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VARIABLE STRUCTURE CONTROLLER DESIGN AND ITS REAL–TIME ANALYSIS FOR MICROPROCESSOR–BASED FLIGHT CONTROL SYSTEMS†

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Abstract

This paper presents a new controller design for flight control systems using variable structure system (VSS) theory. A new variable structure control algorithm combined with a conventional controller applied to missile control systems is derived. Digital and digital–analog hybrid simulations are carried out and both dynamic and static system performance are significantly improved with an exponential convergence law and a satuation function introduced. Some of practical problems encountered in real–time control are discussed for engineering implementation of the design. Various noise, disturbances are dealt with to guarantee the stability of the system with high–frequency unmodelled error. Real–time hybrid simulations indicate that the performance of the digital adaptive control system is superior to that of the conventional system both in precision and robustness.

I . Introduction

The digital adaptive flight control systems (FCS) technology has been developed greatly over the last twenty years for tactical weapon applications.(1). A successful analog adaptive autopilot applied to air–to–air missiles system was reported in 1977, which adopted a simple method to implement parameter identifications of the missile body, so called external sinusoidal signal excitation method.(1) The disadvantage is that the adaptive range is limited. Since then, many reseachers have drawn their attentions to the modern control methods, but the model uncertainty has made the work very difficult due to the complicity of state variable identification and the resolution of Reccati derivative equations. Therefore, a new digital adaptive control law was developed for a typical FCS of air–to–air missile based on the conventional control strategy.(1)(5) As a result, some usful results were obtained through theoretical analysis and hybrid simulations. The recent development of this project further verified the results of reference (1) by hardware–in–the–loop simulations,Theoretically, the robustness of the system need to be solved, furthermore, it is seen from the test that the main problems are how to maintain proper operation in small input signal and how to optimize the adaptive controller parameters to obtain the global system stability of robustness and control precision. Some other methodology have been studied on the subject,(3) few papers have been reported on the design of the digital adaptive robust autopilot especially on robustness for practical flight control systems of tactical weapons. This paper is to find a solution to this problem, using variable structure control system methodology.

The theory of variable structure control system(VSCS) has been developed over the past thirty years.(2) Up to now, great achievement have been made for the applications to robotics flexible structure vehicles and electrical power systems.(3)(4)

The principle of a VSCS is that the control logic changes its structure when the system state crosses and immediately recrosses a discontinuous surface in the state space. This idea can result in a special phenomenon, that is so called sliding mode, in which the motion of the system is constrained to lie within a certain subspace of the full state space. As this appears, the system is then equivalent to a system of lower order. The trajectory of the system, therefore, consists of two independent stages, a reaching phase with the motion towards the switching surface and the sliding mode in which the state slides towards the state space origin within the equivalent system. So a VSCS may give a rapid response, robustness to parameter variation and invariance to certain external disturbance. For the methodology of variable structure system design, the switching surface is first selected and then the control logic is defined.

This paper is mainly concerned with the adaptive controller design based on VSCS

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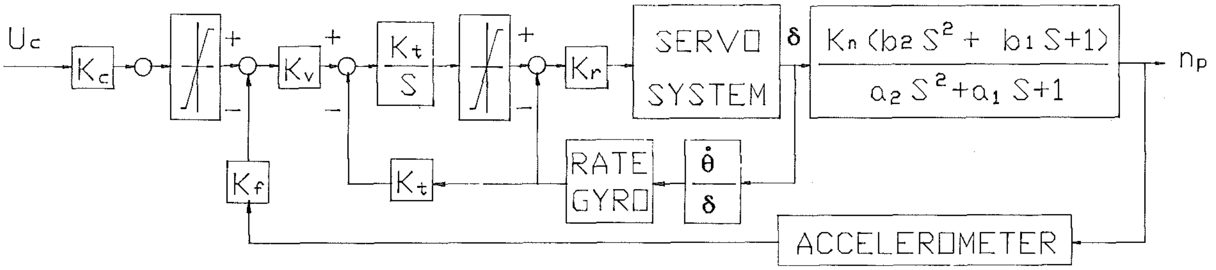

Figure 1 Conventional Flight Control System

theory. As shown in Section Ⅱ and Ⅲ the dynamic properties and static control precision were investigated through theoretical analysis and real−time simulation. The paper is organised as follows. The system modelling is established and the controller algorithm based on VSCS theory is derived in Section Ⅱ and digital−analog hybrid simulation and its real−time analysis are given in Section Ⅲ. Then in Section IV the main points of the paper and some conclusions are presented.

Ⅱ. System Modelling and Algorithm Design

System Modelling

The flight control system for typical intercept tactical missile actually is a ninth order complicated system. It is difficult to derive the control law. Therefore, it is assumed that any conventional accelerometer flight control system shown in Figure 1 can be simplified as a second order, time−varying, linear plant using fast reduction order method, in order to easily derive the adaptive law based on VSCS theory. However, to approach the real situation, actual high order flight control system including dynamics of the actuator, rate gyro and accelerometer combined with the new digital controller is used in the all digital simulations instead of simplified second model used for controller design. So the simplified plant can be described as

$$\begin{bmatrix}\dot{x}_{p1}\\ \dot{x}_{p2}\end{bmatrix}=\begin{bmatrix}0 & 1\\ -a_{p1} & -a_{p2}\end{bmatrix}\begin{bmatrix}x_{p1}\\ x_{p2}\end{bmatrix}+\begin{bmatrix}0\\ b_p\end{bmatrix}u_c \qquad (1)$$

where a_{p1},a_{p2} and b_p are fuctions of the altitude H and speed V of the flight. Uc is the control signal to the plant. To use variable structure control in model−following control, the reference model which presents the desired performance for different flight trajectories is defined as the following form

$$\begin{bmatrix}\dot{x}_{m1}\\ \dot{x}_{m2}\end{bmatrix}=\begin{bmatrix}0 & 1\\ -a_{m1} & -a_{m2}\end{bmatrix}\begin{bmatrix}x_{m1}\\ x_{m2}\end{bmatrix}+\begin{bmatrix}0\\ b_m\end{bmatrix}r \qquad (2)$$

where a_{m1},a_{m2} and b_m are time−invariant coefficients determined according to damping ratio and natural frequency required, and r is the reference input.

Derivation of Control Algorithm

Based on the plant and model derivative equations (1) and (2), generalized error state equation is established as following

$$\begin{bmatrix}\dot{e}_1\\ \dot{e}_2\end{bmatrix}=\begin{bmatrix}0 & 1\\ -a_{m1} & -a_{m2}\end{bmatrix}\begin{bmatrix}e_1\\ e_2\end{bmatrix}+$$

$$\begin{bmatrix}0 & 0\\ -(a_{m1}-a_{p1}) & -(a_{m2}-a_{p2})\end{bmatrix}\begin{bmatrix}x_{p1}\\ x_{p2}\end{bmatrix}$$

$$+\begin{bmatrix}0\\ b_m\end{bmatrix}r-\begin{bmatrix}0\\ b_p\end{bmatrix}u_c \qquad (3)$$

where $e_1=x_{m1}-x_{p1}$,$e_2=x_{m1}-x_{p2}$ The switching function is selected as

$$s=c_1e_1+e_2,\quad c_1>0 \qquad (4)$$

In order to guarantee the error state to move to the sliding line, the synthetic adaptation signal Uc should compensate for the change of the plant parameters and take the form as following

$$u_c=\psi_{e1}e_1+\psi_{p1}x_{p1}+\psi_{p2}x_{p2}+\psi_m r \qquad (5)$$

Then

$$\begin{aligned}\dot{s}&=c_1\dot{e}_1+\dot{e}_2\\ &=c_1e_2+(-a_{m1}e_1-a_{m2}e_2)-(a_{m1}-a_{p1})x_{p1}\\ &\quad-(a_{m2}-a_{p2})x_{p2}+b_m r-b_p u_c\end{aligned} \qquad (6)$$

Substituting equation (5) into equation (6) with consideration of equation (3), $\dot{S}$ becomes

$$\begin{aligned}\dot{s}=&(-a_{m1}-b_p\psi_{e1})e_1+(c_1-a_{m2}-b_p\psi_{e2})e_2\\ &+(-b_p\psi_{p1}-a_{m1}+a_{p2})x_{p2}+(b_m-b_p\psi_m)r\end{aligned}$$

We suppose sliding mode occurs on the line S=0, and find $U_+$and U_- in the neighbourhood of the line such that

$$s\dot{s}<0 \tag{7}$$

This inequality which is the reaching condition guarantees that the state trajectories move towards the line $S=0$ and continue on it after reaching it. Condition (7) can be further written as following inequality

$$s\dot{s}=(-a_{m1}-b_p\psi_{e1})e_1s+(c_1-a_{m2}-b_p\psi_{e2})e_2s +(-b_p\psi_{p1}-a_{m1}+a_{p2})x_{p2}\cdot s+(b_m-b_p\psi_m) rs<0$$

Therefore, we can select the following inequalities to satisfy the reaching condition (7),

$$(-a_{m1}-b_p\psi_{e1})se_1<0 \tag{8}$$
$$(c_1-a_{m2}-b_p\psi_{e2})se_2<0 \tag{9}$$
$$(-b_p\psi_{p1}-a_{m1}+a_{p1})sx_{p1}<0 \tag{10}$$
$$(-b_p\psi_{p2}-a_{m2}+a_{p2})sx_{p2}<0 \tag{11}$$
$$(b_m-b_p\psi_m)sr<0 \tag{12}$$

where e_1, e_2, x_{p1}, x_{p2} and r are available for measurement or their filtered forms. If the boundaries of parameters b_p, a_{p1} and a_{p2} are known. the discontinuous variable controller parameters $\psi_{e1},\psi_{e2},\psi_{p2}$, ψ_m can be selected. With conditions (8) to (12), the control (5) can guarantee both asymptotically stable sliding mode and the reaching conditions $SS<0$. However, the dynamical properties in the reaching phase are uncertain so that the state trajectory reaching form needs further improved and the chattering in the sliding mode has to be eliminated to obtain a controller for practical applications.

Improvement on Dynamic Properties

The phylosophy of improving the dynamic properties is to introduce the idea of certain approaching law towards the switching surface. Here we recommend an exponential law in addition to a constant rate defined as the following form

$$\dot{s}=-\delta\,\mathrm{sgn}S-KS,\quad \delta>0,\ K>0 \tag{13}$$

Obviously, S still satisfies the reaching condition, that is, $SS<0$. Instead of control scheme of equation (5), we choose the control logic as the following

$$u_c=\psi_{e1}e_1+\psi_{e2}e_2+\psi_{p1}x_{p1}+\psi_{p2}x_{p2} +\psi_m r-\delta\,\mathrm{sgn}S-KS \tag{14}$$

considering the reaching condition of inequality (7), we can again obtain inequalities (8) through (12). Apparently, the implementation of the control law (14) does not require knowledge of the disturbance nor the exact plant parameters. Only the ranges of the plant parameters variations are needed.

Chattering Rejection

When the variable structure system with the control algorithm (14) is in sliding mode, its state trajectories lie in the switching surface. However, the theoretical sliding mode is an idealization. Due to the switching delays, high-frequency unmodelled error and other nonideal factors, the control law (14) which satisfies the sliding condition (7) is discontinuous across the surface S, so leading to control chattering. Chattering is generally undesirable in practice, since it involves extremely high control activity, and may excite high-frequency dynamic neglected in the course of modelling. This can result in the failure of whole flight control system, while working in real environment, especially, as concerning with elasticity of the missile body. This problem has been investigated by many researchers for different applications,(3) in which the most effective solution to this problem is to smooth out the control discontinuity in this boundary layer neighbouring the switch surface

$$B=\{x,\ |s|<\varepsilon\}\quad \varepsilon>0 \tag{15}$$

Where ε is the boundary layer width. This is achieved by choosing control law U_c outside B as before, that is, satisfying the sliding condition (7), which guarantees the boundary layer attractiveness and then interpolating U_c inside B for instance, replacing in the expression of U_c the term $\mathrm{sgn}(S)$ by $[S/\varepsilon]$, inside B. This leads to tracking within a guaranteed precision ε, while allowing avoidance of control chattering. Thus, the tradeoff can now be achieved between tracking precision and robustness to unmodelled high-frequency dynamics.

Finally, the variable structure control algorithm is presented as the following formula

$$u_c=\psi_{e1}e_1+\psi_{e2}e_2+\psi_{p1}x_{p1}+\psi_{p2}x_{p2} +\psi_m r-\delta\,\mathrm{sat}[S/\varepsilon]-KS \tag{16}$$

in which the function sat is defined as $\mathrm{sat}(y)=y$ when $|y|<1$ and $\mathrm{sat}(y)=\mathrm{sgn}(y)$ when $|y|>1$, and $\psi_{e1},\psi_{e2},\psi_{p2}$ and ψ_m are selected according to the boundary of the dynamic parameters, δ can be determined by simulation and parameter optimization, the tracking error of ε is given in accordiance with system requirement.

To the engineering consideration, x_{p1} and $x_{p2}=\dot{x}_{p1}$ are normal acceleration and its derivative of the missile. However, it is evident that derivative of the normal acceleration is difficult to measure in the actual autopilot. But we can approximately use the pitch altitude rate of the missile to replace X_p according to the following equation

$$\dot{N}_p+R(t)\cdot N_p=Q(t)\cdot\dot{\theta}$$

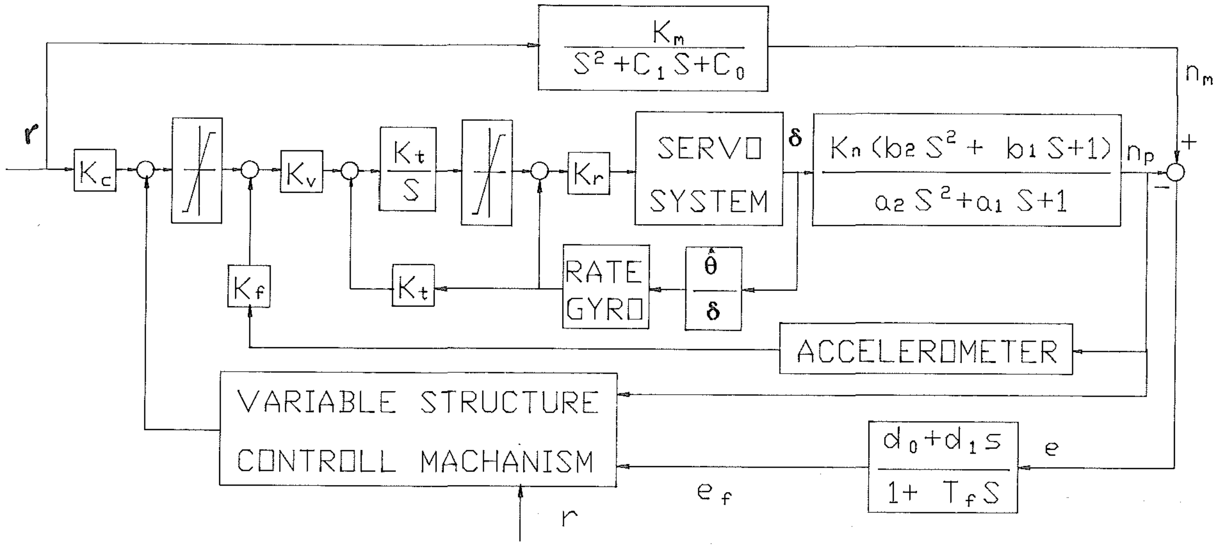

Figure 2 Flight Control System with Variable Structure Control

where $N_p=x_{p1},N_p=x_{p1}=x_{p2}$
The block diagram of the adaptive control system is shown in Figure 2.

Ⅲ. Hybrid Simulation

The real–time hybrid simulations were conducted to investigate the sliding motions of the flight control system in Figure 2 under variable structure control. The purpose of simulating the system in a hybrid environment, based on digital parameter optimization and system simulation is twofold, first, to observe the nonideal sliding motions due to delay caused by the implementation of the control law and other imperfections and second, to demonstrate that variable structure control law is suitable to be implemented on microcomputers or microprocessors. A laboratory real–time simulation configuration with a microcomputer PC/286, coprocessor 80287 and a general purpose interface board Lab–Master including DADIO are developed. The hybrid simulation hardware configuration is shown in Figure 3. Analog computer DMJ–3B is used to realize the conventional autopilot with time–varying missile body dynamics. The PC/286 implements the main program designed in Fortran language and variable structure control algorithm in 80287 assembly language. Three analog signals n_m,n_p and r are input through Lab–Master and the controller output Uc is converted into analog control signal by DADIO and then feedbacked to the system, the hybrid simulation block diagram for the variable structure control FCS is shown in Figure 3. The control logic is performed on PC/286. It is pointed out that the control law can be implemented as sum of linear state feedbacd terms and relay terms. The feedback gains and relay magnitudes are switched depending on the sign of S. Computation of the function S and the determination of the sign of S and each state variable are performed by a Fortran program. However, the sum of each term in (16) is calculated in 80–bit floating–point of 80287. The whole program can be linked with A/D convertion modual, D/A convertion modual and control algorithm subroutine by FORTRAN compiler. The main program flow chart is given in Figure 4

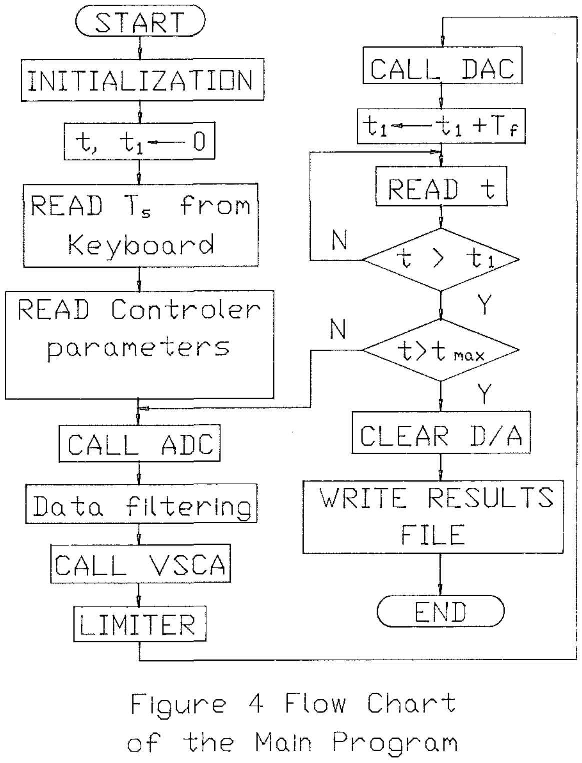

Figure 4 Flow Chart of the Main Program

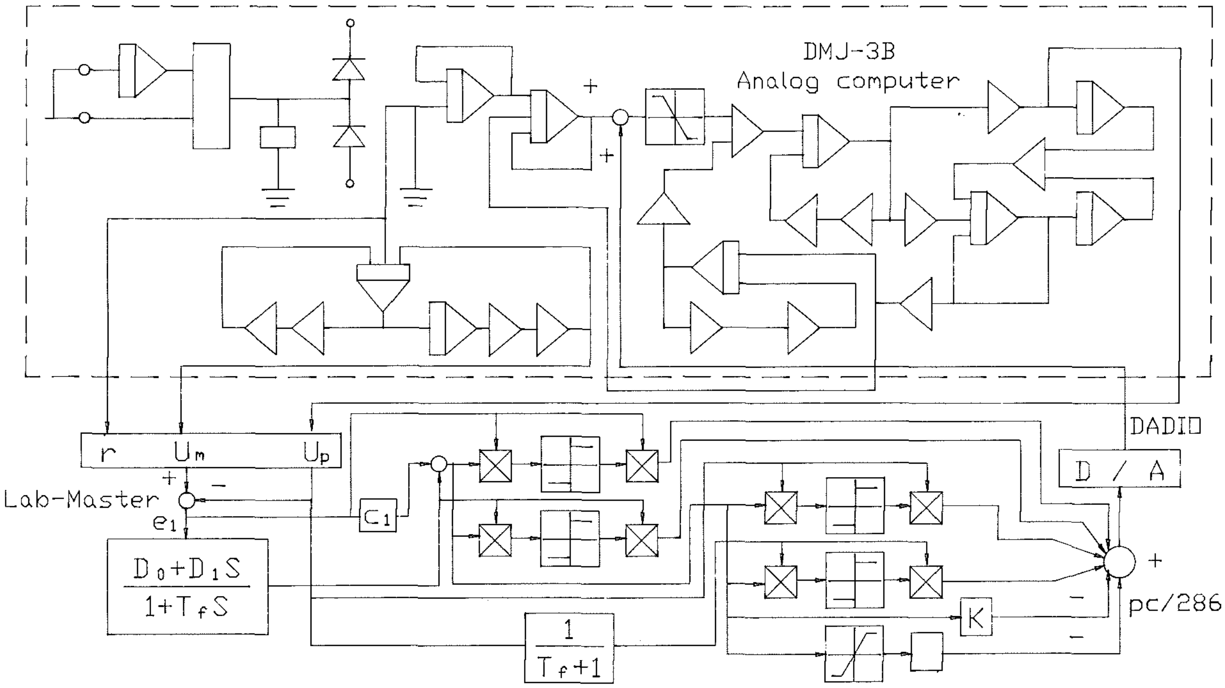

Figure 3 Block Diagram of Hybrid Simulation

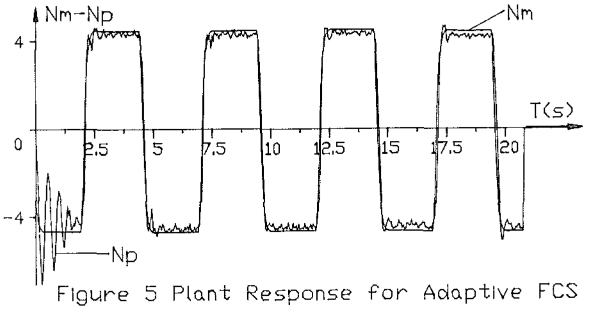

Figure 5 Plant Response for Adaptive FCS

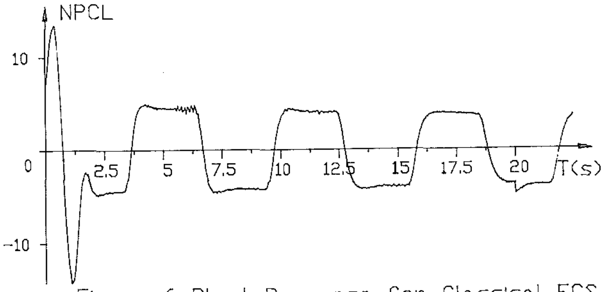

Figure 6 Plant Response for Classical FCS

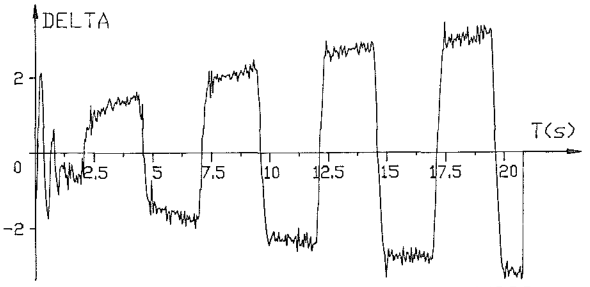

Figure 7 Actuator Response for VSCS

The real-time hybrid simulations were carried out for typical flight trajectories and different reference input. The same results as those of the all digital simulations were obtained as shown in Figure 5 to Figure 7. From the comparison of the variable structure control with the classical control, it is clear that the variable structure controller makes dynamical and static properties of the FCS greatly improved. It is alse seen that the effect of the chattering due to the control delay of the FCS properties is considerably acceptable. Besides, it is shown that despite chattering phenomenon the speed of the sliding mode is close to the designed speed determined by the choice of the switching line S . In our simulation experiments performed, some implementation considerations are taken into account. In particular, the effect of model order uncertainty, the effect of the sampling rate and the effect of the magnitude of input signal are studied on the FCS. Consequently, it proves that model order uncertainty does not significantly change the dynamic response of the system as shown in Figure 5. In addition, sampling rate is better selected to 5 msec for the autopilot of tactical missiles. The results also shown that the FCS based on the variable structure control possesses high robustness to the perturbation of the system parameters, gust wind and random disturbance by adding the disturbance signal into the sytem while tested.

IV. Conclusions

The digital–analog hybrid simulation has indicated that the VSCS approach is applicable to the FCS with large range of time–varying parameters. Both the dynamical and static properties of the system are significantly improved by the introduction of an exponential convergence law and the saturation function. Based on the classical design of the system, the robustness of the system can be achieved with the conventional configuration and the new digital controller. Meanwhile,the desirable tracking precision is maintained due to the elimination of chattering in sliding mode. Our simulation experiment results also show that the plant output is quite smooth. By comparison all digital hybrid simulation results are quite close to theoretical analysis despite the presence of some type of nonidealities. In the view of implementation of the configuration, simulation results also show that the variable structure controller is easy to realize with state–of–the–art onboard microprocessor in real time.

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