 54.7                                                           | 8.8%       |
|           |                     |                                               | 0.8                                         | 50.3                                                           | 16.2%      |
| 58.5      | 0.4                 | 0.6–0.75                                      | 0.6                                         | 60                                                            | 0          |
|           |                     |                                               | 0.65                                        | 60                                                            | 0          |
|           |                     |                                               | 0.7                                         | 56.6                                                           | 5.7%       |
|           |                     |                                               | 0.75                                        | 55.5                                                           | 7.5%       |
| 78.5      | 0.5                 | 0.55–0.8                                      | 0.55                                        | 58.9                                                           | 1.8%       |
|           |                     |                                               | 0.6                                         | 59.1                                                           | 1.5%       |
|           |                     |                                               | 0.65                                        | 60                                                            | 0          |
|           |                     |                                               | 0.7                                         | 60                                                            | 0          |
|           |                     |                                               | 0.75                                        | 58.2                                                           | 3.0%       |
|           |                     |                                               | 0.8                                         | 55.6                                                           | 7.3%       |
| 108.5     | 0.7                 | 0.5–0.85                                      | 0.5                                         | 44.2                                                           | 26.3%      |
|           |                     |                                               | 0.55                                        | 45.9                                                           | 23.5%      |
|           |                     |                                               | 0.6                                         | 56.7                                                           | 5.5%       |
|           |                     |                                               | 0.65                                        | 59.2                                                           | 1.3%       |
|           |                     |                                               | 0.7                                         | 60                                                            | 0          |
|           |                     |                                               | 0.75                                        | 60                                                            | 0          |
|           |                     |                                               | 0.8                                         | 60                                                            | 0          |
|           |                     |                                               | 0.85                                        | 58.8                                                           | 2.0%       |
(1) For each working condition, there was one or more on–off time sequences of the switch valve that made the piston reach the end stroke;
(2) The full travel time range available in the experiment as significantly smaller than the full travel time range available for optimization, but as the air pressure increased, the full travel time range available in the experiment also increased;
(3) If the travel time set was too short, the piston would experience different degrees of impact and rebound; if the travel time set was too long, the piston would not arrived at the stroke end.

The conclusion obtained in the third section applies to the two bridge circuits with different cylinder diameters—that is, when the air pressure was within the range of 0.3–0.7 MPa, each working condition corresponded to one or more on–off time sequences of the switch valve that could make the piston finish the stroke. If the travel time set was too short or too long, the cylinder experienced impact and rebound to varying degrees, or the piston did not arrived at the stroke end.

As noted in Section 3.3, when D = 16 mm and L = 300 mm, the bridge circuit achieved an ideal optimization result as the load ranged from 3.2 kg to 9.2 kg. According to the parameters in Table 6, when different full stroke times were set in the optimization, the displacements of the piston were measured (Table 10).

As shown in Table 10, for the bridge circuit with D = 16 mm and L = 300 mm, when the load mass ranged from 3.2 kg to 9.2 kg, the following was observed:

(1) For each working condition, there was one on–off time sequence of the switch valve that made the piston reach the end stroke;
(2) The full travel time range available in the experiment was significantly smaller than the full travel time range available for optimization;
(3) If the travel time set was too short or too long, the cylinder would experience impact and rebound to varying degrees;
(4) When the air pressure was 0.7 MPa and the load mass was 7.2 kg, the piston would not arrived at the stroke end regardless of any change in the travel time. When the load mass was relatively small, the friction force model used in the optimization differed greatly from the actual frictional force of the test bench, and switch valve 1 would open for a short time, so the piston could not arrived at the stroke end.

As noted in Section 3.3, when D = 63 mm and L = 600 mm, the bridge circuit achieved a good optimization result within a load range of 28.5–118.5 kg. On the basis of the parameters in Table 5, when different full stroke times were set in the optimization, the displacements of the piston were measured (Table 11).

As shown in Table 11, for the bridge circuit with a bore of 63 mm and a stroke of 600 mm, when the load mass was in the range of 38.5 kg–118.5 kg, the following was observed:

(1) For each working condition, there was an on–off time sequence of the switch valve that made the piston reach the end stroke;
(2) The full travel time range available in the experiment was significantly smaller than the full travel time range available for optimization, but as the load mass increased, the full travel time range available in the experiment increased as well;
(3) If the travel time was too short, the cylinder would experience different degrees of impact and rebound; if the travel time was too long, the piston can not arrived at the stroke end;
(4) When \( P_0 = 0.3 \) MPa and \( m = 28.5 \) kg, the piston did not arrived at the stroke end regardless of any change in the travel time.

### Table 10. Applicable range under different loads with D = 16 mm.

| Load [kg] | Air pressure [MPa] | Time range obtained by dynamic optimization [s] | Full stroke time set in the optimization [s] | Displacement of the piston in the bridge circuit experiment [cm] | Error rate |
|-----------|--------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------------------------|------------|
| 3.2       | 0.3                | 0.45–0.5                                      | 0.45                                        | 24.5                                                          | 18.3%      |
|           |                    |                                               | 0.5                                         | 30                                                            | 0          |
| 4.2       | 0.3                | 0.5–0.55                                      | 0.5                                         | 25.8                                                          | 14%        |
|           |                    |                                               | 0.55                                        | 30                                                            | 0          |
| 5.2       | 0.5                | 0.35–0.5                                      | 0.35                                        | 6.5                                                           | 78.3%      |
|           |                    |                                               | 0.4                                         | 20.1                                                          | 33%        |
| 5.2       | 0.5                | 0.35–0.5                                      | 0.45                                        | 30                                                            | 0          |
|           |                    |                                               | 0.5                                         | 27.1                                                          | 9.6%       |
| 6.2       | 0.5                | 0.4–0.55                                      | 0.4                                         | 12.2                                                          | 59.3%      |
|           |                    |                                               | 0.45                                        | 18.4                                                          | 38.7%      |
|           |                    |                                               | 0.5                                         | 25.5                                                          | 15%        |
|           |                    |                                               | 0.55                                        | 30                                                            | 0          |
| 7.2       | 0.7                | 0.35–0.55                                     | 0.35                                        | 10.9                                                          | 63.7%      |
|           |                    |                                               | 0.4                                         | 15.7                                                          | 47.7%      |
|           |                    |                                               | 0.45                                        | 18.2                                                          | 39.3%      |
|           |                    |                                               | 0.5                                         | 24.5                                                          | 18.3%      |
|           |                    |                                               | 0.55                                        | 19.7                                                          | 34.3%      |
| 8.2       | 0.7                | 0.4–0.55                                      | 0.4                                         | 15.5                                                          | 48.3%      |
|           |                    |                                               | 0.45                                        | 21.2                                                          | 29.3%      |
|           |                    |                                               | 0.5                                         | 30                                                            | 0          |
|           |                    |                                               | 0.55                                        | 24.8                                                          | 17.3%      |
| 9.2       | 0.7                | 0.4–0.55                                      | 0.4                                         | 10.6                                                          | 64.7%      |
|           |                    |                                               | 0.45                                        | 18.2                                                          | 39.3%      |
|           |                    |                                               | 0.5                                         | 26.9                                                          | 10.3%      |
|           |                    |                                               | 0.55                                        | 30                                                            | 0          |
5. Conclusion

The basic principle of the bridge-type pneumatic energy-saving system is to control the intake and exhaust time sequences of the air cylinder with the four switch valves by applying the expansion energy of air for work to achieve energy-savings. Because of the compressibility of the air, however, the pneumatic system is often sensitive and the control accuracy thus can be rather poor. Therefore, the applicability of the bridge-type pneumatic energy-saving system needed to be further tested. To solve this problem, a method was proposed in this study to explore and experimentally test the applicability of the bridge-type pneumatic energy-saving system. A nonlinear dynamic optimization model with the air consumption as the objective function was established. The model was solved based on the simultaneous collocation method to obtain the on–off time sequences of the four switch valves. The idea of optimization performance was introduced rating to evaluate the energy-saving performance and stability of the bridge circuit under different working conditions. The main conclusions are as follows:

(1) The applicable range of the bridge circuit was studied. Given the different cylinder diameters, air pressures, and loads, a large number of optimizations and simulations in an AMPL environment were conducted by setting different full stroke times and numbers of discrete points to obtain the applicable range of the bridge circuit. When D was within the range of 16–63 mm and the travel time varied from 0.3 s to 0.9 s, the bridge circuit featured great applicability and could completely replace the traditional circuit, which not only saved energy and but also ensured stability. The larger the cylinder diameter and stroke, and the longer the travel time, the more stable the operation of the bridge circuit;

(2) When D = 16 mm, the bridge circuit was applicable at air pressure ranging from 0.3 MPa to 0.7 MPa, and the load mass varied from 3.2 kg to 9.2 kg. With a cylinder diameter of 63 mm, the bridge circuit was applicable within an air pressure range of 0.3 MPa–0.7 MPa and a load mass range of 38.5 kg–118.5 kg. If the travel time set was too short or too long, the piston experienced impact and rebound to varying degrees, or the piston would not be able to arrived at the stroke end.

Compared with existed research by Doll et al. (2011) and Du et al. (2018, 2020), the applicability and sensitivity of the bridge pneumatic circuit have been established by using an orthogonal collocation optimization method and multiple-variable experiments. It is concluded that the pneumatic system is quite sensitive to changes in operating conditions and the bridge circuit has significantly different performances under different working conditions, because of the strong compressibility of the air. In general, the bridge circuit proposed in this study not only performs well in energy-saving and stability but also has a wide range of applicability, under different working conditions, laying a solid technical foundation for research on the energy-saving performance of pneumatic systems. In this study, it was demonstrated only that the bridge circuit had the potential to replace the

| Load [kg] | Air pressure [MPa] | Time range obtained by dynamic optimization [s] | Full stroke time set in the optimization [s] | Displacement of the piston in the bridge circuit experiment [cm] | Error rate |
|----------|-------------------|-----------------------------------------------|------------------------------------------|-------------------------------------------------|-----------|
| 28.5     | 0.3               | 0.65–0.8                                      | 0.65                                    | 54.2                                            | 9.7%      |
|          |                   |                                               | 0                                        | 55.6                                            | 7.3%      |
|          |                   |                                               | 0.75                                    | 50.9                                            | 15.2%     |
|          |                   |                                               | 0.8                                     | 49.2                                            | 18.0%     |
| 48.5     | 0.3               | 0.7–0.8                                       | 0.7                                     | 59.3                                            | 1.2%      |
|          |                   |                                               | 0.75                                    | 60                                              | 0         |
|          |                   |                                               | 0.8                                     | 58.4                                            | 2.7%      |
| 58.5     | 0.5               | 0.6–0.75                                      | 0.6                                     | 60                                              | 0         |
|          |                   |                                               | 0.65                                    | 57.4                                            | 4.3%      |
|          |                   |                                               | 0.7                                     | 52.9                                            | 11.8%     |
|          |                   |                                               | 0.75                                    | 51.9                                            | 13.5%     |
| 78.5     | 0.5               | 0.55–0.8                                      | 0.55                                    | 58.9                                            | 1.8%      |
|          |                   |                                               | 0.6                                     | 59.1                                            | 1.5%      |
|          |                   |                                               | 0.65                                    | 60                                              | 0         |
| 78.5     | 0.5               | 0.55–0.8                                      | 0.7                                     | 60                                              | 0         |
|          |                   |                                               | 0.75                                    | 58.2                                            | 3.0%      |
|          |                   |                                               | 0.8                                     | 55.6                                            | 7.3%      |
| 98.5     | 0.7               | 0.5–0.8                                       | 0.5                                     | 47.8                                            | 20.3%     |
|          |                   |                                               | 0.55                                    | 48.6                                            | 19.0%     |
|          |                   |                                               | 0.6                                     | 58.9                                            | 1.8%      |
|          |                   |                                               | 0.65                                    | 60                                              | 0         |
|          |                   |                                               | 0.7                                     | 60                                              | 0         |
|          |                   |                                               | 0.75                                    | 59.0                                            | 1.7%      |
|          |                   |                                               | 0.8                                     | 57.2                                            | 4.7%      |
| 118.5    | 0.7               | 0.55–0.9                                      | 0.55                                    | 45.6                                            | 24.0%     |
|          |                   |                                               | 0.6                                     | 54.3                                            | 9.5%      |
|          |                   |                                               | 0.65                                    | 58.6                                            | 2.3%      |
|          |                   |                                               | 0.7                                     | 59.1                                            | 1.5%      |
|          |                   |                                               | 0.75                                    | 60                                              | 0         |
|          |                   |                                               | 0.8                                     | 60                                              | 0         |
|          |                   |                                               | 0.85                                    | 60                                              | 0         |
|          |                   |                                               | 0.9                                     | 56.9                                            | 5.2%      |
traditional circuit. The point of applicability for engineering practice has not yet been reached and a significant amount of work remains, including the following:

(1) Research on the operation characteristics of the bridge circuit based on five switch valves;

(2) Research on other control performance of the bridge circuit—for example, whether buffering can be replaced and whether servo control can be realized;

(3) Development of a digital control valve based on the bridge circuit to finally apply this idea to engineering practice.

Declarations

Author contribution statement

Hongwang Du, Chaoshun Hu, Wei Xiong & Lu Wang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

The work in this paper was supported by the National Natural Science Foundation of China (51175053) and the Fundamental Research Funds for the Central Universities of China (3132019352 and 3132020123).

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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