Passive velocity field control for die-cutting machine

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Abstract. To solve the problem that new die-cutting machine needs to cut the contour of any shape by XY table, the passive velocity field control is applied to enhance position synchronization of biaxial motions and reduce the contour error. The mathematical model of the die-cutting machine DC servo system is established. And the passive velocity field controller and uniaxial velocity controller are designed. Finally, the validity of the die-cutting machine servo system is verified based on MATLAB/Simulink. The hardware of the servo system based on the STM32F407 produced by ST and the DC servo motor produced by MAXON is completed and circular contour cutting experiment is done.

1. Introduction

In the post-processing of printed products, there is an important cutting process which is called die-cutting indentation technology. Printed products is cut on their surface according to the outline of the pattern. So that it has a logo and artistic aesthetic function, and the level of packaging and printing products have been increased greatly. The added value of the product is increased. For example, a label product with die-cutting is shown in figure 1. Therefore, the die-cutting indentation technology has become an important process in printed products processing. The equipment with die-cutting indentation technology is called die-cutting machine.

Figure 1. A label product with die-cutting.

Traditional die-cutting machine need knife mold, so they are high production costs and long production cycle. The need of die-cutting task with small quantities, fast delivery and patterns of any shape can not be satisfied. The new die-cutting machine have a burin which is driven by XY-biaxial motions. They can cut any contour that is designed in the computer software. Usually, workers send data to the die-cutting machine by computer, and then the machine complete the printed products cutting task immediately. Such die-cutting machine is usually composed of four parts: the paper feed system, the cutting servo system, paper winding system and cleaning system [1]. The cutting system is
the key part of the die-cutting machine, but also the core of die-cutting machine technology. To improve the cutting accuracy is the focus of research.

In the research of position servo control, two types of error are considered, the tracking error and contour error [2]. As shown in figure 2, the distance between the desired position $P$ and the actual position $P^*$ is tracking error. The minimum distance between the desired contour and the actual position $P^*$ is contour error. In the research of die-cutting machine, contour error is paid more attention. But the traditional feedback control only focuses on reducing the tracking error, which leads to contour error becoming larger sometimes [3][4]. In this paper, passive velocity field control is applied to convert the position synchronization of biaxial motions problem to uniaxial velocity control problem. So that the contour error is reduced directly by reducing velocity vector error.

![Figure 2. Tracking error and contour error.](image)

2. Dynamic model of the die-cutting machine servo system

In this paper, DC servo motors are used because of its low inertia, small volume and simple control of speed. H-bridge circuit is used to drive the motors. At the assumption of continuous armature current of motor, the dynamic voltage equation is given as [5]:

$$U_d = RI_d + L\frac{dI_d}{dt} + C_e n$$

(1)

Where $U_d$ is average armature voltage, $R$ is total resistance of armature circuit, $I_d$ is armature current of motor, $L$ is armature inductance of motor, $C_e$ is electromotive coefficient and $n$ is motor rotation speed.

Without friction and elastic torque, the kinematics equation is given as:

$$C_m I_d - T_L = J \frac{d\Omega}{dt}$$

(2)

Where $C_m$ is torque coefficient, $T_L$ is load torque, $J$ is rotary inertia and $\Omega$ is angular velocity. The relationship of rotation speed $n$ and angular velocity $\Omega$ is:

$$\Omega = \frac{2\pi n}{60}$$

(3)

Considering the gear ratio of the gearbox $k$ and the lead of screw $Ph$, the displacement is given:

$$x = \frac{Ph}{60k} \int ndt$$

(4)

On the basis of equation (1), equation (2), equation (3) and equation (4) the mathematical model and dynamic structure for DC motor servo system is established as shown in figure 3.
3. Passive velocity field control

Unlike traditional closed-loop control which is based on time mapping, passive velocity field control (PVFC) is a type of location-based mapping. Each point in space maps a velocity vector related to the desired contour. The component of this velocity vector on each axis is the desired velocity for each axis velocity controller.

Define $G = \{q\}$ be a two-dimensional configuration manifold. Where $q$ is arbitrary point in $G$. Let $T_q G$ be the tangent space of $G$. A desired velocity field $V$ is a map [6]:

$$ V : G \rightarrow T_q G; q \rightarrow V(q) \in T_q G $$  \hspace{1cm} (5)

In figure 4, $(x, y)$ is a point in the two-dimensional configuration manifold. $g(x, y) = 0$ is the desired contour, $P_0$ is nearest point to $(x, y)$ on the desired contour. The velocity vector $v(q(x, y))$ at point $q(x, y)$ is:

$$ v(q(x, y)) = v_t + \lambda d $$  \hspace{1cm} (6)

Where $v_t$ is the tangent vector of $g(x, y) = 0$ at $P_0$, $d$ is distance vector and $\lambda > 0$ is a constant.

![Figure 4](image_url)  

**Figure 4.** The velocity vector at point $q$.

Figure 5 show an example of velocity field for a circle contour. The function of circle contour is $x^2 + y^2 = 1$, the tangent vector norm is 1, and $\lambda = 5$. To make the figure more intuitive, the unit vectors of the velocity vectors are shown.
Figure 5. Example of velocity field for a circle contour.

Specifically, the control law guarantees passivity with the respect to the supply rate $s(\tau_c, v)$ as [7]:

$$s(\tau_c, v) = \tau_c^T v$$

(7)

Where $\tau_e = [\tau_{ex}, \tau_{ey}]^T$ is external forces inputs, $v = [v_x, v_y]^T$ is velocity vector.

The following relationship is satisfied:

$$\int_0^t \tau_e^T v d\tau \geq -c^2$$

(8)

Where $c$ is a real number.

So that the task of reducing contour error is converted to the task of reducing velocity vector error. That is [8]:

$$\lim_{t \to \infty} \left( v(t) - \beta v(q(t)) \right) = 0$$

(9)

Where $\beta > 0$ is a real number.

4. Experiment on simulation platform and hardware platform

The parameter of die-cutting machine and its motors is shown in table 1.

| Parameter                                | Value          |
|------------------------------------------|----------------|
| Rated voltage                            | 24V            |
| Rated Power                              | 20W            |
| Total resistance of armature circuit     | 2.2Ω           |
| Armature inductance                      | $2.38 \times 10^{-3}$H |
| Rotary inertia                           | $3.44 \times 10^{-3}$ kg m² |
| Electromotive coefficient                | 1.2 V/rpm      |
| Torque coefficient                       | 11.459 N m/A   |
| Lead of screw                            | 4mm            |
| Gear radio of the gearbox                | 81:1           |
4.1. Experiment on simulation platform
To verify the feasibility and validity of the control algorithm, simulation model of the servo system is established on Matlab/Simulink platform. The task of the model is to track a circle contour.

The PVFC needs velocity control to realize the velocity closed-loop control of each axis. Velocity and torque double closed-loop PI controller is used. The transfer function of PI controller is:

\[ U(s) = P + \frac{I}{s} \]  \hspace{2cm} (10)

The Simulink model of velocity and torque double closed-loop control system is shown in figure 6.

**Figure 6.** Velocity and torque double closed-loop control system.

The Simulink model of PVFC is shown in figure 7. Its task is to track a circle with a radius of 1.

**Figure 7.** The Simulink model of PVFC.

The control structure diagram of die-cutting machine servo system is shown in figure 8. The initial position is \( x = 1\, \text{mm}, y = 1\, \text{mm} \). The parameter of torque controller is \( P_i = 2.603, I_i = -818.039 \). And the parameter of velocity controller is \( P_n = 2.896, I_n = 51.257 \).

**Figure 8.** The die-cutting machine servo system model.
4.2. Experiment on hardware platform
The hardware platform of die-cutting machine and its PCB board is shown in figure 9 and figure 10. The controller is based on STM32F407. And the DC servo motors are produced by MAXON. The motors contain three parts: a motor body, an encoder and a gearbox. The parameter of motor is shown in table 1.

What’s more, a PC program based on C# language is designed to collect real-time data and to show data in figure. In this experiment, PC program is used to order the machine to cut a circle contour. The initial position of the burin is \( x = 1 \text{mm}, y = 1 \text{mm} \).

5. Results and conclusions
The results of experiment on simulation platform is shown in figure 11 and figure 12. It is shown in figure 9 that the actual contour converges to desired circle contour smoothly. And it is shown in figure 10 that the contour error converges to zero.

The result of experiment on hardware platform is shown in figure 13 and figure 14. It is shown in figure 13 that the burin converges to the desired circle. It is shown in figure 14 that the contour error is no more than 0.009mm after about 1 second.
The simulation model and hardware platform of die-cutting machine is established in this paper. The die-cutting machine with PFVC realize the synchronization of biaxial motions. The trajectory of burin will converge to desired contour smoothly. The contour error is close to zero when the burin is cutting. The simulation and experimental results show the accurate and validity of the PVFC algorithm.

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