Simulation research on control algorithm of differential pressure casting process

*Chai Yan¹, Jie Wanqi¹ and Yang Bo²

(1. School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China; 2. The Second Artillery Engineering College, Xi'an 710025, China)

Abstract: To improve the precision of the filling pressure curve of differential pressure casting controlled with PID controller, the model of differential pressure casting process is established and two pressure-difference control systems using PID algorithm and Dahlin algorithm are separately designed in MATLAB. The scheduled pressure curves controlled with PID algorithm and Dahlin algorithm, respectively, are comparatively simulated in MATLAB. The simulated pressure curves obtained show that the control precision with Dahlin algorithm is higher than that with PID algorithm in the differential pressure casting process, and it was further verified by production practice.

Key words: differential pressure casting; control algorithm; PID; Dahlin; MATLAB; simulation


The liquid filling curve is the major and critical character of the control system for differential pressure casting process and determined by filling pressure, filling speed, pressurizing speed, holding pressure and some other parameters. These parameters seriously influence the microstructures, surface qualities and mechanical properties of castings. The fluctuation of pressure during casting process could cause liquid surface fluctuation, and as a result, introduce various casting defects, especially on surfaces and deteriorate the mechanical properties. The precision and reliability of the filling control system enable to ensure the equipment to produce castings in high quality, therefore it is very important to make sure that the distribution of the operational pressure-difference between the upper and bottom containers match the scheduled filling curve predetermined by calculation.

Due to the longer transfer and response time on the measurement device and the pneumatic film values, the time-delay in the conventional control system, based on the pneumatic film valves, is significantly higher, which decreases the system’s static and dynamic properties. To improve the equipment for good performance, one method is to decrease the transferring and the responding time, the other is to use a proper algorithm for the control system. In this paper, the precisions of the control systems using PID algorithm and Dahlin algorithm are compared with the help of MATLAB.

1 Modeling of differential pressure casting filling process

To illuminate how the algorithms affect the precision of filling curve, a simplified diagram of differential pressure casting’s filling process is given in Fig.1.

![Fig.1: Schematic diagram of differential pressure casting's filling process](image)

In differential pressure casting process, after the synchronous pressure has been established, which means the pressure in the upper container is the same as that in the bottom container, the
pressure in the upper container, \( p_0 \), is required to be constant. Then, the compressed air is introduced into the bottom container and brings pressure to bear on the liquid metal surface. Thus, the pressure in the bottom container, \( p_1 \), is higher than \( p_0 \) and a pressure-difference \( \Delta p = p_1 - p_0 \) exists between the upper and bottom container. This enables to force the liquid metal to overcome the gravity itself and fill up to the casting cavity through the rising tube. According to literature [1], the variation of the pressure difference \( \Delta p \) follows equation (1).

\[
\frac{d\Delta p}{dt} = \frac{RT\gamma'}{V_0 + \frac{F_f}{(F-f)\gamma}} \frac{p_0}{Y} q(t) - c_s \gamma' q(t)
\]

(1)

Where

\[
V_0: \text{The air volume in the crucible at the beginning;}
\]
\[ F: \text{The cross section area of the crucible;}
\[ p_0: \text{The air pressure in the upper container;}
\[ \gamma: \text{The density of aluminum alloy liquid;}
\[ \gamma': \text{The density of air;}
\[ R: \text{Air constant;}
\]
\[ T: \text{The air temperature in the crucible, which can be seen as constant.}
\]
\[ q(t): \text{Air flux flow into the bottom container.}
\]

Carrying out Laplace transform action on equation (1), the transfer function of the crucible can be obtained as follows,

\[
G_s(s) = \frac{\Delta p(s)}{Q(s)} = \frac{1}{T_s s} + \frac{Y}{c_s s}
\]

(2)

Where

\[
T_s = \frac{c_s \gamma'}{Y RT \gamma'}
\]

is the integral time constant of the crucible, \( s \) is the Laplace transform gene in engineering mathematics.

To ensure the precision of the filling curve, the adjustment valve must be taken into consideration and its transfer function is

\[
G_f(s) = \frac{K_f e^{-\tau s}}{T_f s + 1}
\]

(3)

Where

\[
K_f: \text{The magnifying modulus of the adjustment valve;}
\[ T_f: \text{The inertia time constant of the adjustment valve;}
\[ \gamma: \text{The delay time of the adjustment valve.}
\]

Combining equation (2) and equation (3), the transfer function of the liquid surface pressurizing control system can be expressed as bellow,

\[
G(s) = \frac{K_f}{T_s s + 1} e^{-\tau s}
\]

(4)

According to equation (4), it is apparent that the control system of the differential pressure casting can be approximately thought as a second-order retardation system, which consists of delayed subsystem, integral system and inertia subsystem.

All of the parameters of the equipment sampled in this study are as those provided from equation group (5) and the scheduled filling curve of differential pressure casting process, for the purpose of comparison, is as shown in Fig.2.

\[
\begin{align*}
V_0 &= 8.428 \times 10^{-2} m^3 \\
p_0 &= 0.6080 MPa \\
F &= 0.3192 m^2 \\
f &= 3.237 \times 10^{-2} m^2 \\
Y &= 2700 kg \cdot m^3 \\
Y' &= 1.3 kg \cdot m^3 \\
T &= 973 K \\
K_f &= 0.2 / V \\
T_f &= 2.2347 \\
K_f &= 0.8 s
\end{align*}
\]

(5)

Fig.2: The scheduled filling curve of differential pressure casting process

Submitting equation group (5) into equation (4), \( G(s) \) is determined to be as follows:

\[
G(s) = \frac{3.1324}{s(0.8s+1)} e^{0.8s}
\]

(6)

2 PID controller design and the corresponding simulated curve of the control system

2.1 PID controller design

Owing to its simple configuration, high stability and good reliability, PID algorithm is extensively used in industry control systems, such as temperature control, pressure control, flux control, and so on.

The major tasks of PID controller design are to select proper values for proportion coefficient \( K_p \), integral coefficient \( K_i \) and differential coefficient \( K_d \). Before designing the PID controller in MATLAB, suppose \( G'(s) \) as the transfer function of the control system whose time-delay is close to zero, \( G'(s) \) can be written as:

\[
G'(s) = \frac{3.1324}{s(0.8s+1)}
\]

(7)

Then, use critical stability method [2], or so-called Ziegler-
Nichols method to design the PID controller.

First, select \( t = 0.1 \) s as the sampling period, and suppose \( K_i = 0 \) and \( K_d = 0 \), then in the control system applying PID controller designed in MATLAB, as shown in Fig.3, where \( D_p = K_p (P_o - P) \), only proportion adjustment works.

![Fig.3: Control system designed in MATLAB using proportion adjustment only](image)

Then, gradually increases \( K_p \) until the simulation curve begins to oscillate with constant-amplitude, as shown in Fig.4. From Fig.4 the values of \( T_s \) and \( K_s \) are achieved as

\[
\begin{align*}
T_s & = 1.25s \\
K_p & = 6.525
\end{align*}
\]

(8)

![Fig.4: MATLAB simulation curve oscillating with constant-amplitude when \( K_i = K_d = 0 \)](image)

Where

- \( T_s \)-The critical oscillation period;
- \( K_s \)-The critical proportional gain.

According to literature [3], the values of all the parameters of the PID controller, \( K_p \), \( K_i \) and \( K_d \) can be confirmed by derivative calculations and then, the PID controller is designed as

\[
\begin{align*}
K_p & = 0.6 K_i = 3.915 \\
K_i & = \frac{T}{T_s} = \frac{T}{T_s} / 2 = 0.626 \\
K_d & = \frac{T}{T_s} / 8 = K_s = \frac{T}{8T_s} = 6.117
\end{align*}
\]

(9)

2.2 Simulation curve of control system with "zero" time-delay

Suppose the control system’s time-delay is “zero”, applying the PID controller designed by the method in section 2.1 to the control system in MATLAB as shown in Fig.5, where \( z \) is the transform gene. And, the corresponding simulation curve achieved is as shown in Fig.6.

![Fig.5: Control system with "zero" time-delay using PID controller designed in MATLAB](image)
From Fig.6, it can be seen that when the time-delay of the control system is “zero” and using PID controller in the control system of the differential pressure casting filling process, the “actual” pressure-difference curve follows the scheduled curve very well. This means that the precision of control system, when “zero” time-delay, combining the application of PID controller is high.

### 2.3 Simulation curve of control system with “non-zero” time-delay

However, in real control system, it is impossible for the time-delay of the differential pressure casting control system to be “zero”. And, it is true that for the example control system in section 1, its time-delay is 0.5 s. When a time-delay of 0.5 s is taken into consideration, the control system using above PID controller designed in MATLAB is shown in Fig.7, and the MATLAB simulation curve is shown in Fig.8.

Figure 8 clearly shows that the simulated filling pressure curve of the control system with time-delay of 0.5 s oscillates and diverges. At the beginning of the filling process, based on the scheduled pressure difference and the pressure in the upper and bottom containers transferred by the pressure sensor in the bottom container, the PID controller designed in section 2.1 calculates the compressed air needed. If the system has no time delay, with introduction of the compressed air into the bottom container, the pressure values in the bottom container will be changed following the variation of the scheduled curve. However, the system’s time delay causes the pressure transferred to the PID controller lower than the pressure in the bottom container. Thus, the PID controller will order to introduce more compressed air than as needed into the bottom container. This causes the higher “factual” pressure in the bottom container than the scheduled pressure and the relatively higher pressure-difference between the upper and the bottom containers because of the constant pressures maintained on the top. In the simulation curve of the control system with time-delay of 0.5 s, the “factual” pressure-difference simulated in MATLAB has overstepped significantly within no more than 5 s, and the simulated factual pressure-difference between the two containers exceeds the scheduled one more than 100 KPa. Therefore, the precision of the control system is very low.

Comparing Fig. 6 with Fig. 8, it can be concluded that PID algorithm is not suitable for differential pressure casting control system with time-delay.
3 Controller design and the simulation curve of the control system using Dahlin algorithm

3.1 Dahlin digital controller design

With its better control performance than PID algorithm, Dahlin algorithm \(^{[4-6]}\) has been proved to be an effective method to resolve time-delay problem in many control systems and can be used to control the object with one-order subsystem or two-order subsystem with pure time-delay in industry production.

For the differential pressure filling control system with time-delay, the target is to design a proper digital controller called \(D(z)\) using Dahlin algorithm, which builds the transfer function of the whole differential pressure filling control system, \(\Phi(s)\), with a one-order lag subsystem and a one-order inertia subsystem in series. The control system’s transfer function \(\Phi(s)\) and its corresponding pulse transfer function \(\Phi(z)\) are as shown in equation (10).

\[
\begin{align*}
\Phi(s) &= \frac{1}{\lambda s + 1} e^{-\tau s} \\
\Phi(z) &= z^{-n} \frac{1 - e^{-T/\lambda} z^{-1}}{1 - e^{-T/\tau} z^{-1}}
\end{align*}
\]  

(10)

Where

- \(\lambda\): The inertia time constant of the crucible;
- \(\tau\): The delay time of the control system;
- \(n\): An integer and its value is equal to \(\tau / T\);
- \(T\): The sampling period.

After analysis on equation (10), it is known that the controlled object, pressure-difference, of the control system designed with Dahlin algorithm will not overstep in control process \(^{[2]}\). This is just the control target of the differential pressure casting control process.

Taking into account the time-delay of the differential pressure casting control system, the computer control system can be designed with the framework as shown in Fig.9, where \(D(z)\) refers to the digital controller of the loop discrete-time control system, \(r(t)\) refers to the input, \(y(t)\) refers to the output, and \(E(z)\) refers to the deviation.

According to the loop feedback control theory, the expression of \(D(z)\) in Fig.9 can be obtained as follows,

\[
D(z) = \frac{1}{G(z)} \Phi(z)
\]  

(11)

Combining equation (4), equation (10) and equation (11), the expression of \(D(z)\) can be expressed as

\[
G(z) = \frac{K_o e^{-\tau z^{-1}}(T(1-e^{-T/\tau} z^{-1}))+T_{e} (e^{-T/\tau} z^{-1}-1)(1-z^{-1})}{(1-z^{-1})(1-e^{-T/\tau} z^{-1})}
\]  

(12)

From equation (6) the parameters used in equation (11) can be obtained as,

\[
\begin{align*}
K_o &= 3.1324 \\
T_e &= 0.1s \\
T_{e} &= 0.8s \\
\lambda &= 0.8 \\
n &= 5
\end{align*}
\]  

(13)

Substituting equation (12) and equation (13) into equation (11), the Dahlin digital controller of the computer control system is finally as follows.

\[
D(z) = \frac{1-1.8825 z^{-1} + 0.8825 z^{-2}}{0.16 + 0.0121 z^{-1} - 0.1353 z^{-2} - 0.0188 z^{-3} - 0.018 z^{-4}}
\]  

(14)

3.2 Simulation curve of control system with “non-zero” time-delay

As for using PID controller in the control system with “zero” time delay, the control precision is high. However, the control system with “zero” time delay is not designed with Dahlin algorithm in this section and only the control system with “non-zero” time delay using Dahlin algorithm is designed and simulated.

Supposing the control system’s time-delay as 0.5 s, the control system using Dahlin digital controller \(D(z)\) designed in MATLAB is as shown in Fig.10 and the simulation curve is as shown in Fig.11.

In Fig.11, the “factual” pressure-difference curve simulated in MATLAB almost overlaps with the scheduled pressure-difference. This indicates that when the control system with time delay of 0.5 s is designed with Dahlin algorithm, the
4 Practices and conclusions

4.1 Practices

To validate Dahlin algorithm’s advantage, a ZL114A aluminum alloy casting in size of 300 mm × 30 mm × 60 mm is produced by differential pressure casting equipment whose control system adopts PID algorithm and Dahlin algorithm, respectively, and the factual control curves of the filling periods are as shown in Fig.12 and Fig.13.

Comparing Fig.12 with Fig.13, it can be seen that the control system using Dahlin algorithm achieves higher precision than that using PID algorithm in aluminum alloy differential pressure casting process.

4.2 Conclusions

In this paper, the model of the differential pressure casting process is established, which generates the principle base for the control system design and simulation in MATLAB. In the control system design, not only PID algorithm but also Dahlin algorithm can be used. Both the MATLAB simulation curves and the factual filling curves indicate that Dahlin algorithm is better than PID algorithm in the pressure-difference control system. PID algorithm is comparatively suitable only for the control system with time-delay small enough to be negligible. To obtain a sufficient precision of the differential pressure casting filling control system, it is better to adopt Dahlin algorithm in the control system.

References


