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Pneumatic Feeding System Research of the Low-temperature Deposition Manufacturing Based on System Identification and PID Control Method

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Based on the principle of low-temperature deposition manufacturing (LDM), the feeding velocity can be regulated by air pressure. During the whole forming process, the stability of feeding has directly impact on the forming result of scaffold. Under the matching condition of optimal velocity, an appropriate extrusion velocity is the key factor to fabricate perfect structure of macro pore, which avoids collapse between layers and over accumulation. Based system identification theory, this paper builds the model of pressure and extrusion velocity by analyzing the process of Pneumatic material feeding, and then designs PI controller by simulation to guarantee the stability and rapidity. Experiments verifies that the phenomenon of over accumulation and less-lap caused by feeding pressure has been solved at some extent by regulating air inflate and exhaust valve. Conclusion shows the effective control of feeding velocity has great significance for improving the technical level of the bionic bone scaffold fabrication process and fulfilling the automation of bone scaffold molding equipment.

Key words: Bone scaffold, LDM, Pneumatic Feeding, System Identification, Simulation, PID.

Tissue engineering fabricates biological scaffold instead of defective tissue by combining with living cells, scaffold and active factors(b. Subia,*et al*.,2010). With the development of bioengineering technology and bone tissue engineering, some aspects concerned about the bionic scaffold modeling method, manufacture technology research and the development of bone scaffold manufacturing equipment have been improved greatly. For example, By means of Bone Scaffold Low-Temperature Deposition Manufacturing Method (LDM)(Yan,*et al*.,2010), Tsinghua University developed low temperature extrusion equipment named TissForm. So it is possible to industrialize the bone manufacturing technology and develop the bone scaffold fabricating equipment combing the computer technology and automation technology. On the basic of rapid prototyping technology, LDM method has been further developed with the goal of maintaining the activity of biological materials and the free control of scaffold porosity.

Hao fabricated PLGA/â-TCP Scaffold with 90% porosity, pore diameter 300~350ìm by Single Nozzle LDM Technology, meantime dropped the rabbit adipose derivation MSCs coated by I-collagen on scaffold and repaired the rabbit radial bone with 15 mm long defect(Hao W,*et al*.,2010). Compared with the blank control group, the bone-growth was improved and the bone defect was repaired in the bracket group. Kai fabricated the bone scaffold with the aim of stimulating the

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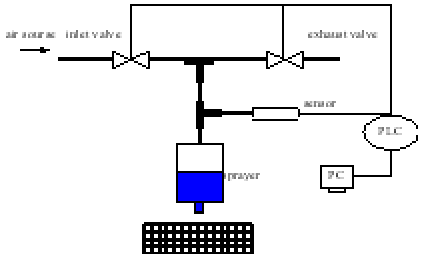
activity of well bone cells and restraining the activity of destructed bone cells by Dual-Nozzle LDM Technology(Kai H,*et al*.,2009). The scaffold material consists of PLGA/â-TCP, Phosphonic Chitosan (stimulate formation) and Sulfur Am monia Chitosan (restrain bone destruction), this kind of scaffold has some good characteristics at the aspect of porosity, water-content and mechanical properties.

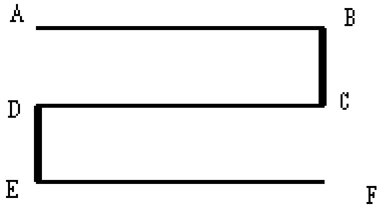
The technical level of bone scaffold forming technology and the automation of equipment are the key factors of realizing the industrialization of bone tissue engineering technology. The results of forming process are mainly determined by LDM parameter, including extrusion velocity, receiving velocity, material temperature and so on(Wang,*et al*.,2008). Importantly, the extrusion velocity has direct impact on the forming quality. When the extrusion velocity is higher, the material will accumulate, which will effect the quality of macro pore .when the extrusion velocity is lower ,there are some less-lap between layers which causes collapse of follow-up forming. So an appropriate feeding is essential for good forming.

Stable pneumatic feeding and response control

The adjustable pressure is offered from air compressor connected with the inlet valve through the pipeline. The three-way pipe acts as a connected pipe to connect with the exhaust valve and the sprayer, which as shown in Fig.1 (a). The deposition path of scaffold is the XY cross grid, a three-dimensional scaffold is accumulated and fabricated by layer and layer. Importantly, the speed of feeding has an important influence on the forming effect, such as overlap between layers, over-accumulation at the edge of paths and so on. If the feeding speed is too fast beyond its upper limit, it will cause the deposition fibers too thick to guarantee the formation of macro-hole size. And a lower feeding speed may lead to the bad overlap between layers, causing the forming process interrupted. When the deposition path is from A to F, it is very important to maintain the material feeding speed stable. During the process of B to C, the receiving speed is changing. The material will be over accumulated because of the alternating movement at X-axis and Y axis, so the phenomenon is inevitable. Therefore, in order to ensure uniform fiber deposition and maintain good forming effect, the material feeding speed and the receiving speed should be maintained stable. Combined with the characteristics of movement receiver-board, the process of feeding is also a continuous process.



(a) Pneumatic feeding system



(b) Forming path

Fig. 1. Structure of Pneumatic Feeding System

To solve the problem of over-accumulation in the corner, at near the end of deposition path of AB segment, close the inlet valve and open the exhaust valve to release the high pressure gas rapidly. At begin of deposition path of CD segment, open the inlet valve and close the exhaust valve to make the gas pressure rapidly rising. By this way, the feeding system can be matched with the movement of receive platform, avoiding the over-accumulated phenomenon in the corner of deposition path.

Control strategy

Analysis of Feeding Model

Ideally, the pressure reaches the set value P0 at the point of time t0. Because of the

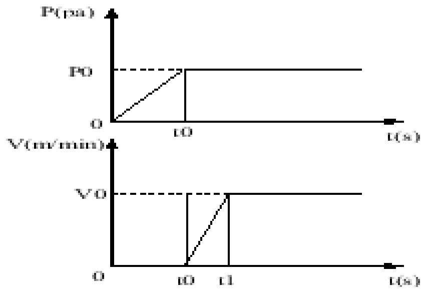


Fig. 2. Pressure and Material Extrusion Velocity with Time

compressibility of air and viscidity of material, the feeding speed is not increasing immediately. When the pressure reaches the set value, the extrusion velocity of materials is gradually increased from 0, and finally become stable after delay-time: $\Delta t = t1 - t0$. However, due to the instability of the gas pressure and time delay, the extrusion velocity and the feeding pressure can not quickly reach stably, generally causing the lack of materials which results in less-lap during the period of Δt . Stable control system for material supply is a necessary condition to ensure the perfect forming effect.

After the above analysis, the typical first-order linear and lag model can exactly describe the pressure - velocity model

$$G(s) = \frac{K}{TS+1} e^{-\tau s} \quad ...(1)$$

Where T is the time constant, K is the proportional coefficient, τ is the lag times.
Laplasse transformation of (1).

$$\frac{v}{p} = \frac{K}{Ts+1} \cdot \frac{1-\tau s/2}{1+\tau s/2} \quad ...(2)$$

After finishing, transformed to differential equations

$$\frac{\tau T}{2}\frac{d^2 v}{dt} + \left(\frac{\tau}{2}+T\right)\frac{d v}{dt} + v = \frac{\tau K}{2}\frac{d p}{dt} + Kp \quad ...(3)$$

Then the discrete differential equation of the above equation

$$v(k) + \frac{\tau+2T}{\tau T} v(k-1) + \frac{2}{\tau T} v(k-2) = -\frac{K}{T} p(k-1) + \frac{2K}{\tau T} p(k-2) \quad ...(4)$$

$\{v(k), v(k-1), v(k-2)\}$ is input sequence, $v(k)$ is pressure set valve at present moment, $\{p(k), p(k-1), p(k-2)\}$ is output sequence, $p(k)$ is the theoretical value of extrusion velocity.

Model Identification

Utilizing the least squares fitting method, a quantitative relationship between feeding pressure and material extrusion velocity is established based on the above data. The process is as shown:

The Matrix equation of the least square fitting is listed:

$$\begin{cases} \theta = [a_1, a_2, \dots, a_{n_a}, b_1, b_2, \dots, b_{n_b}]^T \\ h_f(k) = [-z_f(k-1), \dots, -z_f(k-n_a), u_f(k-1), \dots, u_f(k-n_b)]^T \end{cases} \quad ...(5)$$

Where, $u(k)$ is the pressure input signal, $z(k)$ is the material extrusion velocity, $h(k)$ is the observable quantity, a and b are the recognition factor for algorithm. The expression of least squares identification method is as shown

$$z_f(k) = h_f^T(k)\theta + v(k) \quad ...(6)$$

Where $v(k)$ represents the white noise, θ represents the fitting results needed. Utilize the least squares function of Mat-lab software to obtain parameters: a_1, a_2, b_1, b_2, further determine the each parameter of first-order model according to fitting results.

$$v(k) + b_1 v(k-1) + b_2 v(k-2) = a_1 p(k-1) + a_2 p(k-2) \quad ...(7)$$

Data involved in the identification adopt the mixed solution composed of about 25% gelatin and 3% chitosan.The mixing ratio:1:1, environment temperature: -25°C, material temperature:50°C. According to regulating the original air pressure, calculate the data about pressure and the material flow velocity, which is as shown in Table 1.

Table 1. Different Feeding Pressure and Extrusion Velocity

pressure (Mpa)	Extrusion velocity(m/s)
0.10	0
0.11	0.0269
0.12	0.0539
0.13	0.0673
0.14	0.1044
0.15	0.1212
0.16	0.1431
0.17	0.1852
0.18	0.2189

The transfer function is further obtained.

$$\frac{V}{P} = G(s) = \frac{1.418}{0.945S+1} e^{-4.286s} \quad ...(8)$$

Clearly, extrusion velocity cannot be quickly reached the stable status because of the characteristic of big time delay, and fibers will be broken and less overlap caused by discontinuous material supply in the multi-layers forming process. So it is necessary to design appropriate controllers to satisfy the requirements for the stability and the rapidity of gas supply in the process of scaffold forming. Generally, PID controller, as a major controller, is widely used in different industrial control system, such as temperature, pressure and other systems(Liu,*et al.*,2009) .

The PID controller determines the control deviation e (t) according to the gap between the given value r(t) and the actual output value y(t), and regulates the control deviation e (t) by means of the proportion method, the integral method, the differential method. The continuous form of PID controller is shown:

$$u(t)=k_p[e(t)+\frac{1}{T_i}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}] \quad ...(9)$$

Where $e(t)=r(t)-y(t)$, the system error. k_p, T_i, T_d respectively represent the proportional coefficient, the integral coefficient and the differential coefficient. Therefore, it is the key to determine the parameters:,,in the process of designing PID controller. Different PID parameters have different effects on the performance of control system, so the regulation and the optimization of PID parameters are the core parts in controller design process.

Parameters Setting of PID Controller

The optimal set parameters are the group of parameters which make control system the best condition according to a certain evaluation system. C-C engineering setting method, as the optimal parameters setting formula of PID controller, is improved and concluded on the basis of Z-N engineering setting method. The formulas all make the decay rate:as their performance index, which PID control setting is as follows.

$$T_i/T=\begin{cases} k_c k=1.35(\tau/T)^{-1}+0.27 \\ [2.5(\tau/T)+0.5(\tau/T)^2]/[1+0.6(\tau/T)] \\ T_d/T=0.37(\tau/T)/[1+0.2(\tau/T)] \end{cases} \quad ...(10)$$

According to the setting method, obtain PID control parameters:

$$k_c=0.4,\ T_i=5.49,\ T_d=0.83$$

$$G_c=0.4+0.183/S+0.83S$$

Utilize Simulink of Matlab to simulate, the step response of PID control system is as shown in Fig.3. The system has a heavy oscillation, eventually get stable with a longer transition time. Besides, other parameters are obtained by critical proportion method. Firstly, the system will be equal amplitude oscillation with specific proportion. Secondly, obtain the following parameters by means of the empirical formula. The proportion is 0.36, the integral constant: I=0.12, the step response of system is as shown in Fig 3.

$$G_c=0.36+0.12/S$$

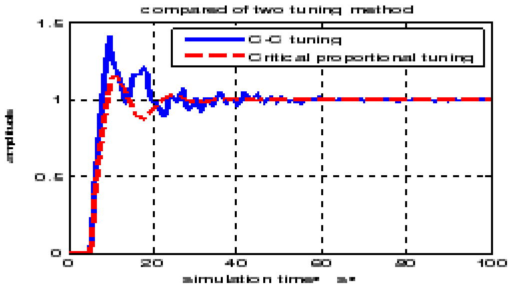


Fig. 3. Step Response of Tuning Methods

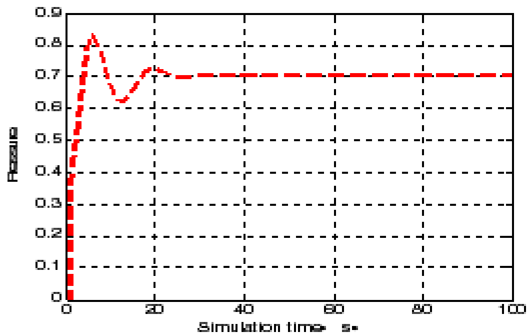


Fig. 4. The Pressure Curve under PID Controller

As shown from the characteristics of the controlled object, the error has been restrained by controller, and serious overshoot has also been avoided generally. By comparison of the two setting methods, the PI controller improves the dynamic characteristics of the system requirements. Ultimately the PI controller is selected based on the results of step response. The pressure curve under the regulation of PI controller is obtained, as shown in Fig.4.

Pressure control method

In order to make pressure accurately controlled, adopt the intake valve and the exhaust valve with high frequency to regulate the pressure of material supply. In the system, the real-time pressure can be measured by pressure sensor, and the PID controller and the pressure sensor compose a closed-loop controller, which block diagram is as shown in Fig 5.

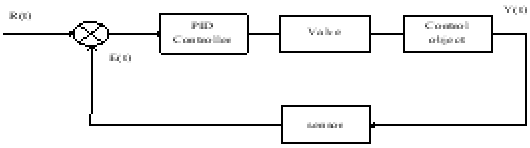


Fig. 5. The Block Diagram of Pressure Closed-loop Controller

Sectional Adjustment of Pressure

As to the sprayer pressure, it is difficult to regulate the real pressure smoothly close to the ideal pressure curve according to the adjustment of PI controller, so the pressure will be handled by different section, as show in Fig.6

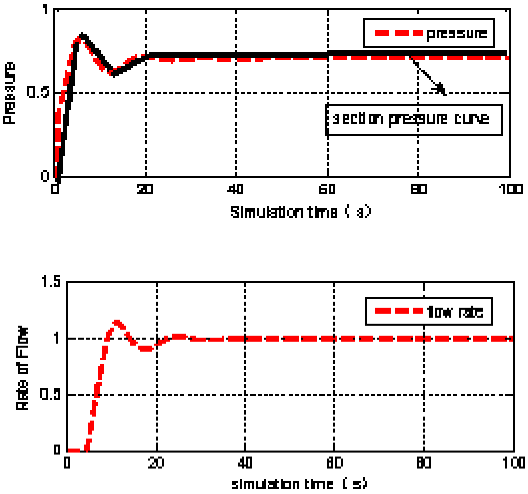


Fig.6. The Curve of Pressure and Extrusion Velocity

Valve Timing Control

Pressure can be regulated by inflating and exhausting air into the fixed container. The inflating time is calculated by the following Equation(Wang,*et al*.,2008).

$$\tau = 5.23\frac{V}{KS}\sqrt{\frac{273}{T_1}} \qquad \text{...(11)}$$

$$\tau_1 = \left(1.285 - \frac{P_0}{P_1}\right)\tau \qquad \text{...(12)}$$

The exhausting time is obtained by the following Equation[8].

$$\tau_2 = \left\{\frac{2K}{K-1}\left[\left(\frac{P_1}{1.893P_a}\right)^{\frac{K-1}{2K}} - 1\right] + 0.945\left(\frac{P_1}{P_a}\right)^{\frac{K-1}{2K}}\right\}\tau \qquad \text{...(13)}$$

P_0 -Initial absolute pressure of the sprayer (MPa);

P_1 -Absolute pressure of gas source (MPa);

τ - Time constant of inflating and deflating (s);

V -Volume; V=0.04249L;

S -Sectional area;

T_1 -Absolute temperature of the gas source (K);

P_a - Absolute pressure of the gas source

The time control of two valves can be calculated by the above formula. According to the required pressure, the curve of inflating time from the atmospheric pressure to the required feeding pressure is obtained and the curve of exhausting time from the required pressure to atmospheric pressure is obtained, as shown in Fig.7

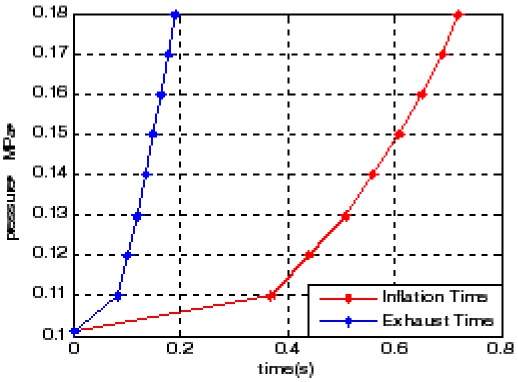


Fig. 7. Curve of Inflating Time and Exhaust Time

The magnetic valve is controlled by the coordinate values of the moving platform in the forming process. Close the intake valve and open the exhaust valve at near the end of the path in advance, make sure that material can not flow out, until the pressure is decreasing to 0.101MPa. In the process, PLC controller realizes the open and

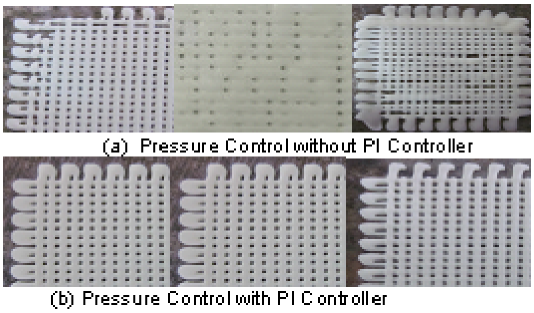


Fig. 8. Results of Experimental

the close of intake valve and exhaust valve with the digital output modular. By regulating the PI controller, the pressure is increasing rapidly to a stable value further improving the dynamic performance of the system.

Experimental verification

Two groups of results of experiment are shown in Fig.8. Because the feeding is unstable, the phenomenon of less-lap and over accumulation is obvious in the group (a). Under the regulation of PI controller, the pressure regulation system has a good stability and rapidity, which ensure the normal overlap, as shown in group (b). By regulating the inflate valve and the exhaust valve, the phenomenon of over accumulation in the corner gets solved to some extent. As known from Fig.8, the rapidity and stability of the feeding pressure is the key factor to a good forming effect.

CONCLUSION

By analyzing the pneumatic feeding system of LDM forming process, establish a pressure and extrusion velocity model by means of identification methods. Then design PID controller to guarantee the stability and rapidity of scaffold fabricating process. Combine the inflating and exhausting time-control, regulate the switching time of intake valve and exhaust valve quickly and effectively, and obtain different pressure in order to solve the phenomenon such as over-accumulation and less-lap in forming process. Finally experiment shows that it is feasible to feed material by regulating pressure, which provides a theoretical basis for the research of feeding system in the field of bone fabrication.

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