# 永磁无刷直流电动机的变结构控制

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**摘要**：本文针对电动车辆这一大惯量负载及变化的电动机参数这一特点，分别对 PMBDC 的转速和加速度采用变结构控制，提高了系统的鲁棒性。仿真实验结果表明，该控制方式不但控制性能很好，而且系统运行速度快，实时性能好。

**关键词**：永磁无刷直流电动机；变结构控制；电动车

## 0　前言

由于石油、天然气将在较短的时间内告罄，使用电动车将是不可抗拒的发展方向，另外，电动车本身作为一种无污染的绿色交通工具在世界各国已引起广泛的关注。电动机驱动系统是电动车的核心。永磁无刷直流电动机（PMBDC）由于具有较高的功率密度和宽广的调速范围，已经在电动车中获得了广泛的应用。为了能实现电动车的自动驾驶，对于这种电动机驱动系统的速度和加速度控制控制的研究具有重大的实用意义[1]。

在众多的现代控制算法中，变结构控制针对电动车辆这一大惯量负载及电动机参数变化较大造成电机模型不准确这一特点具有较大的优势。较大的负载惯量能有效地消除变结构控制的抖动现象，同时变结构控制的抗摄动、抗干扰的强鲁棒性的特点为系统提供了优良的控制性能，而且控制系统结构简单、可靠、实时性能好，硬件实现也很方便[2]。

## 1　PMBDC 的数学模型

PMBDC 主要由电机本体、转子位置传感器及驱动电路、逆变器电路三部分组成，其中转子是永磁体，定子是三相绕组，位置传感器随时判断转子的当前位置，利用这个位置信号来决定逆变器中开关管的导通与关断。

定子电势平衡方程：

$$u_d = e + r_a \cdot i_a + L \cdot \frac{\mathrm{d}i_a}{\mathrm{d}t} \tag{1}$$

$$e = c_e \cdot \omega \tag{2}$$

转矩平衡方程：

$$T = T_L + J \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} \tag{3}$$

$$T = c_m \cdot i_a \tag{4}$$

以上就是电机的运动方程式。

式中：$u_d$ ——加在电枢端的直流电压；

$i_a$ ——电枢电流；

$r_a$ ——电枢绕组的平均电阻；

$e$ ——电枢绕组反电势；

$\omega$ ——机械角速度；

$c_e$、$c_m$ ——分别为反电动势系数和转矩系数；

$T$、$T_L$ ——分别为电磁转矩和负载转矩；

$J$ ——电机转动部分（包括负载）的转动惯量。

其中 $u_d$，$i_a$，$e$ 都是平均值，由于与有效值相差较小，所以工程上多采用以平均值代替有效值。

## 2　转速控制变结构控制律[3]

在电机的运动方程式（1）～（4）中，令 $x_1 = \phi$，$x_2 = \omega$，$x_3 = i_a$，可得

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{J}[c_m x_3 - T_L]$$

$$\dot{x}_3 = -\frac{c_e x_2}{L} - \frac{r_a x_3}{L} + \frac{u}{L}$$

做状态变换 $y = T(x)$，将其转化成正则型后求其控制律[4]。

令 $y_1 = x_1, y_2 = \dot{y}_1 = x_2, y_3 = \dot{y}_2 = \dot{x}_2 = \frac{1}{J}[c_m x_3 - T_L]$。

则有：
$$\begin{cases} \dot{y}_1 = y_2 \\ \dot{y}_2 = y_3 \\ \dot{y}_3 = \beta(x) + \gamma(x)\, u \end{cases} \tag{5}$$

其中 $\beta(x) = -\frac{c_m c_e}{JL} x_2 - \frac{c_m r_a}{JL} x_3$；$\gamma(x) = \frac{c_m}{JL}$

令滑动模态 $S = c(\omega - \omega_0) + \frac{\mathrm{d}}{\mathrm{d}t}(\omega - \omega_0)$，

则 $\dot{S} = c\frac{\mathrm{d}\omega}{\mathrm{d}t} + \frac{\mathrm{d}^2\omega}{\mathrm{d}t^2} = cy_3 + \beta(x) + \gamma(x)\, u$

式中：$\omega_0$ 为给定转速，令 $\dot{S} = -(k\mathrm{sign}S + qS)$，其中 $k$、$q$ 为大于零的正数。

从而：$u = -\frac{1}{\gamma(x)}[k\mathrm{sign}S + qS + cy_3 + \beta(x)]$ (7)

此式即为所求的变结构控制律，其中 $\gamma(x) \neq 0$。

在滑动模态 $S = c(\omega - \omega_0) + \frac{\mathrm{d}}{\mathrm{d}t}(\omega - \omega_0) = 0$ 上可解得 $\omega = \omega_0(1 - e^{-ct})$，由 $c > 0$ 可知 $\lim_{t\to\infty}\omega = \omega_0$。

由于采用 PWM 控制，控制电压存在控制上限，即 $u \le u_N$（额定电压），所以实际控制律为：

$$y = \begin{cases} u_N, & u \ge u_N \\ -\frac{1}{\gamma(x)}[k\mathrm{sign}S + qS + cy_3 + \beta(x)], & u < u_N \end{cases} \tag{8}$$

## 3　加速度变结构控制律

在汽车行驶过程中，特别是在启动过程中，从乘客的乘坐舒适性来说，采用适当的加速曲线可以大大提高其舒适性，这就要求我们能对汽车的加速度进行有效的控制，而传统的力矩控制由于受到负载波动的影响并不能进行有效的加速度控制。本文提出的变结构控制加速度较好地解决了这一问题。

同理，令滑动模态 $S = \varepsilon - \varepsilon_0$，由 (5) 式可知

$$\dot{S} = \beta(x) + \gamma(x)\, u \qquad (9)$$

其中 $\beta(x) = -\frac{c_m c_e}{JL} x_2 - \frac{c_m r_a}{JL} x_3$；$\gamma(x) = \frac{c_m}{JL}$

同理我们可以推导出加速度的变结构控制律为：

$$u = -[k\,\mathrm{sign}S + qS + \beta(x)]/\gamma(x) \qquad (10)$$

在滑动模态上可解得，由可知呈指数趋近于零。可以写出其实际控制律为：

$$y = \begin{cases} u_N, & u \geq u_N \\ -\frac{1}{\gamma(x)}[k\,\mathrm{sign}S + qS + cy_3 + \beta(x)], & u < u_N \end{cases} \qquad (11)$$

## 4 仿真实验分析

仿真实验电机参数为：额定功率 $P_N = 4.5\mathrm{kW}$，额定电压 $u_d = 200\mathrm{V}$，额定电流 $I_N = 22.5\mathrm{A}$，最大电流 $I_{\max} = 67.5\mathrm{A}$，额定转速 $n_N = 3000\mathrm{r/min}$，转子惯量 $J_0 = 0.0017\mathrm{kgm}^2$，绕组电阻 $r_a = 0.218\Omega$，极对数 $p = 2$，电势常数 $c_e = 0.0667\mathrm{V/(r/min)}$，转矩常数 $c_m = 0.6356\mathrm{N\cdot m/A}$。

以实验用电动车净重 330kg，允许乘客及行李 1.7MN，当电动车的最高时速为 30km/h 时，折算到电机的转动惯量约为 $J_L = 0.35\mathrm{kgm}^2$，此时电机转子的转动惯量可以忽略。

电动车在行驶过程中，所受到的阻力是随机变化的，为了仿真方便，取 $T_L = 10 + 2\sin 50t$ (N·m)。

图 1 和图 2 是速度阶跃输入时的加速度响应和速度响应。

图 3 是给定加速度曲线，图 4 和图 5 是给定加速度曲线时的加速度响应和速度响应。

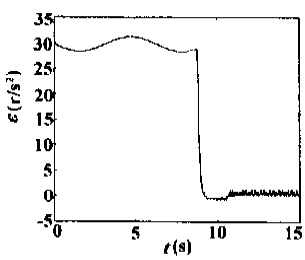


图 1 速度阶跃输入时加速度响应

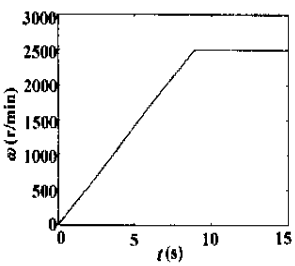


图 2 速度阶跃输入时速度响应

从图 1 和图 2 可以看出，当电动车进行恒速控制时，虽然系统速度具有很好的动静态响应曲线，但控制系统对于加速度的波动是无能为力的，这种加速度的波动在汽车恒速行驶时严重地影响了汽车的乘坐舒适性。

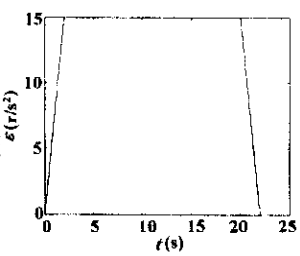


图 3 输入加速度曲线

图 4 是系统采用变结构控制后的输出的加速度曲线。可以看出，此时系统能够较好地跟综任意给定的加速度输入，从而可以通过适当的加减速曲线来实现减弱汽车启、停过程中的不舒适感，提高汽车的乘坐舒适性。

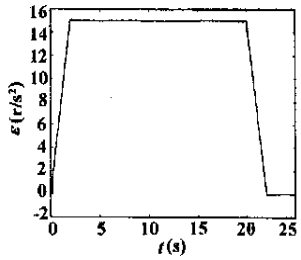


图 4 输出加速度响应曲线

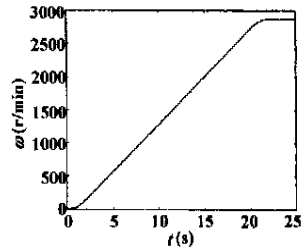


图 5 输出速度响应曲线

## 5 结论

(1) 本文利用计算机仿真方法，对以电动车作为负载的永磁无刷直流电动机系统进行了变结构控制研究，结果表明该控制方法对于电动车这种大惯量系统具有很好的控制效果，系统响应速度快，实时性能好，并且由于大的负载惯量，有效地减弱了变结构控制本身所不可克服的抖振。

(2) 仿真表明，采用变结构控制的电动车驱动系统可以以任一给定的加速度曲线运行，从而有效地减小车辆在启动过程中的冲击和不舒适感。

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收稿时间: 2001 - 03 - 29

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收稿时间: 2001 - 09 - 18

# MACHINE TOOL & HYDRAULICS

No. 6, 2001 (Total Issue No. 174)

## Abstracts and Keywords in English



**Abstract:** There is different identification means between magnetic bearing and common bearing because of different structure. This paper identifies cotructure sefficients of magnetic bearing - rotor system via multi - frequency current excitation method and least - square method. The simulation proves that this identification method is simple and satisfactory precision is obtained.

**Keywords:** Magnetic bearing - rotor system; Multi - frequency current excitation method; Least - square method; Parameter identification



**Abstract:** A FMS distributed & hierarchical control architecture has been constructed in this paper. On the basis of indicated above, the analysis and modeling methods of FMS distributed & hierarchical control system have been proposed. To obtain the ability of partly autonomy and the uniform communicational interface in each of functional entities, the software architecture model of the control system is proposed on the CORBA infrastructure.

**Keywords:** Distributed & hierarchical control; Modeling methods; Control software; CORBA



**Abstract:** The precision expressions are presented for the reultant forces coefficient $K_f$ of the greatest carrying capacity $F_{max}$ under normal and unnroral operating of radial magnetic bearing. All kinds of effect factors and the sensitivity are analyzed. The result of an application example indicates that $K_f$ is the function of magnetic poles $N_p$, bearing clearance $S_r$ and radial displacement $x$ of rotor departure from balance point.

**Keywords:** Radial magnetic bearing; Electro - magnetic bearing; Resultant forces coefficient; Createst carrying capacity



**Abstract:** The traditional Newton finite element method is ameliorated. Combining traditional Newton finite element method with declining method, the Gauss method is applied for the calculation of elasticity distortion in elastohydrodynamic lubrication. The practicable weighted Newton finite element method is found. The convergence of numerical calculation and the suitabiliby of engineering deign for point contact elastohydrodynamic lubrication is solved. The numerical solution of elastohydrodynamic lubrication is given out witin the range of multifarious parameters.

**Keywords:** Point contact elastohydrodynamic lubrication; Weighted Newton finite element method; Bevel gear



**Abstract:** In order to analyze the frequence reponse and time - domain response performance of the two - degree electrohydraulic position servo system of the two - stage electrohydraulic active vibration isolation control system, the transfer function and bond graph modeling and simulating method is applied. The simulation results show that the two - degree electrohydraulic position servo system responds very fast. The experimental results show that both the transfer function model and bond graph model of the two - degree electrohydraulic position servo system are right.

**Keywords:** High response; Two - degree electrohydraulic position servo sytem; Two - stage electrohydraulic active vibration isolation system; Bond graph model



**Abstract:** Ergonomics activities in product development are described based on a schematic representation of product design cycles. A method of integrating ergonomics with the product design cycle is put forward, it makes the successful optimization of products and their user interfaces possible as it helps ergonomic aspects systematically embedded into the product design cycle. Finally, these ergonomics activities are discussed for major ergonomic design and evaluation tasks.

**Keywords:** Ergonomics activities; Product life cycle; User interface



**Abstract:** In this paper, the constant zero - line of rotation error during calibration is defined based on the idea of error separation and the analysis of tool path. Besides, for the position errors of the joint centers on the base are very difficult to gain directly, an simple indirect mothod, named object oriented inverse kinematic calibration (OOIKC), is presented. Moreover, a new concept of gradual calibration is brought forward.

**Keyword:** The variable - axes numeric control machine tool; Stewart platform; Object oriented; Calibration



**Abstract:** An approach of improving general grinding machine by computer was presented and the PC - based control system was designed in this paper. Computer control system for displacement of worktable of plane grinding machine is designed by using usual fluid cylinder and a set of general throttles in this paper. This system can control worktable to move according to definite moving disciplinarian through controlling electromagnetism throttle with definite opening area to open or close. By fast startup, even velocity moving and slowly near target point, the influence of inertia can be deduced, and the displacement precision can be increased greatly. The precision control of arbitrariness displacement of worktable can be realized by the self - studying control principle and slender adjustment strategy.

**Keywords:** Plane grinding machine; Worktable displacement; Computer control system; Self - studying control strategy.



**Abstract:** The motion formula of driven part was converted into cam - contour by the autolisp, then the NC code was generated in the mastercam. It could get rid of the error and trouble caused by manual points drawing and curve fitting, which provided a practical method for cam designing and manufacturing that is complicated, precise and high speed, and for cam parameterized design.

**Keywords:** Cam; Contour; Parameterization; Manufacture



**Abstract:** Nutation is introduced into gear drive. On the basis of dynamics, computing method of gyro mommentin nutation drive of bevel differential is presented. Furthermore, a new kind of optimal metbod is given using MATLAB Optimization Toolbox.

**Keywords:** Bevel gear; Differential teeth; Nutation drive; Gyro moment; MATLAB; Optimization Toolbox



**Abstract:** In this paper, finite element method is used to simulate the flow field of hydraulic integrated block which is widely used in hydraulic technique, and the structure of the flow fieldis given in the visualized picture, with providing the theoretical base for the analysis of energy loss and the optimized design of flow channel.

**Keywords:** Integrated block; Finite element method; Flow channel; Flow field



**Abstract:** This paper recommends the method that how to use Delphi language to second - design line - incision programming system on AutoCAD.

**Keywords:** AutoCAD; Delphi; Line - incision programming system



**Abstract:** The Newton - Euler backward force (moment) recursive equation of robotic manipulator is invalidated when Robotic Manipulator acts on unknown environment because of unknown acting force (moment). In this paper, a forward force (moment) recursive equation of robotic manipulator is given based on 6 - dimension wrist force sensor, and, a kinetic behavior is analyzed and investigated based on 6 - dimension wrist force sensor.

**Keywords:** Robotic manipulator wrist force sensor; Force (moment); Recursive equation



**Abstract:** The paper presents the theory of steam to promote burning, reduce pollution and save energy. The establishment of chemical and physical models of steam promoting burning proves that the theory is feasible.

**Keywords:** Boiler; Steam; Promoting burning; Reducing pollution; Saving energy



**Abstract:** In this paper, aiming at large load inertia and variable electromotive parameter of the electric vehicle, variable structure control is used in the speed and acceleration control of PMBDC, which improved the robusticity of the system. Computer simulation proved that this kind of control has not only excellent control performance, but also rapid running speed and real - time performance.

**Keywords:** PMBDC; VSC control; Electric vehicle



**Abstract:** This papaer describes the filter type incomplete differential PID control algorithm with 2 degrees of freedom and carries out simualtion analysis in accordance with the characteristic of hydraulic servo system in flight simulation swivel - table. Results show that it is superior to traditional PID controller in performance and improves greatly system performance.

**Keywords:** Flight swivel - table; Electrohydraulic servo PID with 2 degrees of freedom



**Abstract:** Because gas viscosity is very small, air hydrostatic bearing has such advantages as low frictions, high rotational accuracy of spindle, stability, reliability, no wear either pollution, and long life etc. For use in high speed ultrasonic rotating head and CNC ultrasonic rotating machine tool, air hydrostatic bearing is advantaging and applicable. This paper describes mainly operation principle and design method of the ultrasonic rotating head with air bearing.

**Keywords:** Air bearing; Ultrasonic rotating; Dsign



**Abstract:** This papers show a new manufacturing system named Realtime Manufacturing, which is a kind of digit manufacturing system that integrate 3 - Ddigit measuring technology and modeling technology with rapid prototyping. And by applying it, the design and manufacturing of product not only would be a very flexible intelligent progress highly integrated and automated, but also would become so short that the corporations could have a very quick feedback to the marketplace.

**Keywords:** Realtime manufacturing; Reverse engineering; Rapid prototyping



**Abstract:** The basic frame, the software and controlling features of the numerical control curling machine are introduced and the mathematical model is established in this paper. The experiment shows that the numerical control system is successful and the machine can be used to machining many sorts of the stamping parts with non - round curve.

**Keywords:** Numerical control curling machine; Numerical control system; Mathematical model



**Abstract:** The authors of this article have systematically made research on the main factors affecting the contact fatigue strength of the tooth surfaces of a gearing, and derived the formulas for calculating the contact fatigue strength of the tooth surfaces of a gearing subjected to the actual external loads including the sliding friction. It has been proved by the researches that the effect of the friction between teeth on the contact fatigue strength of the tooth surfaces of a gearing should not be neglected.

**Keywords:** Gearing; Friction between teeth; Contact fatigue strength.



**Abstract:** In this paper, an algorithm of interference - free electrode motion contrail for 5 - axis machining of freeform suffaces using simple column shape electrode is proposed toward EDM generating of die cavity with complex freeform sufaces. And the spoilage of electrode in the machining process is compensated in this algorithm. So the machining quality and precision is advanced greatly.

**Keywords:** EDM generating machining; Free - form surface; Interference detection



**Abstracts:** An analysis is made on existing tube - cutting machine tool, and based on circle interpolation principle, a new automatic machine tool with feed system driving by x - stepping motor and y - stepping motor is suggested in this paper. The machine's construction is simple, cutting efficiency is high and tool's life is lengthened.

**Keywords:** Tube; Tube - cutting machine tool; Circle interpolation



**Abstract:** It should be guaranteed that the radome has uniform electric thickness after grinding. To grind the radome is difficult because of its complicated rotational shape and special material. So how to carry out the computerized numerical controller (CNC) is an essential problem for the grinding machine tool of radome of missile. This paper presents a dual - CPU hardware structure by means of industrial personal computer (IPC) and PMAC high performance motion control card. The electric circuit has been constructed and the software structure for the CNC system is developed with object - oriented programming technique under Windows98/2000. Some key techniques for CNC system are discussed. The application demonstrate that this system can meet the requirement perfectly.

**Keywords:** Radome; CNC system; Dual - CPU; PMAC



**Abstract:** In this paper, a method of real time automatic tracking to two - dimensional curve was put forward. Based on the principle of light - electricity sensation, the light - point scanned the curve, which forms the light - ring, has determined the orientation of one mioro segment curve to be tracked. Accoring with the information, that is diameter of the light - ring and the orientation of the micro segment curve, the two - dimensional CNC system can fit the curve by the micro segment line and automatically track it at last. The system can widely apply in weld, copy machining and other fields.

**Keywords:** Light - electricity sensation; CNC



**Abstract:** The vibration characteristics of bend axis piston pumpand and its producing mechanism are studied in this paper. The main conclusions for this research are the follwing. The vibration of cylinder is a non - simple forced vibration, which amplitude changes along with rotational speed of plate of principal axis and increases along with pendulum angle. The uneven driving of connecting rods lead to torsional vibration.

**Keywords:** Bend axis piston pump; Cylinder; Torsional vibration; Rotational speed



**Abstract:** Through the method of flow based measurements, not only the controllability of ER fluid power transmssion in applying electric field, but also the correctness of theoretical deducing of control model is proved.

**Keywords:** ER fluid; Fluid power transimission; Controllability



**Abstract:** In this paper a new high - speed solenoid on/off valve with large flow rate is presented. It's construction and work principle are introduced and it's characters is tested. The new construction improves the technical properties of the conventional three - ways on/off valve, solves the contradiction between high speed and large flow rate. It's application to electronically controlled fuel injection system of diesel engine is studied.

**Keywords:** Solenoid valve; High speed on/off; Electronically controlled fuel injection



**Abstract:** The basic concept of CBR is discussed and the methods of design case - based process and retrieval are proposed. The methods are of great importance to flexibility and practicality of CAPP.

**Keywords:** case; case - based process; target process



**Abstract:** Air pressure parameter is multi - variable, non - linear, cunctative and coupling in plasma nitriding process.

**Keywords:** Plasma nitriding; Air pressure; Dynamic charateristic