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Application of Mechanical Arm Sliding Mode Variable Structure Control in Thermal Cutting of Metal Materials

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In this paper, two aspects of the sliding mode surface and the approach law are introduced in the design process of the sliding mode controller, and the manipulator sliding mode variable structure controller is also designed. A fast segment sliding mode surface is designed based on tracking error, which increases the speed of the system reaching the equilibrium point from any initial state. The fuzzy theory is used to design the power reaching law, which not only guarantees the buffeting suppression but also increases the approaching speed of the system. The simulation results of the manipulator show that this control law not only has faster convergence speed and tracking accuracy, but also can effectively suppress the chattering in the system and has better control performance.

1. Introduction

Cutting means the behaviour to cut the object, which is tightly bound to human production and living. The cutting technology has a long history. But in terms of cutting tools (originated in the Stone age), only the cutter and backsaw were used over a long period (Chen,1982).

In 1901, French engineer Edmond Fouche invented the welding torch using acetylene gas, which made the processing method of metal material leap forward. With the development of modern industry, energy, light energy, electromagnetic wave and other energy sources have been continuously applied, and technological development related to cutting has been developed rapidly. In this paper, two aspects of the sliding mode surface and the approach law are introduced in the design process of the sliding mode controller, and the manipulator sliding mode variable structure controller is designed. A fast segment sliding mode surface is designed based on tracking error, which increases the speed of the system reaching the equilibrium point from any initial state. The fuzzy theory is used to design the power reaching law, which not only guarantees the buffeting suppression but also increases the approaching speed of the system.

1.1 Thermal cutting process method of metal materials

The classification of cutting methods for metal materials is depicted in Fig.1, where mechanical cutting means the process both to partially destroy the material and cut the target material at the same time (Xi, 2012). That is, through the tool contact material, the load damage is carried out on the cutting material. Hot cutting is the process of using high temperature thermal energy to melt metal material, which is used to blow away the melted material and cut off the material. As one necessary process method in the modern industry, the thermal cutting is the basic technique complementary with welding. Its development level is always the important index to influence and measure the basic processing and manufacturing of one country. With the government support for basic equipment manufacturing industry etc., the rapid development and autonomous development of other important industries such as large vessels, oceanographic engineering, railway vehicles, engineering machinery and petroleum/petrochemical, the thermal cutting technology has been developed flourishingly in China (Fu et al., 2017).

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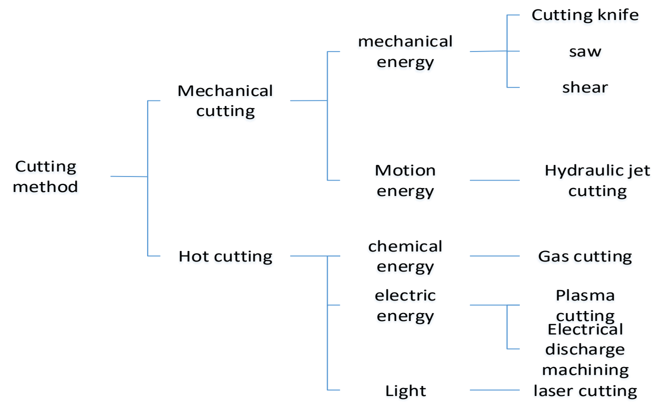

Figure 1: Classification of cutting methods for metal materials

In Fig.1, the laser cutting produces the narrower slot, with the minimum deformation among the thermal cutting techniques, so it is best suitable for precision cutting. In the laser cutting system, the automation can be easily realized, due to a longer working life for the consumable part and no use of combustible gas (Rahmandad et al., 2010). The typical laser cutting device is shown in Fig.2.

Figure 2: Typical laser cutting device

1.2 Mechanical arm sliding mode variable structure

By rotation and movement of all joints, the terminal motion control is made to operate the mechanical arm. The control of mechanical arm is one hard point. For the multi-joint arm widely applied in the modern industry, the control aims to ensure the location of arm terminal moving in the given track, i.e. location tracking issue. However, in addition to the features of highly non-linearity, strong coupling and time-variance, the multi-joint mechanical arm also has some uncertainty such as model error and external disturbance etc. (Li, 1991). The traditional control method cannot make effective control, due to the weak robustness and lower control accuracy etc. But as one common control scheme for robustness, the sliding mode variable structure control has strong robustness for system parameter perturbation and external disturbance, with simply structure and rapid response, so as to be widely applied in the control of mechanical arm (Guo, 2000).

2. Implementation method of Sliding mode variable structure control

2.1 Dynamical model of mechanical arm

For the common n-joint mechanical arm, considering the influence of friction force, unmodeled dynamics and disturbance, the dynamical equation can be given as:

$$M(q)q''+C(q,q')q'=u+f \quad (1)$$

where $q \in R^n$ is position vector; q' and q'' are velocity vector and acceleration vector; $M(q) \in R^{n\times n}$ is the positive definite inertial matrix; $G(q) \in R^n$ is the gravity component vector applied in the joint; $q \in R$ is joint control moment; C(q,q') is centrifugal force and Coriolis matrix; F is external disturbance signal, including mainly the model error, parameter variation and other uncertain factors (Zonglong Wang et al., 2009).

2.2 Design of sliding mode control law

The sliding mode surface is designed to mainly ensure the performance in the sliding motion phase, while the performance in reaching motion phase is effectively improved by the reaching law design. Power reaching law is the common one, which is expressed as:

$$s'=-k|s|^{y}\operatorname{sgn}(s), k>0, 0<y<1 \quad (2)$$

Due to 0 <γ <1 in power reaching law, when the system state approaches to the sliding surface, the approach velocity shall decrease with the distance, so as to eliminate chattering. But when the state goes away from the sliding surface, the velocity of power reaching law would be very low so that the reaching process time is lengthened and further system property is influenced. Therefore, this section aims to improve the power reaching law, and by maintaining its original advantages, promote the reaching performance when the state is away from the sliding surface.

For power reaching law, when the state is far from sliding surface, increasing the value γ can enhance the reaching velocity; when the state approaches to the sliding surface, reducing the γ shall weaken the chattering. So, in terms of the reaching velocity and chattering attenuation, γ can be designed by using the fuzzy method (Zhang et al., 2012).

The position error e of mechanical arm must be influenced by disturbance; with the sliding surface s as the related function of e, the disturbance shall surely affect s value size, so s value can be used to make indirect estimation. Based on this concept, a one-dimensional fuzzy controller can be designed to make real-time adjustment of reaching law parameter γ according to the absolute value of s (Enns, 2011) (Fig.3).

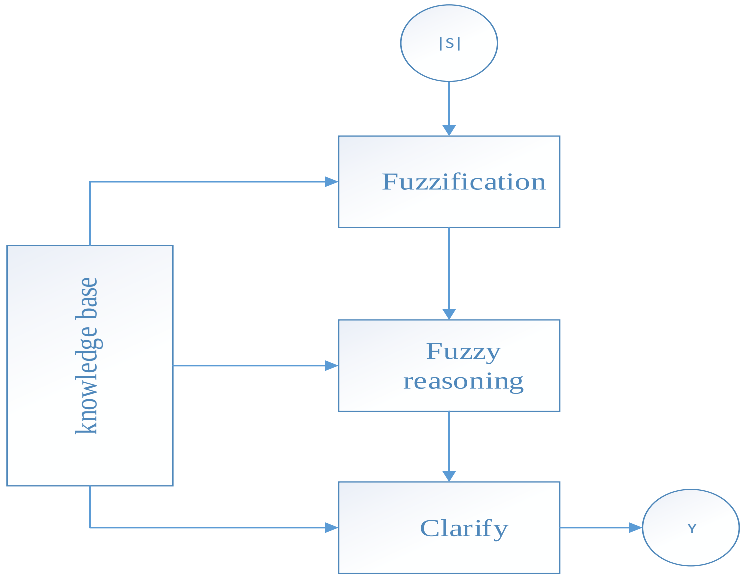

Figure 3: One-dimensional fuzzy controller principle

where the input variable of the fuzzy controller is |s|; output variable is γ. The fuzzy subsets for linguistic value of input and output variables are shown as:

$$ZR, PS, PM, PB \quad (3)$$

Based on the control experiences, if |s| is PB, the system state is far from the sliding surface, so one larger parameter γ should be used to accelerate the reaching, i.e. γ should be PB; if |s| is PS, the system state approaches to the sliding surface, so one smaller parameter γ should be used to slow down the reaching and reduce chattering, i.e. γ should be PS. Above all, the control chart is given in Table 1.

Table 1: Chart of the control regularity

|s|	ZR	PS	PM	PB
Y	ZR	PS	PM	PB

This reaching law can overcome the defect of sliding motion switching band in the exponential reaching law, ensure the rapidness of reaching process, and also effectively reduce the initial system chattering on sliding surface with the reaching velocity close to 0 when approaching to the sliding surface. Based on the new rapid sliding surface and fuzzy power reaching law designed in this paper, the control law can not only increase the system tracking velocity, but also restrain the system chattering in some degree, so as to improve the system control performance.

2.3 Dead Zone Fuzzy Compensator

As is known to all, dead zone compensation rules can be designed as follows:

$$\left.\begin{aligned} &IF\left(\omega \text{ is positive}\right), THEN\left(u=\omega+\hat{d}_{+}\right)\\ &IF\left(\omega \text{ is negative}\right), THEN\left(u=\omega-\hat{d}_{+}\right)\end{aligned}\right\} \tag{4}$$

Where $\hat{d}=[\hat{d}_{+}\ \hat{d}_{-}]^{T}$ is the estimate value of $d=[d_{+}\ d_{-}]^{T}$.

Membership function is designed as:

$$\begin{cases} X_{+}\left(\omega\right)=\begin{cases}0, & \omega<0\\ 1, & 0\le\omega\end{cases}\\ X_{-}\left(\omega\right)=\begin{cases}1, & \omega<0\\ 0, & 0\le\omega\end{cases}\end{cases} \tag{5}$$

Control input after fuzzy compensation is:

$$u=\omega+\omega_{F} \tag{6}$$

ω_{F} is obtained, according to the following fuzzy rules

$$\left.\begin{aligned} &IF\left(\omega\in X_{+}\left(\omega\right)\right), THEN\left(\omega_{F}=\hat{d}_{+}\right)\\ &IF\left(\omega\in X_{-}\left(\omega\right)\right), THEN\left(\omega_{F}=-\hat{d}_{-}\right)\end{aligned}\right\} \tag{7}$$

Output of the fuzzy system is as follow

$$\omega_{F}=\frac{\hat{d}_{+}X_{+}\left(\omega\right)-\hat{d}_{-}X_{-}\left(\omega\right)}{X_{+}\left(\omega\right)+X_{-}\left(\omega\right)} \tag{8}$$

Because of $X_{+}\left(\omega\right)+X_{-}\left(\omega\right)=1$, so we can obtain that

$$\omega_{F}=\hat{d}^{T}X\left(\omega\right) \tag{9}$$

Where $\hat{d}=[\hat{d}_{+}\ \hat{d}_{-}]^{T}$.

$$X\left(\omega\right)=\begin{bmatrix}X_{+}\left(\omega\right)\\ -X_{-}\left(\omega\right)\end{bmatrix} \tag{10}$$

From equations (6) and (10), we can obtain:

$$\tau = D_u\left(u\right) = D_u\left(\omega + \omega_F\right) = \omega + \left[\omega_F - sat_d\left(\omega + \omega_F\right)\right] \tag{11}$$

Theorem 1: From equation(7), the control input is

$$\tau = \omega - \tilde{d}^T X\left(\omega\right) + \tilde{d}^T \delta \tag{12}$$

Where The dead zone estimation error is $\tilde{d} = d - \hat{d}$, Here we must set the unmatched item$\|\delta\| \leqq 1$.

3. Thermal cutting technology of mechanical arm

The laser cutting modes mainly include: laser beam + inert gases (nitrogen etc.), laser beam + air, laser beam + oxygen etc; their cutting capacity increases successively in the condition of the same laser power. In this paper, the cutting mode “laser beam + oxygen” was selected.
The laser cutting means to firstly irradiate the work piece by using the focal high-power density laser beam, then enable the irradiated material to rapidly melt, vaporize, erode and reach the fire point, and finally blow down the molten substance with the high-speed air flow in line with light beam, in order to cut down the work piece. The laser beam cutting technology is divided into four types: laser vaporization cutting, laser melting cutting, laser oxygen cutting, and laser scribing and fracture control.

3.1 Laser vaporization cutting

The high-energy density laser beam is used to heat the work piece and increase the temperature quickly; over a short period, the material reaches the boiling point to make vaporization and then form the vapor. The vapours are erupted at such high speed to form the kerf at the same time. The laser vaporization cutting needs the greater power and power density because of high material evaporation heat. The laser vaporization cutting technology is mostly applied in the ultra-thin metal material and non-metal material (paper, cloth, wood, plastic and rubber etc).

3.2 Laser melting cutting

In the laser melting cutting, after melting the metal material, the nozzle in line with light beam is used to blow the non-oxide gas (Ar, He and N etc.), discharging the liquid metal under the great gas pressure and generating the kerf finally. In this cutting technology, the total evaporation for metal isn’t needed, with the required energy only 1/10 of that in the laser vaporization cutting. The laser melting cutting is mainly used to cut some oxidic materials difficult to be oxidized, or some reactive material, such as stainless steel, titanium, aluminium and alloy etc.

3.3 Laser oxygen cutting

The laser oxygen cutting principle is similar to oxyacetylene cutting by adopting the laser as pre-heat source and the reactive gas such as oxygen etc. as cutting gas. The blown gas works on the target metal and makes oxidation reaction, releasing lots of oxidation heat; then it blows the molten oxide and melt out of the reaction zone, so as to generate the kerf in the metal. Owing to much heat out of oxidation reaction in the cutting process, the energy required for laser oxygen cutting is only 1/2 of that in the laser melting cutting, but the cutting speed is beyond over the laser vaporization cutting and melting cutting. The laser oxygen cutting is mainly applicable to the easily oxidable metal materials such as carbon steel, titanium steel and heat-treated steel (Ran et al., 2014).

3.4 Laser scribing and fracture control

The laser scribing means to scan the surface of brittle material by high-energy density laser, then heat the material to generate one kerf on the material, and finally enables the brittle material to be cracked along the slot by applying certain pressure. Q-switching laser and CO_2 laser are generally selected for laser scribing. The fracture control means that based on the uneven temperature distribution generated by laser scribing, local thermal stress is formed in brittle material to break the material along the groove.
For most laser cutting machines, the NC program or cutting robot is applied to make control operation. The laser cutting, as one precise process method, can almost cut all kinds of materials, including 2-dimensional or 3-dimensional cutting of thin metal plate.

4. Conclusions

In this paper, two aspects of the sliding mode surface and the approach law are introduced in the design process of the sliding mode controller, and the manipulator sliding mode variable structure controller is designed. A fast segment sliding mode surface is designed based on tracking error, which increases the speed of the system reaching the equilibrium point from any initial state. The fuzzy theory is used to design the power reaching law, which not only guarantees the buffeting suppression but also increases the approaching speed of the system. The simulation results of the manipulator show that this control law not only has faster convergence speed and tracking accuracy, but also can effectively suppress the chattering in the system and has better control performance. The control technology used in the laser cutting process to achieve precise cutting of metal materials processing, to ensure processing accuracy, reduce processing stress and ensure the residual strength of the material.

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