

# Power Efficiency Optimization of Hydro-pneumatic Transformer of Air-powered Automobile

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**Abstract**—Hydro-pneumatic transform (short for HP transformer) wastes a lot of compressed air when working, and its power efficiency is low. To improve its efficiency, we carry on the parameter optimization which influences the power efficiency of HP transformer system. Firstly, we build up a mathematical model and use the MATLAB software to simulate. Next, we establish the test bench to experiment and verify the mathematical model. Through simulation we set different values to study the relationship between the efficiency and key parameters. We can get some conclusions that, when the input compressed air pressure ranges from 0.5MPa to 0.55MPa, or the area ratio of piston ranges from 4 to 6, the efficiency will exceed 30%. The efficiency nearly keeps constant when the stroke of the piston varies. What's more, with the increase of input pressure and effective piston area ratio, the output power will be rising. When the piston's stroke increases, the output power decreases a little bit. This paper can be a reference of researches on the design and optimizing of HP power system used on air-powered automobile.

**Keywords**—air-powered automobile; efficiency; HP transformer; optimization

## I. INTRODUCTION

As hydro-pneumatic transform (short for HP transformer) has the advantages of smart size, simple structure and excellent performance, it is widely used to transmutation the power of the compressed air to the hydraulic power, such as air-powered automobile and pneumatic machinery [1-3]. However, it still has some disadvantages definitely: its efficiency is low because HP transformer wastes a lot of compressed air when working. Nowadays, studies about HP transformer are mainly refers to its structure and performance, while the efficiency is always ignored. Shen et al [4] research the dynamic performance of an air-powered pump during the air injecting process, and Takeuchi et al [5] design an expansion-type pump by using expansion energy, and they prove the efficiency of the new air booster structure. Shaw et al [6] design a hydraulic motor system which is driven by compressed air. He gets the relationship of speed and efficiency, but he doesn't research the method of parameter improvement. To solve the problem mentioned above, we explore the parameters influencing the efficiency.

In this paper, we introduce the working principle of the HP transformer firstly and then build up a mathematical model based on the principle. To verify the correctness of the mathematical model, we make the Physical object. And though the experiment, we can know that the results of simulation are similar to the experiments'. We also explore the key factors

that influence the power and efficiency. And we can make a conclusion that with the increase of the input compressed air pressure and the stroke of piston, the efficiency increase distinctly within the certain range. But with the effective area ratio of the piston increases, the efficiency decreases distinctly. In response to this situation, we analyzed the reasons in the paper. According to our study, a better choice we suggest is that the input compressed air is range from 0.5MPa to 0.55MPa and the area ratio of the piston floats between 4 and 6, the power efficiency will be optimized, and at this point, the power efficiency will exceed 30 percent. Also, the stroke of the piston can be decided by output power actually needs, because the efficiency keeps constant nearly when the stroke varies. This paper can be a reference of the performance to study and help designing optimization of the HP.

## II. WORKING PRINCIPLES OF THE HP TRANSFORM

A typical HP transformer is shown in figure1, which is composed of two pneumatic chambers, two hydraulic chambers, one relief valve, eight check valves, piston, silencer, pressure regulator, solenoid directional valve and mechanical load.

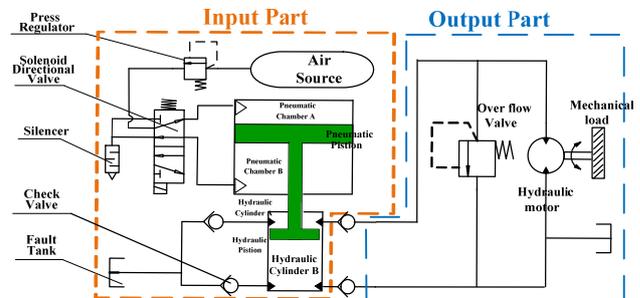


FIGURE I. HP TRANSFORMER STRUCTURE

At the moment that pneumatic chamber A is connected with air source and the pneumatic chamber B connects with atmosphere, low pressure oil will be injected into the hydraulic pumping chamber B. Because stress on the piston is not balance, the pressurized air in pneumatic driving chamber A will drive pistons moving to right. Fuel pressure will increase until it is equal to the output pressure. And then the compressed oil will flow out though the check valve.

When pistons reach the end of their strokes, they will impact the relief valve and lead to change its state. After that, the pneumatic chamber A is connected with the atmosphere and the compressed air flow into air. On the other hand, the pneumatic chamber B is connected to air source and

compressed air flows into it. Also, the low pressure oil flows into the hydraulic pumping A. The piston will move to left as the stress on it is not balance. The pressure of the oil in the hydraulic pumping A will increase until it is equal to the output pressure. Finally, the reversing valve will change its state at the time pistons reach the stroke ends. The high pressure oil will flow out continually by repeating the process mentioned above.

### III. MATHEMATICAL MODEL

Through analyzing the working principles of the HP transformer, we have built a mathematical model, which is verified by the experiment study. The mathematical model of the pneumatic and hydraulic system as follows.

#### A. Pneumatic Energy Equations

We regard the air as ideal. Furthermore, there is no leakage in the chambers and no air comes in and goes out the chamber at the same time. So we can get the energy equation of pneumatic system as follows.

$$C_e M_a \frac{d\theta}{dt} = (A_h \cdot h_c + C \cdot q_e)(\theta_a - \theta_t) + R q_e \theta_a - p \quad (1)$$

$$C_e M_a \frac{d\theta}{dt} = A_h \cdot h_d (\theta_a - \theta_t) + R q_e \theta_a - pA \quad (2)$$

And in the equations,  $C_e$ : specific heat capacity of constant volume, 720J/(kg\*K);  $M_a$ : mass of gas;  $A_h$ : the area of heat transfer;  $q_e$ : air mass flow;  $R$ : Gas constant, 287J/(kg K);  $\theta_t$ : temperature;  $\theta_a$ : the temperature of atmosphere;  $p$ : pressure;  $A$ : piston's area;  $u$ : piston's velocity;  $t$ : time.

#### B. Pneumatic Continuity Equations

The continuity equation of pneumatic system can be expressed as follows according to the ratio of  $p_b/p_d$ .

If  $\frac{p_b}{p_d} > 0.528$ , then:

$$q = \frac{A_e p_d}{\sqrt{\theta_t}} \sqrt{\frac{2k}{R(k-1)}} \left[ \left( \frac{p_b}{p_d} \right)^{\frac{2}{k}} - \left( \frac{p_b}{p_d} \right)^{\frac{k+1}{k}} \right] \quad (3)$$

else if  $\frac{p_b}{p_d} \leq 0.528$ , then:

$$q = \frac{A_e p_h}{\sqrt{\theta_t}} \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{R(k-1)}} \quad (4)$$

And in the equations,  $A_e$ : the area of pneumatic intake and exhaust port;  $p_d$ : pressure of the upstream side;  $p_b$ : pressure of the downstream side;  $k$ : specific heat ratio;  $\theta_t$ : temperature of the upstream side;

#### C. Pneumatic State Equations

The state equation of the compressed air in each pneumatic chamber can be written as follows:

$$\frac{dp}{dt} = \frac{1}{V} \left[ \frac{pV}{\theta_t} \cdot \frac{d\theta_t}{dt} + R \theta_t q_e - p A_h u \right] \quad (5)$$

And in the equations,  $V$ : Volume.

#### D. Motion Equations

The total friction force  $F_f$  includes the viscous friction and Coulomb friction. According to the Newton's second law, we can get the motion equation of the piston as follows:

$$\frac{d^2x}{dt^2} = \frac{1}{M_p} (p_{dA} \cdot A_{dI} - p_{dB} \cdot A_{bI} - p_{bA} \cdot A_{bI} - p_{bB} \cdot A_{bR} - F_f) \quad (6)$$

$$\frac{dx}{dt} = 0 \quad x = 0, L \quad (7)$$

$$F_f = \begin{cases} F_s & u = 0 \\ F_c + Cu & u \neq 0 \end{cases} \quad (8)$$

And in the equations,  $x$ : piston displace;  $p_{dA}$ : Pressure of pneumatic chamber A;  $p_{dB}$ : Pressure of pneumatic chamber B;  $p_{bA}$ : Pressure of hydraulic chamber A;  $p_{bB}$ : Pressure of hydraulic chamber B;  $F_f$ : Friction force;  $F_c$ : coulomb friction;  $F_s$ : maximum static friction;  $C$ : friction coefficient;  $L$ : stroke length;  $M_p$ : total mass of rod and pistons.

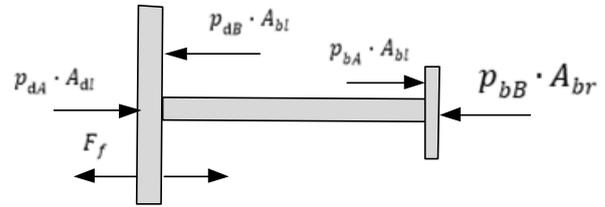


FIGURE II. THE FORCES ON THE PISTONS OF HP SYSTEM.

#### E. Hydraulic Pressure Equations

The pressure equation of the hydraulic pumping chambers can be written as follows:

$$\frac{dp_{dA}}{dt} = \frac{\beta_t}{V} (Q_{A.in} - Q_{A.out} - A_{bh}u) \quad (9)$$

$$\frac{dp_{dB}}{dt} = \frac{\beta_t}{V} (Q_{B.in} - Q_{B.out} - A_{bt}u) \quad (10)$$

And in the equations,  $\beta_t$ : bulk modulus;  $Q_{A.in}$ : input flow to hydraulic chamber A;  $Q_{A.out}$ : output flow from hydraulic chamber A;  $Q_{B.in}$ : input flow to hydraulic chamber B;  $Q_{B.out}$ : output flow from hydraulic chamber B.

#### F. Hydraulic Flow Equations

The flow equation of the oil can be written as follows:

$$Q_{out} = C_f A_h \sqrt{\frac{2(p_h - p_l)}{\rho_o}} \quad (11)$$

And in the equation,  $C_f$ : flow coefficient of the check valve orifice;  $\rho_o$ : oil's density;  $A_h$ : the area of hydraulic intake and exhaust port.

G. Hydraulic Motor Equations

$$q_{mo} = C_{Im}(p_{o1} - p_{o2}) + C_{Em}p_1 + D_{Em} \frac{d\theta_{om}}{dt} + \frac{V_0}{\beta} \cdot \frac{dp_1}{dt} \quad (12)$$

$$D_{Em}(p_{o1} - p_{o2}) = J_{Im} \frac{d^2\theta_m}{dt^2} + B_{Im} \frac{d\theta_{om}}{dt} + G\theta_{om} + T_{IL} \quad (13)$$

And in the equations,  $q_{mo}$ : hydraulic flow through the motor;  $C_{Im}$ ,  $C_{Em}$ : hydraulic motor flow coefficient;  $D_{Em}$ :displacement of hydraulic motor;  $J_{Im}$ : inertia coefficient;  $B_{Im}$ : damp coefficient;  $G$ : stiffness coefficient;  $T_{IL}$ : extra load.

IV. SIMULATION AND EXPERIMENTAL STUDIES ON SYSTEM OPTIMIZATION

We use the mathematical software MATLAB/Simulation to analyze the system. The pressure of the input compressed air and the output oil is set at 0.6MPa and 2MPa. The figure 5a describes the output flow of experiments and simulation; figure 5b describes the rotated speed of the piston.

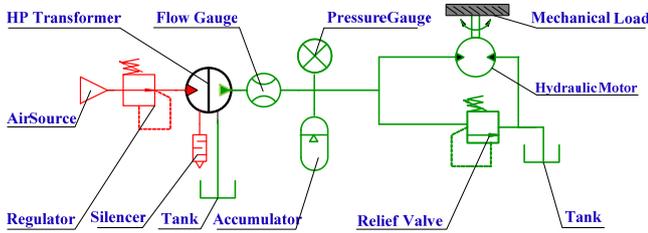


FIGURE III. GRAPHIC OF THE EXPERIMENT SYSTEM

As we can see from figure 5(a), the simulation’s results of the output flow are consistent with the experiments’, which verifies the mathematical model of the HP transformer is correct. The pressure of pneumatic chamber A increases to the input pressure and the pressure of chamber B decreases to the atmosphere when the reversing valve’s state is changed. Once the pneumatic force is higher than resistance force towards left, the piston will move to right to build up the oil’s pressure until it reaches its terminus. Then the pressure of the pneumatic chambers and hydraulic chambers changes with the reversing valve changing its state again.

One thing is clear that the amplitude of the experiments’ result varies up and down compared with the simulation in the figure 5a and 5b, while the curves of the simulation are smoother. This is because the piston’s stress is not evenness and the condition of the device is unstable.



FIGURE IV. EXPERIMENTAL STATION.

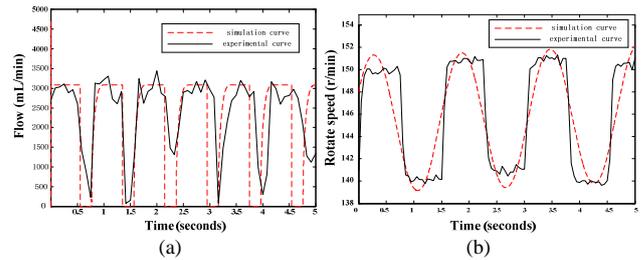


FIGURE V. SIMULATION AND EXPERIMENTAL COMPARISON CURVES. (A) FLOW (B) ROTATE SPEED

We set key parameters influencing the efficiency is input air pressure, including the stroke of the piston and the effective area ratio of the piston on the pneumatic chambers and hydraulic chambers. To explore the relationship between the each parameter and the efficiency, we take the control variable method that changes one variable while others keep constant.

A. Influence of Input Compressed Air’s Pressure

The output pressure of the pumping chamber can be adjusted though the compressed air’s pressure. The output oil’s flow and efficiency is studied when the stroke of the piston and area ratio is set at 0.09 and 6, and the compressed air’s pressure is set at 0.50MPa, 0.55MPa, 0.60MPa, 0.65MPa and 0.700MPa. Figure 5 describes the output power under the difference situation and the figure 6 shows the value of efficiency when input compressed air’s pressure varies.

As we can see from the figure 6 and 7, the output power increases with the increase of the input air pressure, but it is also obviously that efficiency decreases in this process. This is because more expansion energy is wasted when the pneumatic chamber is connected with the atmosphere. And if the expansion energy of the compressed air can be reused, the efficiency of the HP transformer will be increase. Considering the output power and efficiency, we suggested that input pressure of compressed air is range from 0.5-0.55MPa.

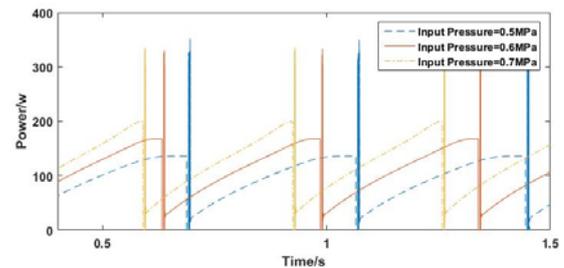


FIGURE VI. POWER-TIME CURVES.

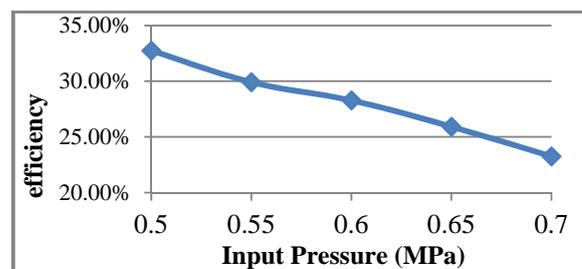


FIGURE VII. EFFICIENCY CURVES.

**B. Influence of Piston's Stroke**

Piston's stroke is up to chamber's size. The output power and efficiency is studied at the time input pressure and area ratio is set at 0.60MPa and 6, and the stroke of the piston is set at 600mm, 750mm, 900mm, 1050mm and 1200mm. Figure 8 describes the output power under the difference situation. Figure 9 shows relationship of efficiency and stroke of pistons.

As can be seen in figure 8 and 9, output power has a little bit decreasing with the increase of the piston's stroke, but the efficiency keeps the constant nearly in this process. This is because the speed of doing work is slowing down when the stroke of the piston increase. So the stroke of the piston is mainly up to output power, and we can select the value of the stroke according to the actual power needs. And during the process of our study, the value of the stroke floating around 0.09m is a better choice.

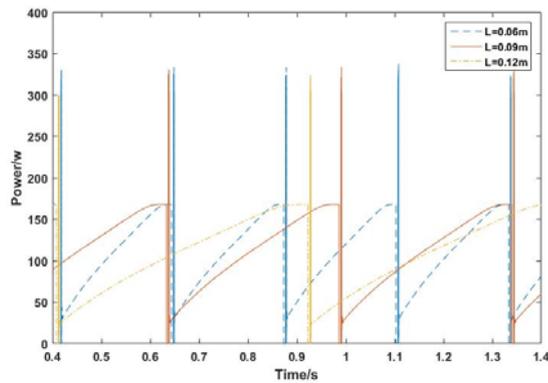


FIGURE VIII. POWER-TIME CURVES

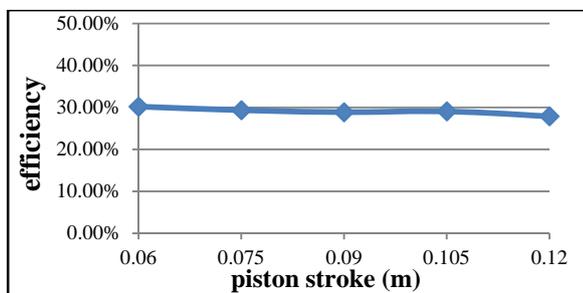


FIGURE IX. EFFICIENCY CURVES

**C. Influence of Piston Area ratio**

The area ratio of the piston is that the effective area of the piston in pneumatic chamber divided by the effective area of the piston in pneumatic chamber. The output power and efficiency is studied when the stroke of the piston and input pressure is set at 0.09m and 0.60MPa, and then piston area ratio is set 4.0, 5.0, 6.0, 7.0 and 8.0. Figure 10 describes the output power under the difference situation. Figure 11 shows the value of efficiency when the area ratio of the piston varies.

From the picture 10 and 11, we would know that enlarging the area ratio will lead to output power increasing, but the efficiency decreases linear in this process. Because the driving chamber's area is bigger, the more expansion energy will be

wasted when the pneumatic chamber is connected with the atmosphere. In order to maximize efficiency and power at the same time, the area ratio of the piston can be range from 4 to 6, which assure that efficiency would exceed 30%.

**V. CONCLUSION**

We build up a mathematical model of the hydro-pneumatic transformer. To optimize the efficiency performance, we study the key parameters influencing the output power and power efficiency. And some conclusions can be draw as follows:

(1).Output power increases with the increase of the input air pressure, but efficiency decreases in this process. Considering the output power and efficiency, we suggested that input pressure of compressed air is range from 0.5-0.55MPa.

(2).The output power has a little bit decreasing with the increase of the piston's stroke, but the efficiency keeps the constant nearly in this process. So the stroke of the piston is mainly up to output power.

(3). Enlarging the area ratio will lead to output power increasing, but the efficiency decreases linear in this process. And the area ratio of the piston can be range from 4 to 6 in order to maximize efficiency and power at the same time, which assure that efficiency would exceed 30%.

This paper can be a reference in designing and optimizing of the HP transformer used on air-powered automobile.

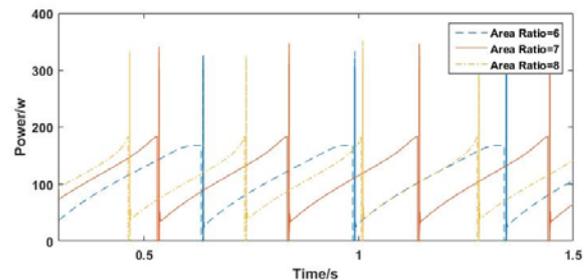


FIGURE X. POWER-TIME CURVES

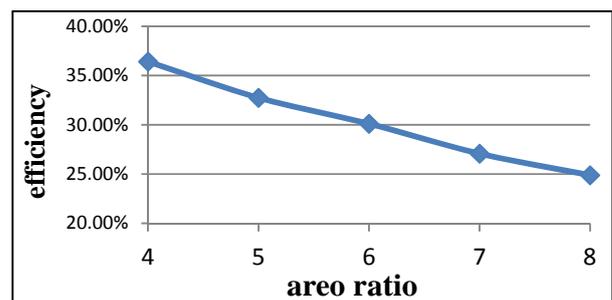


FIGURE XI. EFFICIENCY CURVES

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