Controller Analysis and Synthesis Based on Data Modeling for Hypersonic Vehicles

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Abstract

Owing to lack of enough experimental data, currently it mostly focuses on the longitudinal model to research the controller of hypersonic vehicles, mostly oversight of strong coupling and nonlinearity between different subsystems of hypersonic vehicles. This paper uses NASA's open aerodynamic derivative data graph and modeling method of hypersonic vehicle to build a general hypersonic vehicle longitudinal model, and calculate the equilibrium value, longitudinal and transverse modal characteristic roots of hypersonic vehicle in different flight conditions, and according to the linear model, using H_∞ *method to design controller to improve the performance of the system. By comparing the regulation performance and anti-jamming performance of the feed-back systems designed, their respective advantages and disadvantages of control schemes are summarized. Although the research object mainly aim to aircraft longitudinal models in hypersonic flight condition, but these design methods and ideas are equally applicable to the lateral model.*

Key words: *Hypersonic Vehicles, Data Modeling,* H_∞ *Controller*

1. Introduction

Similar to other control systems, the control system of hypersonic vehicle is mainly reflected in the stability, control performance, the robustness and so on [1, 2]. According to open literatures, owing to lack of enough experimental data and the relevant data are strictly confidential, currently the research on hypersonic flight control mostly focuses on the longitudinal model, strong coupling and nonlinearity between different subsystems of hypersonic vehicles are ignored. The models applied in open literatures are usually the simplified longitudinal models of hypersonic vehicle, which mainly include the linear model under the balanced point [3-8] and the nonlinear model with velocity and flight path coupling [9-12]. After getting the hypersonic vehicle models, introducing the relevant parameters or structural uncertainty according to the control requirements, Then application such as the sliding mode control, H_∞ control, u control and other advanced controlling methods to design a control system according to these models. And finally by simulation analysis, test and verify if the controller has restrained the effect of nonlinear coupling and uncertain factors [13-19].

At present, the research on flight control system of hypersonic vehicle is on the premise of ignoring the mutual coupling effects of the model, namely mainly designs the longitudinal modality controller of hypersonic vehicles. Yet the lateral modality controller of hypersonic vehicles is only briefly introduced in [13-14]. Possible dynamic characteristics for lateral modality controller of hypersonic vehicles are analyzed, and adopting common gain presetting method in engineering to design the controller. But the design process of these lateral modal controllers is very preliminary, even the models controlled are not given too. Therefore, if further considering the lateral and longitudinal coupling model, the control problem becomes more complex [14-19].

This paper deeply explores hypersonic vehicle modeling and its advanced control mechanism. In the process of modeling, this paper takes the NASA's open aerodynamic derivative data graph of the hypersonic vehicle and combines data modeling methods to build a general hypersonic vehicle longitudinal model and calculates the equilibrium value, characteristic roots of the longitudinal and lateral modality and approximate flight envelope in different flight modes of hypersonic vehicle. According to the mathematical model with serious nonlinear, strong input-output coupling and structure and parameter uncertainty characteristics, using H_∞ methods to design the controller, and the regulation performance and anti-jamming performance of a hypersonic vehicle are analyzed, its basic flight characteristics are grasped, a good design platform is provided for the control system.

The paper is organized as follows. Section 2 introduces the data modeling and model analyzing method. Section 3.1 derives H_∞ controller algorithm for hypersonic vehicles, provides an example to verify the effectiveness of the proposed algorithm. For comparison, respective simulation results of pole placement, LQR and H_∞ controller are given in Section 3.2. Finally, concluding remarks are given in Section 4.

2. Data Modeling and Model Analyzing

This paper adopts the hypersonic general nonlinear longitudinal model, for the sake of simplicity, first of all do some appropriate hypothesis for the air-vehicle itself and the flight environment. Without loss of generality, assume:

(1)The hypersonic vehicle is an ideal rigid body, namely, not consider elastic wing.

(2) The mass center and rotational inertia are functions of mass. The mass center always changes on the vertical axis of the body.

(3) The vehicle center and the reference torque center are on X axis of the body.

(4) Aircraft layout is symmetrical, namely, the products of inertia I_{xy}, I_{xz}, I_{yz} are constantly zero.

(5)Ignoring the rotational inertia of control surface and the engine installation angle of the thrust.

Each force acting on the center of rigid body is shown in Figure 1.

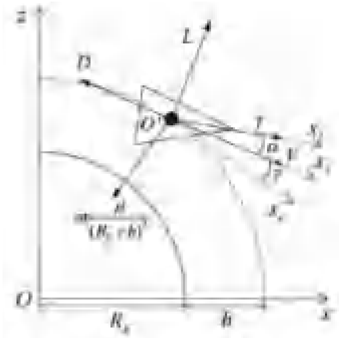

Figure 1. Analysis of the universal longitudinal model of hypersonic vehicle

In the course of modeling for the longitudinal motion of hypersonic vehicle, assume that thrust direction is along the engine axis and parallel to the axis of the fuselage. On the law of universal gravitation, the Newtonian second law, circular motion theory and the differential equation of the rigid body rotation, take the opening degree of the throttle valve η, the lifting rudder deflection angle δ_e as the input, and select the flight speed, flight path angle, angle of attack, pitch angle speed and altitude respectively as the state of variables $x=[V \quad \gamma \quad \alpha \quad q \quad h]^T$. According to the force, on the speed coordinate system, the non-linear dynamics equation set of longitudinal dynamical model of a hypersonic vehicle can be described as follows:

$$\dot{V} = \frac{T\cos\alpha - D}{m} - \frac{\mu}{(R_E + h)^2}\sin\gamma \tag{1}$$

$$\dot{\gamma} = \frac{L + T\sin\alpha}{mV} - \frac{\mu}{V(R_E + h)^2}\cos\gamma + \frac{V}{R_E + h}\cos\gamma \tag{2}$$

$$\dot{\alpha} = q - \dot{\gamma} \tag{3}$$

$$\dot{q} = \frac{M_{yy}}{I_{yy}} \tag{4}$$

$$\dot{h} = V \sin\gamma \tag{5}$$

The meanings of the symbols mentioned above are shown in Table 1.

Table 1. List of symbols

symbol	meaning
v	sound velocity
C_D	traction coefficient (drag coefficient)
C_L	lift coefficient
$C_M(q)$	pitching moment coefficient
$C_M(\alpha)$	angle of incidence moment coefficient
$C_M(\delta_e)$	elevator moment coefficient
C_T	thrust coefficient
$\overline{c}$	average aerodynamic chord
D	resistance
h	height
I_{yy}	rotational inertia
L	elevating force
M_α	Mach number
m	the mass of air-vehicle
q	gradient
R_E	earth radius
S	reference plane (datum plane)
T	thrust
V	flight speed
α	angle of incidence
α_0	angle of incidence in the designated area
η	throttle valve opening
γ	track angle
δ_e	elevator angle
θ	helical angle
μ	gravitation constant
ρ	air density

$T=\frac{1}{2}\rho v^2 SC_T$, $L=\frac{1}{2}\rho v^2 SC_L$, $D=\frac{1}{2}\rho v^2 SC_D$. M_{yy} means the pitch moment, and its expression is $M_{yy}=\frac{1}{2}\rho V^2 S\bar{c}[C_M(\alpha)+C_M(\delta)+C_M(q)]$. $C_M(\alpha)$, $C_M(\delta_e)$, $C_M(q)$ stand for the angle of incidence coefficient, the elevator moment coefficient, and the pitching moment coefficient.

For any group of Mach number, angle of attack and control surface deflection values, the corresponding aerodynamic derivatives values can be got by cubic spline interpolation method, so the required aerodynamic derivatives of the longitudinal and transverse-lateral modes for hypersonic vehicle modeling can be obtained by the following expression.

$$
\begin{cases}
C_L = \alpha(0.493 + \dfrac{1.91}{M_\alpha}) \\
C_D = 0.0082(171.0\alpha^2 + 1.15\alpha + 2.0)(0.0012M_\alpha^2 - 0.054M_\alpha + 1.0) \\
C_T = \begin{cases} 38.0[1.0 - 164.0(\alpha - \alpha_o)^2](1.0 + 17.0/M_\alpha)(1.0 + 0.15)\eta, \eta < 1 \\ 38.0[1.0 - 164.0(\alpha - \alpha_o)^2](1.0 + 17.0/M_\alpha)(1.0 + 0.15)\eta, \eta < 1 \end{cases} \\
C_M(\alpha) = 10^{-4}(0.06 - e^{-M_{\alpha/3}})(-2.0\alpha^2 + 120.0\alpha - 1.0) \\
C_M(q) = \dfrac{\bar{c}}{2V} q(-0.025M_\alpha + 1.37)(-0.0021\alpha^2 + 0.0053\alpha - 0.23) \\
C_M(\delta_e) = 0.0292(\delta_e - \alpha)
\end{cases}
$$

η , δ_e stand for the opening degree of the throttle valve, a lifting rudder angle respectively. As the flight and propulsion system of hypersonic vehicle adopt the integrated design method, the coupling action induced by this method affects on the flight dynamic characteristics and dynamic characteristics of engine. And this paper focuses on the study of flight control; therefore only consider the influence of engine on the flight dynamic characteristics. Under the given flight equilibrium conditions, each input value of the states: $V = 4525.6m/s$, $\gamma = 0\deg$, $\alpha = 0.9780\deg$, $q = 0\deg/s$, $h = 30km$, $\eta = 0.15662$, $\delta_e = -0.2389\deg$. After taking small disturbance linearization at the balance point above, hypersonic vehicle longitudinal linear model can be obtained as follows:

$$
\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{2.7}
$$

$$
A = \begin{bmatrix} a_{11} & -\mu/r^2 & a_{13} & 0 & a_{15} \\ a_{21} & 0 & a_{23} & 0 & a_{25} \\ -a_{21} & 0 & -a_{23} & 1 & -a_{25} \\ a_{41} & 0 & a_{43} & a_{44} & 0 \\ 0 & V & 0 & 0 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} b_{11} & 0 \\ b_{21} & 0 \\ b_{21} & 0 \\ 0 & b_{42} \\ 0 & 0 \end{bmatrix}
$$

Where

$$
\begin{cases}
a_{11} = -(2C_D + C_{DV}V)S\rho V/(2m) - T_V\cos\alpha/m \\
a_{13} = -(C_{D\alpha} + C_D\tan\alpha)S\rho V^2/(2m) - T_V\cos\beta/m \\
a_{15} = -(C_{Dh}\rho + C_D\rho_h)SV^2/(2m) - T_h\cos\alpha \\
a_{21} = (C_D\tan\alpha + C_L + C_{LV})S\rho + 1/r + \mu/(Vr)^2 + T_V\sin\alpha/(mV) \\
a_{23} = (C_D + C_{La})SV\rho/(2m) + T_\alpha\sin\alpha/(mV) \\
a_{24} = (C_{Lh}\rho + C_L\rho_h)SV/(2m) - V/r^2 + 2\mu/(r^3V) + T_h\sin\alpha/(mV) \\
a_{41} = (2C_M + C_{MV}V)S\rho V/(2I_{yy}) \\
a_{43} = C_{M\alpha}Sc\rho V^2/(2I_{yy}) \\
a_{44} = C_{Mq}Sc\rho V^2/(2I_{yy})
\end{cases},
$$

$$
\begin{cases}
b_{11} = T_\eta\cos\alpha/m \\
b_{21} = T_\eta\sin\alpha/mV \\
b_{42} = M_\eta/I_{yy}
\end{cases}
$$

During the cruise flight of hypersonic vehicles in the equilibrium state, small disturbance analysis method can be used to obtain the longitudinal and lateral linear motion equations of hypersonic vehicles. Eigenvalues of the vertical and lateral movement can be obtained according to the motion equation. Based on analysis of these characteristic, the classification of hypersonic vehicle longitudinal and lateral movement modes can be understood to further grasp the dynamic characteristics and flight characteristics of hypersonic vehicles. Eigenvalues of longitudinal and literal motion in given flight condition are shown in Table 2.

Table 2. Eigenvalues of longitudinal and literal motion in given flight condition

Mach number	Flight altitude(m)	Longitudinal motion	Literal motion
0.7	2438.4	1.37,-3.34,-0.01±0.017j,0.04	0.05±0.44j,-0.95±1.1j
1.5	3048	-1.3±2.4j,0.027±0.052j,-0.11	0.05±0.42j,-1.9±2.8j
3	18288	1.7,-2.27,0.007±0.038j,-0.015	0.05±0.18j,-0.4±1.43j
5	21336	2.6,-2.95,0.0003±0.04j,-0.0031	0.54,0.07,0.61±0.63j
7	27432	2.04,-2.21,±0.038j,-0.0036	1.38,0.023,-0.15,-1.5
8	27432	2.52,-2.71,0.001±0.039j,-0.0006	1.81,0.017,-0.136,-1.93
9	27432	3.0,-3.2,0.0023±0.04j,0.0016	2.16,0.013,-0.13,-2.3
10	30480	3.0,-3.15,-0.0013±0.039j,0.0007	1.96,0.011,-0.08,-2.06
12	36576	1.19,-1.24,-0.0006±0.038j,-0.0005	1.6,0.007,-0.04,-1.65
14	36576	1.83,-1.9,-0.0003±0.038j,-0.0007	2,0.006,-0.036,-2.07
16	36576	2.0,-2.1,-0.0003±0.038j,-0.0008	2.38,0.005,-0.036,-2.45
18	36576	2.0,-2.1,-0.0005±0.038j,-0.0007	2.72,0.004,-0.037,-2.78
24	36576	2.0,-2.1,-0.0007±0.038j,-0.0003	3.74,0.003,-0.037,-3.82

Because the flight control system of hypersonic vehicle mainly contains flight speed control and flight height control, so the output should be set as two variables, then $x=[V \quad \gamma \quad \alpha \quad q \quad h]^T$, $u=[\eta \quad \delta_e]^T$ and $y=[V \quad h]^T$. Based on the data, the corresponding system matrix can be drawn as follows:

$$A=\begin{bmatrix} -1.4225\times10^{-13} & -9.9688 & -16.641 & 0 & -5.2784\times10^{-22} \\ 9.7346\times10^{-7} & 0 & 0.086872 & 0 & 5.8625\times10^{-10} \\ -9.7346\times10^{-7} & 0 & -0.086872 & 1 & -5.8625\times10^{-10} \\ -1.6167\times10^{-15} & 0 & 0.78031 & -0.076265 & 0 \\ -1.6645\times10^{-16} & 45256 & 0 & 0 & 0 \end{bmatrix}$$

$$B=\begin{bmatrix} 16.219 & 0 \\ 6.1181\times10^{-5} & 0 \\ -6.1181\times10^{-5} & 0 \\ 0 & 3.6619 \\ 0 & 0 \end{bmatrix} \quad C=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad D=[0]$$

3. Design of H_∞ Controller

According to the control theory and design principles, the actual problem will generally be summarized as H_∞ standard design problem shown in Figure 2. The u stands for the controlling input-signal, the y stands for the observed quantity, w stands for distractive output-signal, z stands for controlled quantity, the P(s) stands for the augmented controlled object, and the K(s) is the controller.

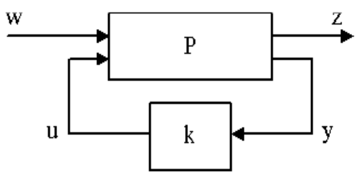

Figure 2. Standard block diagram of H_∞

The state space realization of P(s) is:

$$\begin{cases} \dot{x} = Ax + B_1 w + B_2 u \\ z = C_1 x + D_{11} w + D_{12} u \\ y = C_2 x + D_{21} w + D_{22} u \end{cases} \tag{3.1}$$

For the augmented controlled object P(s), the design principle of H_∞ controller is to design K(s), which makes the closed-loop system internally stable and obedience to H_∞ norm of closed loop transfer function from w to z is minimum, namely $\|T_{wz}(s)\| < \gamma$ (γ is a positive constant).

3.1. Foundation of H_∞ state feedback control theory

The state space of general controlled object P(s) is realized as:

$$\begin{cases} \dot{x} = Ax + B_1 w + B_2 u \\ z = C_1 x + D_{12} u \\ y = C_2 x \end{cases} \tag{3.2}$$

The general system is assumed as follows:
(1) (A, B) can be controlled, (C_2, A) and (C_1, A) can be observed;
(2) $D_{12}^T [C_1 \quad D_{12}] = [0 \quad I]$;
(3) $u = kx$.

Lemma: Given rational function matrices arbitrarily $G(s) = [A, B, C, 0]$ and $\gamma > 0$. Define the Hamilton matrix as follows: $H = \begin{bmatrix} A & \frac{1}{\gamma^2} BB^T \\ -C^T C & -A^T \end{bmatrix}$ If A is a stable matrix, then the following propositions are equivalent: (1) $\|G\|_\infty < \gamma$; (2) None of the real parts of the eigenvalues of H is equal to zero; (3) The Riccati equation $A^T P + PA + P \frac{BB^T}{\gamma^2} P + C^T C = 0$ has the positive semi-definite solution, and when [A,C] can be observed, it has positive definite solution.

Adopting state feedback $u = kx$ and substitution in the generalized object P(s), the closed-loop transfer function matrix from w to z is obtained: $T_{wz} = (C_1 + D_{12} K)(sI - A - B_2 K)^{-1} B_1$. In this moment, $A + B_2 K$ is stable, so the necessary and sufficient condition of $\|T_{wz}(s)\|_\infty < \gamma$ is that the real parts of the eigenvalues of $H_k = \begin{bmatrix} A + B_2 k & \frac{1}{\gamma^2} B_1 B_1^T \\ -(C_1 + D_{12} K)^T (C_1 + D_{12} K) & -A + B_2 k \end{bmatrix}$ are not zero.

Definition: The Hamilton matrix is defined as $H_\infty = \begin{bmatrix} A & \frac{1}{\gamma^2} B_1 B_1^T - B_2 B_2^T \\ -C_1^T C_1 & -A^T \end{bmatrix}$ where, k is the feedback matrix which is expected to be designed. When $K = B_2^T P$, P is the positive definite solution of the Riccati equation $A^T P + PA + P(\frac{B_1 B_1^T}{r^2} - B_2 B_2^T) P + C_1^T C_1 + \varepsilon I = 0$. H_K is similar to H_∞, so the real parts of their eigenvalues are the same. When (1) and (2) are satisfied, according to the lemma, the necessary and sufficient condition of $\|T_{wz}(s)\|_\infty < \gamma$ can be deduced: the Riccati equation $A^T P + PA + P(\frac{B_1 B_1^T}{\gamma^2} - B_2 B_2^T) P + C_1^T C_1 = 0$ has the positive definite solution P>0, thus the feedback is obtained: $K = B_2^T P$.

3.2. Design and simulation of H_∞ controller

Aiming at the longitudinal model of hypersonic vehicle under cruising equilibrium condition, it assumes that there exist wind disturbances which are also bounded disturbances in the flight environment. Based on the data in, it is deduced as follows:

$$B_1 = \begin{bmatrix} -0.003 & 0.96 \\ 0 & 0 \\ 3.91\times10^{-5} & 0.08 \\ -0.002 & -3.03 \\ 0 & 0 \end{bmatrix}$$

The weight matrix is set as

$$C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad D_{12} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

$\gamma = 3.3$. By solving the Riccati equation, obtain:

$$K = \begin{bmatrix} 0.98 & 17.50 & -0.72 & -0.02 & 0.01 \\ -0.01 & 1990.90 & 37.51 & 4.70 & 1.00 \end{bmatrix}.$$

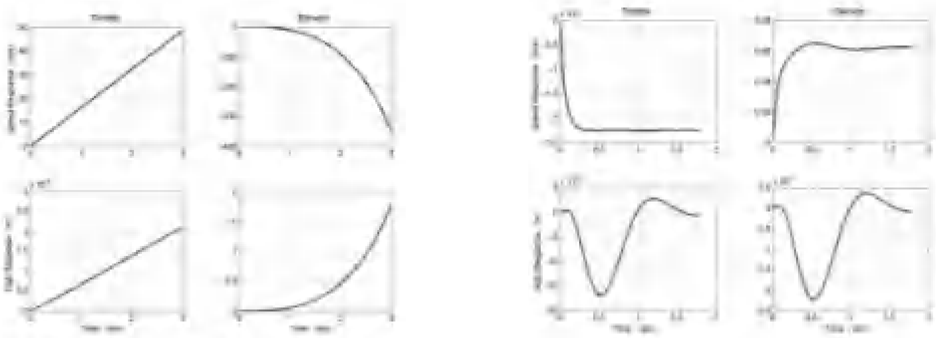

Figure 3. (a) Original system step-response **Figure 3.** (b) Step-response adopting H_∞ control

Judging from the step-response curves in Figure 3. (a), the original system is instable. After adding H_∞ controller in Figuer 3. (b), the system is stable, the steady-state error is tiny, and some overshoot exists in the height response curves. The frequency characteristic by using H_∞ control is analyzed mainly by the Bode diagram. The frequency characteristic from disturbances to output is shown in Figure 4.

High frequency amplitude of amplitude-frequency curve in the diagram and is relatively low, and keep falling with a certain slope, directly shows high frequency signal attenuation of the system is larger, demonstrates that the system has good inhibiting effect on high frequency signal, anti-interference performance is strong. As can be seen from the graph, for very low frequencies of sinusoidal interference signal, H_∞ controller has certain inhibition ability, with the increase of frequency, for the high frequency interference signal, anti interference ability of H_∞ controller increases significantly.

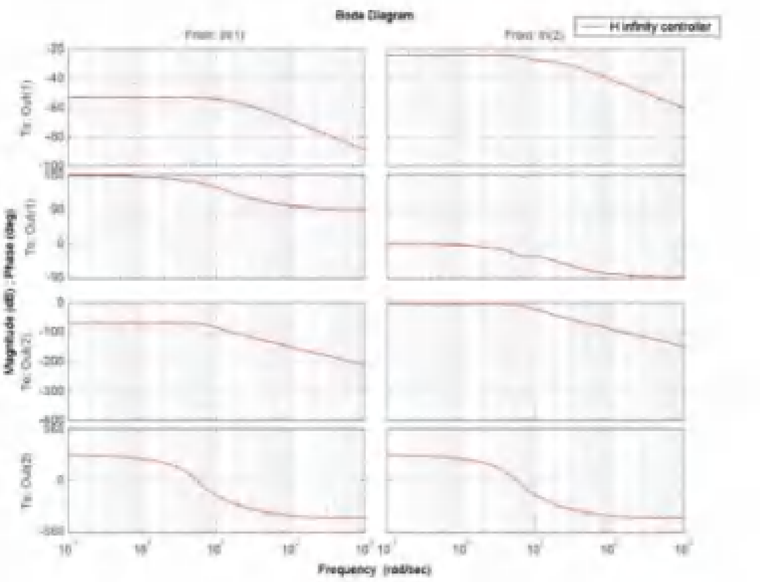

Figure 4. Bode diagram from disturbances to output

●Adjusting performance comparison:

Based on step-response, the dynamic characteristics of LQR and H_∞ controller are analyzed and compared as follows.

It can be seen from Figure 5: in terms of the adjusting performance, LQR is a little better than H_∞, namely, both the adjusting time and overshoot are smaller. But the steady-state errors of them both are relatively small. It turns out that only if the parameters are designed well, the two kinds of controllers can both have relatively great tracking performance.

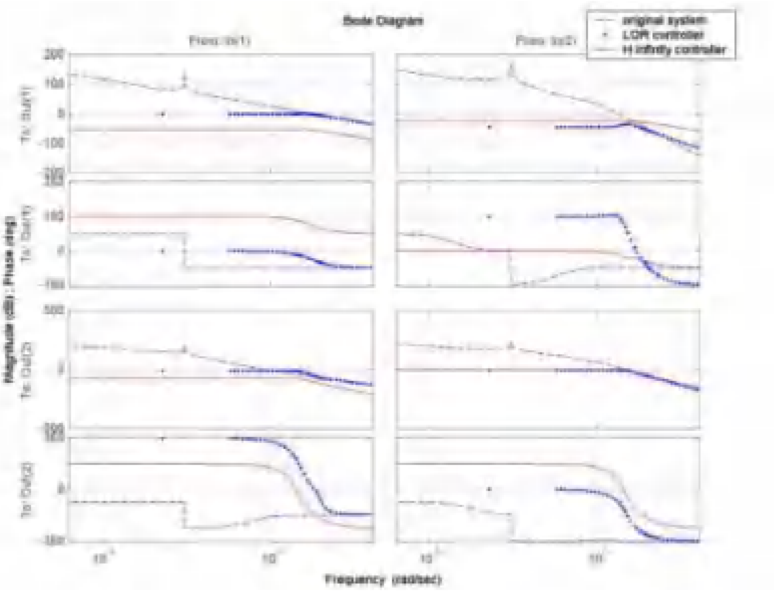

Figure 5. Bode diagrams of original system, LQR controller and H_∞ controller

●comparison of anti-interference performance

By analyzing Figure 5, it can be known that the original system has a peak at low frequency of the Bode diagram. It means that if some disturbance exists in this point, it will be amplified hugely, thus making the system instable. After adding LQR and H_∞ controller, it is seen that the peak at the low-frequency of the system is restrained. Even if there is interference of this frequency, it doesn't lead the system to be instable and out of control.

By comparing the anti-interference performance before adding LQR and H_∞ controller and after, it is clear that with the systemic amplitude-frequency response at low-frequency of H_∞ controller should be smaller than zero, which shows that it also has an inhibitory effect on low frequency interference. Yet the systemic frequency response at low-frequency of LQR controller is nearly equal to zero, which shows that LQR has not good inhibitory effect on low frequency interference. In the mid-frequency, both of them have essentially the same ability to restrain disturbance. At the high-frequency, the anti-interference capability of H_∞ controller is better than LQR. Analyzing comprehensively, it turns out that H_∞ controller can restrain the interference better than LQR.

4. Conclusion

This paper uses NASA's open aerodynamic derivative data graph and modeling method of hypersonic vehicle to derive a general hypersonic vehicle longitudinal model, and calculate the equilibrium value, longitudinal and transverse modal characteristic roots of hypersonic vehicle in different flight conditions, and according to the linear model, using H_∞ method to design controller to improve the performance of the system. By comparing the regulation performance and anti-jamming performance of the feed-back systems designed, their respective advantages and disadvantages of control schemes are summarized. Although the research object mainly aim to aircraft longitudinal models in hypersonic flight condition, but the proposed method and ideas are equally applicable to the lateral model.

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