CHEMICAL ENGINEERING TRANSACTIONS

VOL. 46, 2015

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216 DOI: 10.3303/CET1546027

Research on the Attitude Control Law of Hypersonic Flight Vehicle

Hongcheng Zhou*[a, b], Daobo Wang[b], Juan Yang[a]

[a] Institute of Information, JinLing Institute of Technology, Nanjing, 211169, China
[b] College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China
31750210@qq.com

Hypersonic flight vehicle has strong-nonlinearity, quick time-variability, strong-coupling features. In order to realize its flight effective control, the airflow attitude angle needs to be controlled precisely. Based on the accurate tracking of the airflow attitude angle command, the predetermined flight path can be realized to accomplish flight tasks. Use dynamic surface (DSC) to design the airflow angle attitude control law, which proves the stability and the time-delay compensation effect. The simulation results show that this method has good tracking control and fast convergence.

1. Introduction

Hypersonic flight vehicle has some characteristics, such as strong-nonlinearity, quick time-variability, strong coupling, etc. In order to realize its flight effective control, first it is necessary to realize the accurate control of airflow attitude angle. In particular, because of the extremely high speed of hypersonic flight vehicle, the engine is sensitive to the airflow angle, so the control instantaneity is required to draw enough attention. Through analyses, the control of hypersonic flight vehicle should be based on and center on the controls of the airflow angle and the roll angle. Built on the realization of the accurate tracking of the airflow angle instruction, the predetermined flight path can be realized, thus the flight tasks can be accomplished. Therefore, we study the tracking controls of airflow angles and roll angles for hypersonic flight vehicles. Considering the input time delay induced by the system signal transmission of the aircraft and the actuator dynamic, compensate for the adverse effects caused by it, that realize the tracking controls of airflow angles and roll angles for hypersonic flight vehicles with the input time-delay [B. Song et al (2010) and D. Xu et al (2013) reported].

2. Problem Description

According to the kinematics equation of attitude angle and the kinetics equation of angular rate, abstract the input time-delay effect caused by signal transmission and actuator dynamic as the situation of pure input containing time-delay, and describe the attitude control problem of hypersonic flight vehicle as the control problem of input with time-delay for block strict feedback nonlinear systems. The mathematical description is as follows [G. Cai et al (2008) reported]:where and are nonlinear function vectors; and are control gain matrices; is the time-delay model.

$$\begin{cases} \dot{\Omega} = f_s + g_s \omega \\ \dot{\omega} = f_f + g_f g_{f\delta} \delta\left(t - D(t)\right) \\ y = \Omega \end{cases} \tag{1}$$

where f_s and f_f are nonlinear function vectors; g_s and $g_f g_\delta$ are control gain matrices; $D(t)$ is the time-delay model.

Please cite this article as: Zhou H.C., Wang D.B., Yang J., 2015, Research on the attitude control law of hypersonic flight vehicle, Chemical Engineering Transactions, 46, 157-162 DOI:10.3303/CET1546027

3. Time-delay Compensator

Time-delay systems have a variety of processing modes. Now the method of Lyapunov functional form is often adopted. Yet for nonlinear systems, especially the nonlinear systems with input time-delay, the available results are difficult to be obtained. A time-delay compensating control method developing recently is presented here. This method is of good generality and has special convenience in a complex with other methods. It is suitable for the case of actuation with time-delay for the hypersonic flight vehicle under study [H. Gao, T. Chen. (2008) reported].
Consider a general nonlinear system of input with time-delay, which can be described as follows:

$$\dot{x}(t) = f(x(t), u(t - D(t))) \tag{2}$$

where $x \in R^n$, $u \in R^m$, $t \in R_+$ and f is first-order derivable and continuous. In order to illustrate and prove the validity of the time-delay compensation control in theory, make further assumptions as follows[5].

Hypothesis: when $t \geq 0$, then $\phi(t) \leq t$, $\phi'(t) > 0$,satisfying $\phi(t) = t - D(t)$ and there are:

$$\pi_0^* = \frac{1}{\sup_{\theta \geq \phi^{-1}(0)} (\theta - \phi(\theta))} > 0 \tag{3}$$

$$\pi_1^* = \frac{1}{\sup_{\theta \geq \phi^{-1}(0)} \phi'(\theta)} > 0 \tag{4}$$

If one can be asymptotically positive definite, the controller of no time-delay nominal system $\dot{x} = f(x, u)$ is denoted as $u(t) = k(t, x)$. Then the controller with time-delay compensation has the following form.

$$u(t) = k(\phi^{-1}(t), P(t)) \tag{5}$$

where $P(t)$ has the following form.

$$\begin{aligned} P(\theta) &= (\phi^{-1}(t) - t) \int_0^{\frac{\phi^{-1}(\theta) - t}{\phi^{-1}(t) - t}} f(P(\phi(t + y(\phi^{-1}(t) - t))), u(\phi(t + y(\phi^{-1}(t) - t))))dy + x(t) \\ &= \int_{\phi(t)}^{\theta} f(P(\sigma), u(\sigma)) \frac{d\sigma}{\phi'(\phi^{-1}(\sigma))} + x(t), \qquad \phi(t) \leq \theta \leq t \end{aligned} \tag{6}$$

First, use the ideas of PDE to convert it to a system described by partial differential equations with time and time-delay quantity as the system independent variables. After that, obtain the reversible transformation of the system, which proves that the transformation maintain the nature of the system unchanged. Through the stability demonstration of the target system after transformation, the stability theorem of the system can be obtained further. Time-delay system performs the transformation, and its equivalent expression of the partial differential equation is shown as follows [H. Kim, H. Dharmayanda, T. Kang (2012) reported]:

$$\begin{aligned} &\dot{x}(t) = f(x(t), U(0, t)) \\ &U_t(x, t) = \pi(x, t) U_x(x, t), \quad x \in [0, 1] \\ &U(1, t) = u(t) \end{aligned} \tag{7}$$

where

$$\pi(x, t) = \frac{1 + x\left(\dfrac{d(\phi^{-1}(t))}{dt} - 1\right)}{\phi^{-1}(t) - t} \tag{8}$$

Choose such a transmission rate function for seeking the appropriate form of infinite dimensional actuator state to satisfy $U(0,t)=u(\phi(t))$ and $U(1,t)=u(t)$.

4. Controller design and stability analysis

It can be seen in backstepping design process that with the increase of system hierarchical design steps, it needs to take the derivative of the virtual order of the previous layer. Taking such recursion, the expansion equation of the derivative item will be more and more complicated. When there are noncontiguous items or uncertain items in the system, it cannot take analytical derivative of it directly. The idea of the dynamic surface control method is to deal with this problem in order to simplify the design result and expand the scope of backstepping applications [L.Peng, M.Zhijun, W.Zhe. (2011) reported]. After designing the virtual control law of the subsystem on each layer, the method takes advantage of low pass filter $L(s)$ to filter the virtual instruction. The state equation of filter $L(s)$ is shown as follows.

$$\dot{x}=-\frac{1}{\tau}x+u,\ x(0)=0 \tag{9}$$

Where τ is the time constant of filter, and u is the virtual instruction designed already. By τ, the virtual instructions produced by the subsystem on each layer produce the corresponding outputs. So, when next subsystem is under design, use the filter output instead of the virtual control law, and replace the derivative of virtual instruction with $\left(\frac{\tau u-x}{\tau}\right)$ There's no need to take the derivative of the nonlinear item in the virtual control law directly, that avoid the computation of the expansion problem of the backstepping method and relax the requirement of the method for the system continuity.

The DSC method is applied to the attitude tracking control of hypersonic flight vehicle, and the design steps of the nominal system without time-delay in the input are as follows [S. Xiaojie (2013) reported]:

1) For airflow angles and roll angles, design the virtual control law. Define $\mathbf{x}_1 \triangleq \mathbf{\Omega}, \mathbf{f}_1 \triangleq \mathbf{f}_s, \mathbf{g}_1 \triangleq \mathbf{g}_s, c_1=c_s$, $\mathbf{e}_1 \triangleq \mathbf{e}_s=\mathbf{\Omega}-\mathbf{\Omega}_d$. Similar to backstepping method, the design of the loop control law of the attitude angle is

$$\boldsymbol{\omega}_d=\mathbf{g}_s^{-1}(-c_s\mathbf{e}_s-\mathbf{f}_s+\dot{\mathbf{\Omega}}_d) \tag{10}$$

2) Design the loop control law of angular rate. Instruction ω_d obtains $\hat{\omega}_d$, the angular rate instruction to be traced actually, and its derivative $\dot{\hat{\omega}}_d$. $\dot{\hat{\omega}}_d=-\frac{1}{\tau}\hat{\omega}_d+\omega_d,\quad \omega_d(0)=0$. Define $\mathbf{x}_2 \triangleq \boldsymbol{\omega}$, $\mathbf{f}_2 \triangleq \mathbf{f}_f$, $\mathbf{g}_2 \triangleq g_f g_{f,\delta}, c_f \triangleq c_2, \mathbf{e}_2 \triangleq \mathbf{e}_f=\boldsymbol{\omega}-\hat{\boldsymbol{\omega}}_d$. The design of the loop control law of angular rate is

$$\begin{aligned} &\delta_c=g_2^{-1}(-c_f\mathbf{e}_f-\mathbf{f}_f-\mathbf{g}_s^{\mathrm{T}}\mathbf{e}_s+\dot{\hat{\boldsymbol{\omega}}}_d)\\ &\tau\dot{\hat{\omega}}_d=-\hat{\omega}_d+\omega_d \end{aligned} \tag{11}$$

The error systems after joining DSC include tracking errors and filter tracking errors. Therein, e_1 and e_2 are the reference instruction and the tracking error of the virtual instruction after filtering; e_3 is the tracking error of the input and output signals of filter [X.Su et al(2013) reported].

$$e_1=x_1-x_{1d}\ e_2=x_2-\bar{x}_{2d}\ e_3=\bar{x}_{2d}-x_{2d}$$

The three error states defined above are as follows:

$$\begin{cases} \dot{e}_1 = \dot{x}_1 - \dot{x}_{1d} = f_1 + g_1 x_2 + d_1 - \dot{x}_{1d} \\ \dot{e}_2 = \dot{x}_2 - \dot{\bar{x}}_{2d} = f_2 + g_2 u + d_2 + \dfrac{\bar{x}_{2d} - x_{2d}}{\tau} \\ \dot{e}_3 = \dot{\bar{x}}_{2d} - \dot{x}_{2d} = \dfrac{-e_3}{\tau} - \dot{x}_{2d} \end{cases} \tag{12}$$

Take the virtual instruction as $x_{2d} = g_1^{-1}\left(-f_1 + \dot{x}_{1d} + K_1 e_1\right)$. After finishing the closed-loop system with the additional input is as follows:

$$\begin{cases} \dot{e}_1 = f_1 + g_1\left(e_2 + e_3 + x_{2d}\right) + d_1 - \dot{x}_{1d} \\ \quad = g_1\left(e_2 + e_3\right) + + K_1 e_1 + d_1 \\ \dot{e}_2 = f_2 + g_2 u + d_2 + \dfrac{e_3}{\tau} \\ \dot{e}_3 = \dfrac{-e_3}{\tau} - \dot{x}_{2d} \end{cases} \tag{13}$$

For the equation of the motion attitude system of the hypersonic flight vehicle, when $D(t) = 0$, the tracking controller is designed by using DSC method, and the additional inputs of the system are d_1 and d_2.

5. Simulated experiment verification

It assumes that some parameters of the aircraft are constants, such as mass, moment of inertia, etc. M=136080tKg. The initial flight speed is V_0=2200m/s. The thrust is a constant, namely T=400KN. The initial value of the flight height is H_0=27km. The initial value of the attack angle is $\alpha_0 = 1.0^\circ$. The initial value of the sideslip angle is $\beta_0 = 1.0^\circ$. $\mu_0 = 0.5^\circ$ expresses the initial value of the roll angle around speed. $p_0 = q_0 = r_0 = 0$ rad/s is the initial value of the component of the body angular rate, and the simulation time is 10s. Input time-delay function is $D(t) = \dfrac{1+t}{2(1+2t)}$, which is easy to verify the assumptions satisfying the time-delay model. The expected attack angle instruction is that the 6-degree constant outputs through a first-order link, and $\alpha = \dfrac{6}{s+2}$; sideslip angle instructions are $\beta = 0^\circ$, $\mu = -1^\circ$.

For the same control gain, when using the time-delay compensation, the tracking results and the control signals are as shown in the figures below:

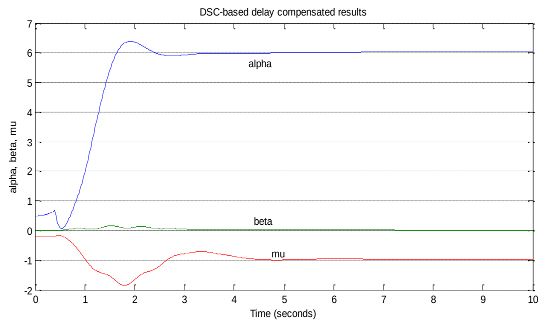

Figure 1: Tracking results with time-delay Compensation

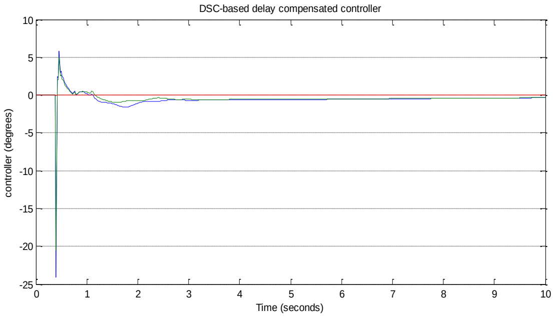

Figure 2: Controlled quantity with time-delay compensation (the deflection angle of the rudder surface)

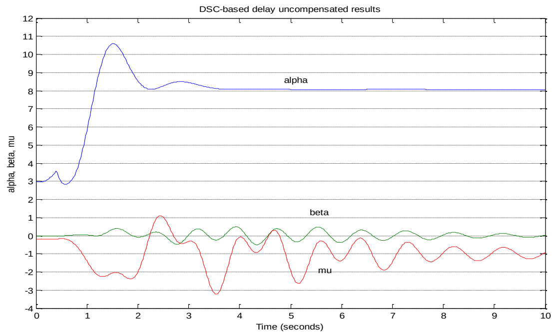

Figure 3: Tracking results without compensation

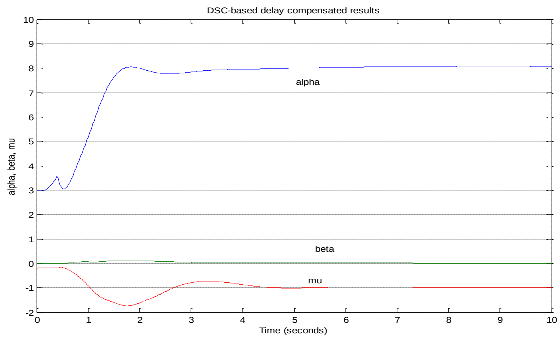

Figure 4: Tracking results with time-delay compensation

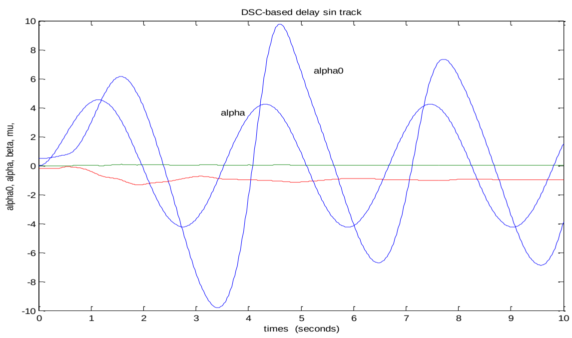

Figure 5: Tracking results without compensation

In the above simulations, the control gains designed for the nominal system are insufficient. There needs to adjust the control gains in the case of time-delay to ensure that the same gain for the nominal case and the time-delay case can guarantee the tracking effects. The control effect of the case that the gain of the virtual instruction is small and the gain of the rudder surface is large is better.

6. Conclusions

Firstly, provide the mathematical expression of nonlinear control problems of aircraft attitude with time-delay input. Secondly, for hypersonic flight vehicle, use the method of dynamic surface to design the airflow angle attitude control law, and prove the stability and the compensation effect for time-delay. Finally, the simulation results of the control method in hypersonic flight vehicles are given, and they show that this method achieves the desired effect.

Acknowledgment

This work was supported by Natural Science Research Project (No. 61302167), Natural Science Foundation of Jiangsu Province No. 15KJB510012.

References

Cai G., Chen B., Peng K., 2008, Modeling and control of the yaw channel of a UAV helicopter. IEEE Trans. on Industrial Electronics, 55(9), 3426-3434, DOI: 10.1109/TIE.2008.926780.

Gao H., Chen T., 2008, Network based H output tracking control. IEEE Trans. on Automatic Control, 53(3), 655-667, DOI: 10.1109/TAC.2008.919850.

Kim H., Dharmayanda H., Kang T., Adiprawita A.B., 2012, Parameter identification and design of a robust attitude controller using H1 methodology for the raptor E620 small-scale helicopter. International Journal of Control, Automation, and Systems. 10(1), 88-101, DOI: 10.1007/s12555-012-0110-5.

Liu P., Meng Z.J., Wu. Z., 2011, A robust flight control system design for a small-scale UAV helicopter. Transactions of the Japan Society for Aeronautical and Space Sciences, 56(2), 96-103. DOI: 10.2322/tjsass.56.96.

Song B., Mills J., Liu Y., Fan C., 2010, Nonlinear dynamic modeling and control of a small-scale helicopter. International Journal of Control, Automation, and Systems. 8(3), 534-543, DOI: 10.1007/s12555-010-0306-5.

Su X.J., Shi P., Wu L.G., Song Y.D., 2013, A novel control design on discrete-time takagi-sugeno fuzzy systems with time-varying delays, IEEE Transactions on Fuzzy Systems, Information and Control, 21(4), 655-671. DOI: 10.1109/TFUZZ.2012.2226941.

Xu D., Jiang B., Shi P., 2013, Global robust tracking control of non-affine nonlinear systems with application to yaw control of UAV helicopter. International Journal of Control, Automation and Systems, 11(5), 957-965, DOI: 10.1007/s12555-012-0335-3.