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# Adaptive Control Design for a Class of Systems with Modal Uncertainty

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ABSTRACT

The continuous development of spacecraft with large flexible structures has resulted in an increase in the mass and aspect ratio of launch vehicles, while the wide application of lightweight materials in the aerospace field has in-creased the flexible modes of launch vehicles. In order to solve the problem of deviation from the nominal control or even destabilization of the system caused by uncertainties such as unknown or unmodelled dynamics, frequency perturbation of the flexible mode, changes in its own parameters and external environmental disturbances during the flight of such large-scale flexible launch vehicles with simultaneous structural deformation, rigid-elastic coupling and multimodal vibrations, an improved adaptive augmentation control method based on model reference adaption and spectral damping is proposed in this paper, including a basic PD controller, a reference model and an adaptive gain adjustment based on spectral damping. The baseline PD controller is used for flight attitude control in the nominal state. In the non-nominal state, the spectral dampers in the adaptive gain adjustment law will extract and process the high-frequency signal from the tracking error and control command error between the reference model and the actual system to generate the adaptive gain. The adjustment gain is multiplied by the baseline controller gain to increase/decrease the overall gain of the system to improve the system performance and robust stability, so that the system has the ability to return to the nominal state when it is affected by various uncertainties and deviates from the nominal state or even destabilizes.



## 1. Introduction

For high-risk aerospace applications, both government and industry rely heavily on classical control theory, and gain scheduling PID control is still the mainstream control method for current launch vehicles (Ting Cai, 2018; Yansheng et al., 2009.). Although the classical control methods can usually meet the flight requirements, the traditional gain scheduling PID control is no longer able to meet the control requirements of launch vehicles with the increasing mass and aspect ratio of the launch vehicle, the increase in the flexible structure of the components carried by the launch vehicle, and the obvious influence of the flexible mode and elastic vibration of large launch vehicles, and is unable to cope with the control instability problems caused by the excessive interference and modal uncertainty during the flight (Jeb and Tanner, 2012).

In response to the limitations of the classical approach, many scholars began to work on advanced control methods, and since 1990, NASA has developed a variety of launch vehicle control techniques in the Advanced Guidance Control program, including trajectory linearization control methods, neural network adaptive control methods, and higher-order sliding mode control methods, and the development of advanced control has the potential to improve system performance and increase robustness(Khoshnood et al., 2014; F. Yang et al., 2016; N. Cui et al., 2009; Z. Guo et al., 2018). Adaptive Control widely used in recent years (Liu, Y., et al., 2018; Song, X. and T. Liu, 2019; J. Liu, et al., 2019; N.T. Diego et al., 2019), is a gain adjustment method based on a model-referenced adaptive control design that generates adaptively adjusted gain from the generalized error between the reference model and the actual system as a supplement to the nominal controller (Luo, X., et al., 2018; Meng, R., 2018;). Orr et al. gave a scheme for adaptive control of multiplicity applicable to rockets (Jeb and Tanner, 2012), and then improved the adaptive control scheme in study (John H. Wall et al., 2014) to improve the performance of the original method with higher sensitivity to external inputs. The method was developed by NASA Marshall Space Center (MSFC) and became a major part of the U.S. Space Launch System (SLS) to adapt to

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unpredictable external environmental disturbances and a variety of flight dynamics characteristics (elastic vibration of flexible modes, control structure coupling, servo delay, etc.) and to reduce the probability of flight destabilization (John H. Wall et al., 2014; J. Orr et al., 2014). NASA included the method in the development of the flight control system for the SLS program in early 2013 and tested the designed method through F/18-A to verify the resilience of the control system in adverse flight conditions (T. VanZwieten et al., 2014; VanZwieten et al., 2015). Brinda. V performed an adaptive gain adjustment controller design for the longitudinal channel of a two-stage launch vehicle using a Chebyshev high-pass filter to improve the problem of insufficient amplitude of the low-frequency part of the control signal in the original adaptive gain adjustment structure of the low-order high-pass filter (Brinda.V et al., 2016; Smrithi U S and Brinda V, 2016), however, there are equal-amplitude ripples in the passband of the Chebyshev filter. Zhang applied fault-tolerant control method and adaptive vibration frequency recognition method to AAC, and designed corresponding correction network based on SMM algorithm to identify each order vibration frequency to improve system control performance and stability (Liang Zhang et al., 2016).

In this paper , we aim to establish a rigid-bullet coupling model of a large flexible spacecraft with second-order vibration signals and design an improved adaptive augmentation control method based on the reference model adaptive control method to address additional dynamics issues such as increased attitude tracking errors and flexible-mode elastic vibrations caused by uncertainty (modeling uncertainty, frequency perturbation of the flexible mode) and external environmental interference during ascent of a large launch vehicle with a flexible mode.

The scheme first determines the adjustment threshold of forward gain on the basis of the baseline PD controller, and takes the tracking error and control command error signals as the input of the two channels of the adaptive control law. The spectral dampers in the two channels (tracking error and control command elastic vibration) process the error signals (high-pass filter extracts the high-frequency signal of a specific frequency from the error signal, and the low-frequency filter lowers the frequency to reduce the influence of the high-frequency signal on the actuator) to produce the corresponding suppression gain (Error suppression gain and elastic suppression gain) to form the overall gain of AAC, and increase or decrease the forward gain of the system to improve the control performance of the system. The AAC controller will not affect the PD controller when the basic PD controller is able to handle the control tasks better [3,10], whereas the AAC controller will adjust the adaptive gain to achieve the overall gain of the system when the impact of external perturbations and uncertainties is significant, so as to recover the system performance when the system deviates severely from the nominal state and meet the performance requirements of attitude control and robust stability of the large flexible launch vehicle in the flight process.

## 2. Adaptive Controller Design

The adaptive controller combines the adaptive controller with a classically designed linear control system using a multiplicative forward gain that enhances the system by adjusting the total loop gain in real time based on the error between the actual output and the output of the reference model. When the baseline controller performs well, the adaptive controller produces little enhancement. When the baseline controller is unable to effectively meet the performance requirements, the adaptive controller adjusts the total gain of the system by increasing/decreasing the adaptive gain to improve the performance of the control system; when the system is in a high degree of uncertainty or deviates from the nominal system, the adaptive controller can compensate the PD baseline controller to a greater extent to avoid system instability. As shown in *错误!未找到引用源。* is the adaptive control block diagram, which mainly consists of two parts: the PD-based baseline controller and the adaptive controller composed of the reference model and the adaptive law.

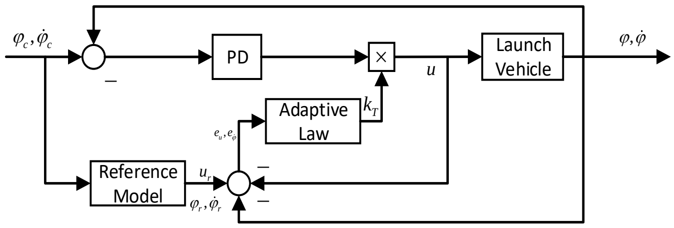



**Fig. 1.** Adaptive Augmentation Control System

*2.1 Mathematical model of the launch vehicle with second-order vibration modes*

In this paper, considering the design of a nominal controller for a second-order elastic vibration model of a launch vehicle, with the input, state variable and output defined as:

$$u = \delta_\varphi$$

$$y = \begin{bmatrix} \Delta\varphi & \Delta\dot{\varphi} \end{bmatrix}^{\mathrm{T}}$$

$$x = \begin{bmatrix} \Delta\varphi & \Delta\dot{\varphi} & q_1 & q_2 & \dot{q}_1 & \dot{q}_2 \end{bmatrix}^{\mathrm{T}}$$

Where $\delta_\varphi$ is Pitch Channel Motor Pendulum, $\Delta\varphi$ is Pitch angle, $q_i$ is the $i^{\text{th}}$ order oscillation pattern of the pitch channel.

The state space of the system is described as(1),

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{2}$$

Where the matrix $A, B, C, D$ are given as follows,

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -b_2 & -b_1 & -b_{21} & -b_{22} & -b_{11} & -b_{12} \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ D_{21} & D_{11} & -\omega_1^2 & 0 & -2\xi_1\omega_1 & 0 \\ D_{22} & D_{12} & 0 & -\omega_2^2 & 0 & -2\xi_2\omega_2 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & -b_3 & 0 & 0 & D_{31} & D_{32} \end{bmatrix}^T$$

$$C=\begin{bmatrix}1 & 0\\ 0 & 1\\ -W_1'(X_T) & 0\\ -W_2'(X_T) & 0\\ 0 & -W_1'(X_{gT})\\ 0 & -W_2'(X_{gT})\end{bmatrix}^T \quad D=\begin{bmatrix}0\\0\end{bmatrix}$$

Where $W_i'(X_T), W_i'(X_{gT})$ are the slope of the pitch angle and the slope of the $i^{th}$ mode shape of the pitch rate, $\omega_i$ is the $i^{th}$ order undamped vibration angular frequency, $\xi_i$ is the $i^{th}$ order damping ratio.

### *3. Reference Model*

The reference model is used to simulate the controlled motion of the rigid body of the launch vehicle in the nominal state, which produces the nominal response to the guidance instruction by adjusting the control parameters, and then the gap with the actual response of the launch vehicle is used as the input of the adaptive control law to adjust the gain of the PD controller. In adaptive gain control, a typical second-order system is used as the reference model (Feiyi He, 2018), and its state space is shown in (3).

$$\begin{aligned}\dot{x}_r &= A_r x_r + B_r u_r\\ y_r &= C_r x_r + D_r u_r\end{aligned} \tag{2}$$

Where $A_r=\begin{bmatrix}0 & 1\\ -b_2 & -b_1\end{bmatrix}$ $B_r=\begin{bmatrix}0 & -b_3\end{bmatrix}^T$

$$C_r=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} \qquad D_r=\begin{bmatrix}0\\0\end{bmatrix}$$

### *4. Baseline PD Controller*

For the stability of elastic vibration, there is a difference between amplitude stability and phase stability. The so-called amplitude stability refers to the amplitude $Gain(\omega)<0$ when the phase frequency curve crosses the $\pm(2n+1)\pi$; the so-called phase stability refers to when the amplitude $Gain(\omega)>0$ the phase frequency curve does not cross the $\pm(2n+1)\pi$. Magnitude stability of the essence of the engine oscillation control force generated by the excitation is less than the elastic vibration in the inherent damping under the role of attenuation, so the magnitude of stability depends on the inherent damping of elastic vibration and control system on the elastic vibration signal of the sufficient attenuation. The essence of phase stability is to take the elastic vibration signal as part of the control signal, through the correction network to get the right phase, the elastic vibration to produce additional damping to achieve the purpose of stability, phase stability does not depend on the inherent damping of elastic vibration, but the phase frequency characteristics of the correction network put forward strict requirements.

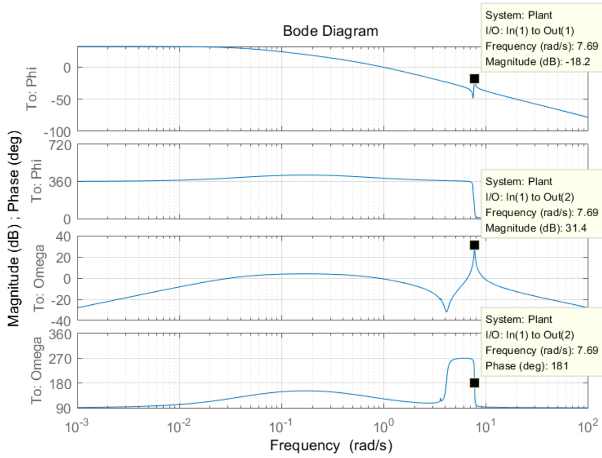



**Fig. 2.** Open-loop frequency characteristics of the system

Fig. 2 shows an open-loop Bode plot of the pitch channel, where the open-loop frequency response of the angle(Phi) satisfies the amplitude stability and phase stability conditions, while the angle rate(Omega) does not satisfy the amplitude stability condition (amplitude $Gain(\omega)>0$ when the phase frequency curve traverses the 180° curve;) and the phase stability condition (amplitude $Gain(\omega)<0$ when the phase frequency curve traverses the 180° line at frequency 7.694 rad/s ).

In adaptive augmentation control the PD controller provides the basic control gain for the launch vehicle and is the basic controller in the adaptive control framework. In a classical PID feedback control system, a higher forward gain can improve the performance and robustness of the system with a fixed ratio of proportional and differential gain. However, due to the special performance requirements and stability requirements of large flexible launch vehicles (presence of high uncertainty, elastic vibration) forward gain needs to be limited to a small range to provide better performance and robustness for the baseline controller, and the design requirements usually limit the allowable forward gain to a range not less than 6 dB from the critical stability value to improve the system's ability to cope with uncertainty. In this paper, we directly select the PD controller parameters $K_p=-9.2$ and $K_d=-3.8$.

### *5. Multiplicative Adaptive Control Law based on Spectral Damping*

For the large launch vehicle elastic vibration, the first-order elastic vibration mode has low frequency and small phase deviation and is usually stabilized by the phase stabilization method, while the second-order and higher-frequency elastic vibration modes have large phase deviation and are usually stabilized by the amplitude stabilization method. In general, the first-order vibration mode can be phase-stabilized by selecting the mounting position of the rate gyro, the second-order vibration mode requires amplitude stabilization, and the higher-order vibration mode is amplitude stabilized by high-frequency filtering of the correction network.

The control command error signal $e_u$ and tracking error $e_{\varphi,\dot{\varphi}}$ between the reference model and the actual model are used as inputs to the adaptive control method, and the adaptive gain $k_T$ is calculated through the two channels of oscillation suppression and error suppression, respectively, to adjust the baseline PD controller gain. The control command error, tracking error and adjustment gain of adaptive control are shown below,

$$e_u = u_r - u \tag{4}$$

$$e_{\varphi,\dot{\varphi}} = e_\varphi + e_{\dot{\varphi}} \tag{5}$$

$$k_T = sat_{k_0}^{k_{\max}}\{k_e y_e - k_s y_s + 1\} \tag{6}$$

where $k_{\max}$ is the upper bounds of the adjustment gain, $k_0$ is the lower bounds of the adjustment gain, $k_e$ is the adjustment gain of tracking error term, $y_e$ is the output signal of the tracking error signal through the high and low pass filters, $k_s$ is the adjustment gain of control command error term, and $y_s$ is the output signal of the control command error signal through the spectrum dampener.

The gains $k_e$ and $k_s$ of the two spectrum dampers adjust the spectrum output signals $y_e$ and $y_s$ of the two channels, which are formed by the tracking error signal and the controller command error signal, as follows,

$$y_e = ErrL_P(s)\left(ErrH_P(s)e_{\varphi,\dot{\varphi}}\right)^2 \tag{7}$$

$$y_s = SDL_P(s)\left(SDH_P(s)e_u\right)^2 \tag{8}$$

In general, the DC gain of the designed high-pass filter should be as small as possible (the pass band gain is usually set to 1), while the transition band should be as steep as possible (limited to 1.5 rad/s), and the form of the high-pass and low-pass filter are shown in (9) and (10),

$$H_P(s) = \frac{s^2}{s^2 + 2\xi_{hp}\omega_{hp}s + \omega_{hp}^2} \tag{11}$$

$$L_P(s) = \frac{\omega_{lp}^2}{s^2 + 2\xi_{lp}\omega_{lp}s + \omega_{lp}^2} \tag{12}$$

Where $\omega_{hp}$ , $\omega_{lp}$ are the cut-off frequencies of the high and low pass filters, and $\xi_{hp}$ , $\xi_{lp}$ are the damping ratios with values ranging from 0.5 to 0.8.

The corresponding parameters of the spectrum dampers in the elastic rejection channel are as in Tab. 1,

**Tab. 1.** For 2-D and 3-D ripples at Re=180,400, the values of of virtual offsets and roughness height obtained by fitting the mean velocity to a log-law, equivalent sand grain roughness in wall-units and wall friction-velocity.

| *Case* | $\omega_{hp}$ | $\zeta_{hp}$ | $\omega_{lp}$ | $\zeta_{lp}$ |
|---|---|---|---|---|
| *Err* | 8.7 | 0.8 | 1.2 | 0.6 |
| *SD* | 24.3 | 0.8 | 7.69 | 0.6 |

## 1. Results and Analysis

In order to illustrate the role of the improved adaptive control scheme in the launch vehicle system, the tracking curves and adaptive control gains of the nominal system and two different failure scenarios are presented and analyzed in the simulation to verify the effectiveness of the designed algorithm. Assume at 10 seconds after the launch vehicle takes off, the angle and rate commands of pitch are given as shown in Fig. 3. The gain saturation function of the adaptive controller in this example is taken as $K_{\max}$=2 and $K_{\min}$=0.5.

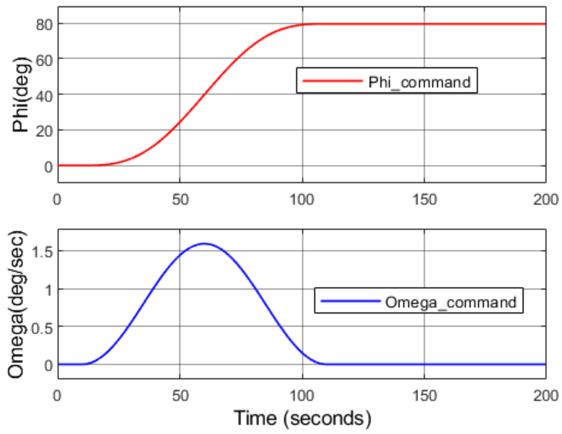
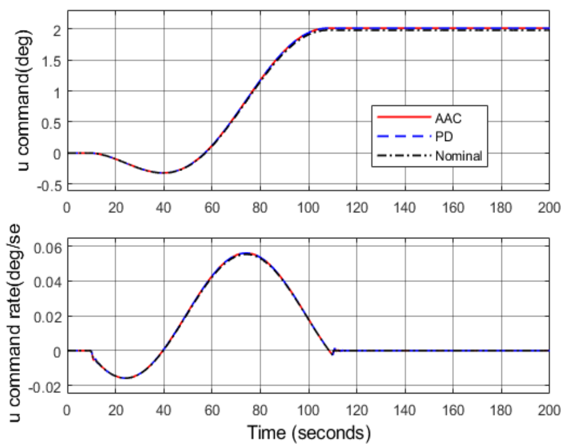


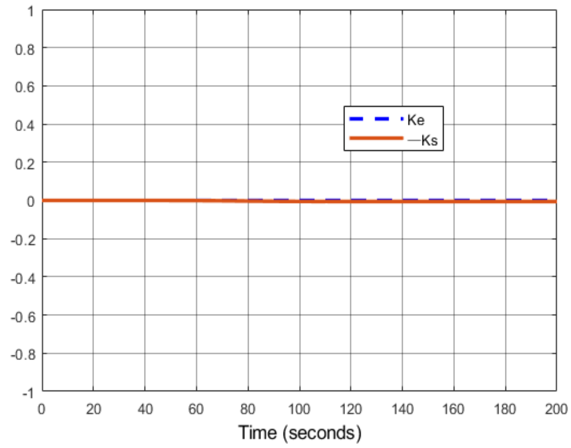

**Fig. 3.** Pitch and angle rate commands

### *3.1 Normal state*

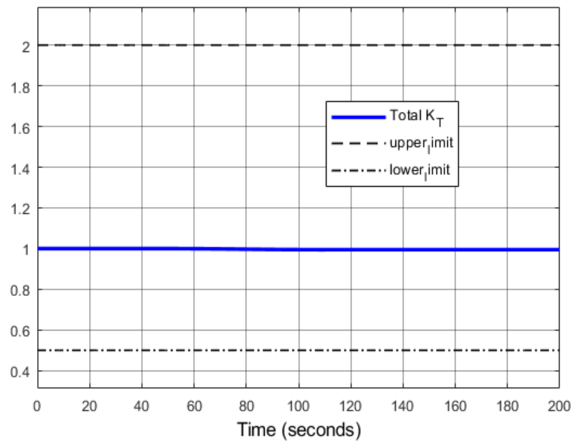
If the system is in the normal state, the output of the system under PD control and AAC are consistent with the rigid body nominal system, as shown in Fig. 4.(a). At the same time, the adjusted gain $k_e$ and $k_s$ of two channels in AAC are close to 0 as shown in Fig. 4.(b), and the overall adaptive gain is always kept at a stable value $k_T = 1$ as shown in Fig. 4.(c), which means that AAC does not produce any effect in the normal state. This is in line with our original design requirement that the AAC is not involved in control activities when the baseline PD controller is able to achieve good performance output.




a) Pitching Attitude




b) Gain adjustment for tracking error and control command error



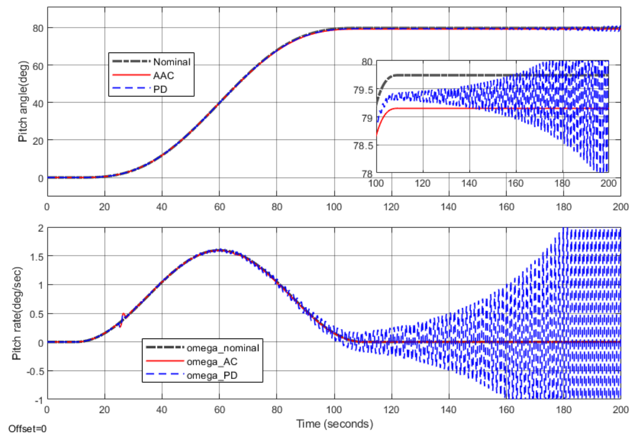

c) Total Gain of Adaptive Augmentation Control

**Fig. 4.** Performance in Nominal State

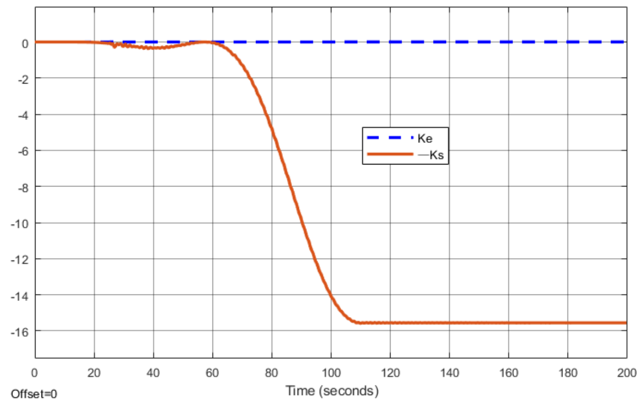
*3.2 Elastic vibration frequency disturbance*

Assuming that there exists uncertainty in establishing the rigid spring coupling model, the elastic vibration frequency of the model is reduced by 30% while the same perturbation signals described above exist. The pitch angle and pitch angle rate signals at this time are shown in Fig. 5(a). The system can be able to follow the control commands to some extent in the early stages when the adaptive channel is closed (i.e., only the baseline PD controller is in action), but with the passage of time and accumulation, the system ends up in a divergent state.

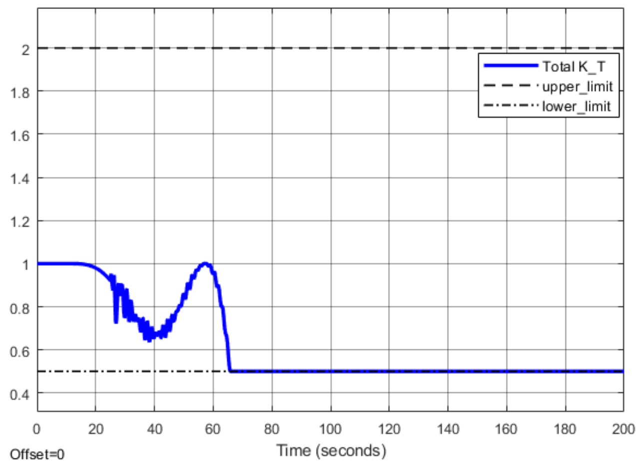
The adjusted gain of the two channels $k_e$, $k_s$ and the overall gain $K_T$ of the AAC control is shown in Fig. 5.(b, c). We observe that in the case where the AAC is involved in the control, the baseline PD controller is not able to achieve a good tracking effect due to the ingress of the elastic mode, then the AAC controller will generate a corresponding gain value $k_s$ (in this case mainly for the suppression of elastic vibration), and then make the AAC gain less than 1 to reduce the overall gain of the system for meeting the requirements. When the baseline controller can achieve the tracking effect better, then the value of AAC gain $K_T$ will remain at 0.5. It is obvious from the above analysis that the adaptive control designed in this paper has a good robust stability to the ingress of the elastic mode, and under the adjustment of the AAC control, the launch vehicle can adjust the control gain online and in real-time to set the engine swing angle of the servo to keep the rocket stable.




a) Pitching Attitude




b) Gain adjustment for tracking error and control command error




c) Total Gain of Adaptive Augmentation Control

**Fig. 5.** Performance at 30% elastic vibration frequency disturbance.

## 2. Summary

The adaptive control has important research significance and development potential for the control of large flexible launch vehicles, which can increase the robustness of the system, avoid oscillations and even destabilization problems caused by the estimation errors of the flexible mode, and improve the safety and reliability of the rocket operation. The improved adaptive control scheme designed in this paper has good performance, and the simulation shows: 1) The baseline PD controller is well controlled when the system is in normal state and the adaptive control is not or less involved in the control scheme. 2) When there is about 40% perturbation of the flexible mode which causes large oscillation (destabilization), the adaptive control can produce a multiplicative adjustment gain less than 1 to reduce the overall gain of the system, thus enhancing the robust stability of the system and enabling the rocket to return to normal and stable operation.

The simulation results of the above different scenarios show that the enhancement provided by the improved adaptive control designed in this paper matches the expected goals and requirements, while the scheme has the same verifiability for the poorer control due to uncertainties caused by large scale variations in thrust, mass and atmospheric characteristics.

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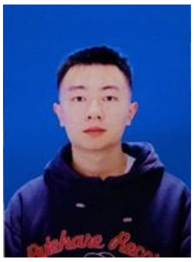

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