High Accuracy Attitude Controlling of Vehicles for launching According to Deformation Reconstruction

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Abstract—To solve the problem that the curvature information of the large flexible rocket body affects the attitude controlling for rocket body, the present study proposes an attitude controlling approach by complying with reconstruction for deformation, which can realize the highly precise attitude controlling of the large flexible vehicle for launching. Firstly, the deformation parameters of the rocket were obtained by using the fiber grating sensing device. Then, the deformation information and attitude information were introduced into the increment-based dynamic inversing control loop at the same time, and the attitude controlling framework containing the deformation information of the rocket was established. Finally, the results achieved based on the simulation show that for flexible vehicles for launching with obvious vibration and deformation, this approach can compensate the faults attributed to elastic deformation and improve the accuracy and stability of attitude control.

1. INTRODUCTION
To reduce the structural mass and improve the delivery efficiency, the development trend of carrier rockets is to increase the slenderness ratio of the vehicle for launching. However, as the slendering ratio of the rocket increases, structural vibration and flexibility characteristics become more obvious, leading to inaccurate pose information measured by the attitude sensing device. In addition, low-order elastic vibration modes of the vehicle for launching are easily excited by external interference, resulting in large vibration, which adversely affects the stability of the attitude motion of the rigid vehicle for launching [1].

In view of the flexible vehicle for launching control problem, domestic and foreign scholars have carried out relevant research. Zhou et al. [2] applied robust state observer to attitude stability control of vehicle for launching and realized the design of anti-jamming attitude controlling device by observing and compensating composite interference. Wu et al. [3] designed an SMM adaptive filter for the flexible rocket control problem and realized the stable control of the rocket attitude. Wei et al. [4] considered the elastic vibration characteristics of carrier rocket during flight, introduced the adaptive filtering attitude controlling algorithm and the norm robust gain scheduling control algorithm to design the controlling device, and verified the effectiveness and robustness of the two control approaches. Shtessel et al. [5] realized the separation and reconstruction of the first two modes of the vehicle for launching by using the sliding mode observer and introduced the mode information into the control loop. At present, to reduce the effect exerted by structural vibration on attitude controlling system, notch filters are mostly used in...
the design of controlling devices to filter low-order modal signals. However, in the design of notch filters, a large range of frequency variation must be considered, and design parameters are usually conservative, leading to low control accuracy. In addition, the notch filter can decrease the phase margin, and it faces difficulty in ensuring that the rigid vehicle for launching and the elastic vehicle for launching have sufficient stability margin at the same time. It is more and more difficult to control the rocket attitude only with attitude information to meet the development needs of carrier rocket, so it is necessary to measure the strain and deformation of the body of the vehicle for launching and introduce the deformation information of the body of the vehicle for launching into the controlling mechanism, to realize the high-precision attitude controlling and stable flight of the rocket.

The fiber Bragg grating sensing device (FBG) has the characteristics of small volume, light weight, corrosion resistance, electromagnetic interference resistance, miniaturization, embedding composite materials and so on [6], which has become the most promising sensing technology in the field of space sensing [7–8]. Since the rise of optical fiber sensing technology at the end of last century, NASA, ESA and other space agencies have paid great attention and made great efforts in research. The strain, temperature, pressure, and other parameters of various structures of different spacecraft such as vehicles for launching, satellites and spacecraft have been measured, laying a foundation for the health monitoring and management of spacecraft structure [9]. By installing fiber Bragg grating sensing device array on the rocket body to measure the strain of the rocket, the stress and deformation of the rocket structure is yielded in real time, and the attitude and elastic deformation information can be decoupled, to obtain the accurate attitude information of the rocket. Combined with the advanced control algorithm, the accuracy and stability of the rocket attitude controlling can achieve an effective improvement.

For solving the issue of poor attitude controlling accuracy of flexible rocket, a high precision attitude controlling approach is developed in the present study, which introduces the shape change information and attitude information into the control loop simultaneously. According to the flexible rocket attitude controlling device design, the dynamic model of the flexible rocket is first built. By complying with INDI, the deformed information is substituted to the design of the attitude controlling device, and an FBG + INDI controlling approaching is developed. Compared with the traditional filter controlling device design, the developed control scheme are confirmed to be effective and robust.

2. DEFORMATION RECONSTRUCTION APPROACH OF FLEXIBLE VEHICLE FOR LAUNCHING

2.1 Euler-Bernoulli beam model

According to Fig 1, a rocket model with large aspect ratio can be regarded as a non-homogeneous Euler–Bernoulli beam [9] with free ends, which is affected by gravity, aerodynamics, and the rocket’s own thrust during flight. In structural vibration analysis, its elastic vibration can be described by the following differential equation:

$$\frac{\partial^2}{\partial x^2} \left( EJ(x) \frac{\partial^2 y(x,t)}{\partial x^2} \right) + m(x) \frac{\partial^2 y(x,t)}{\partial t^2} = P(x,t) \quad (1)$$

where $y(x,t)$ denotes the lateral displacement of the beam model regarding the $x$-axis, $m(x)$ expresses the rocket’s mass distribution function, $EJ(x)$ is the bending stiffness, and $P(x,t)$ represents the transverse force under a unit beam length. The below should be met for the free-beam boundary condition:

$$EJ(0)y''(0) = 0 \quad EJ(L)y''(L) = 0$$

$$EJ(0)y''(0)' = 0 \quad (EJ(L)y''(L))' = 0 \quad (2)$$

When studying the elastic vibration of flexible rocket, in order for generating an $n$-degree of freedom approximate differential equation model in terms of the continuous mechanism, the displacement at a certain point of the body of the vehicle for launching is extended to a linear combination of $N$ shape functions, and the shape function of the body of the vehicle for launching approximated by the deformation $y(x,t)$ is expressed as:
\[ y(x,t) = \sum_{j=1}^{\infty} \phi_j(x) \eta_j(t) \]  
\[ \phi_j(x) \]  is the shape of the \( j \)-th mode shape, and \( \eta_j(t) \) is the time-dependent amplitude of the \( j \)-th mode. \( \phi_j(x) \) can be determined by the finite element approach. Similarly, the rotation angle of the vehicle for launching \( \theta(x,t) \) at a point can be expressed as:

\[ \theta(x,t) = \sum_{j=1}^{\infty} \phi_j'(x) \eta_j(t) \]

In terms of a beam vibration mechanism, the finite element model of the Euler–Bernoulli beams is:

\[ MX(t) + CX(t) + KX(t) = F(t) \]

where \( M \), \( C \), and \( K \) are the inertia matrix, damping matrix, and stiffness matrix, separately; \( X(t) \), \( \dot{X}(t) \), and \( \ddot{X}(t) \) are the displacement, speed, and acceleration of the system, separately; and \( F(t) \) is the excitation force vector.

2.2 Deformation Reconstruction of Flexible Rocket by complying with Legendre Polynomials

Since the mass of the rocket changes and the mass distribution is not uniform during the flight, the mode of the equivalent beam model changes with time, and there is no fixed analytic function. It is necessary to use continuous function to fit discrete mode points. Legendre polynomials are a set of orthogonal sequence functions on \([-1,1]\]. Legendre continuous functions are used to approximate the discrete points extracted from theoretical calculations or finite element software. Legendre polynomials are expressed as follows:

\[ P_0(x) = 1, \]
\[ P_1(x) = 2x - 1, \]
\[ P_{i+1}(x) = \frac{(2i+1)(2x-1)P_i(x) - iP_{i-1}(x)}{i+1} \]

And the first six Legendre polynomials are shown in Fig 2:

\[ \text{Figure 1. Beam representation of flexible rocket.} \]

\[ \text{Figure 2. First seven shifted Legendre polynomials.} \]
The mode shape \( \varphi_j(x) \) can be fitted by the linear combination of \(( m + 1)\) Legendre polynomials as follows:

\[
\varphi_j = \sum_{i=0}^{\infty} a_i P_i(x) \approx a_0 P_0(x) + a_1 P_1(x) + \cdots + a_m P_m(x)
\]  

where \( a_i \) is the Legendre polynomial coefficient. For the first \( n \)-order modes, the approximate values can be fitted by the linear combinations of the first \( m + 1 \) shifted Legendre polynomials:

\[
\Phi(x) = [\varphi_1 \varphi_2 \ldots \varphi_n]
\]

\[
= [P_0(x) P_1(x) \cdots P_n(x)]
\]

\[
= P(x)A
\]

The matrix \( A \) of feature coefficient is yielded:

\[
A = P(x)^{-1}\Phi(x)
\]

Once the matrix \( A \) of feature coefficient pertaining to the model is achieved, the nodal rotation mode shape is able to be achieved based on \( P(x) \) derivative:

\[
\Phi(x) = [\varphi_1 \varphi_2 \ldots \varphi_n] = P'(x)A
\]

Given kinematics, the tensile strain as impacted by the beam bending \( (\varepsilon) \) shows a relation with the nodal displacement:

\[
\varepsilon(x,t) = -z_0 y''(x,t)
\]

where \( z_0 \) denotes the distance from beam reference line (here, the beam center axis is adopted to be the baseline) to the of the FBG sensing device position, with the general arrangement on the beam surface for measuring the strain. When \( \varepsilon(x,t) \) receives the measurement with FBG sensing devices, the instantaneous modal coordinates \( \eta(t) \) are acquired:

\[
\varepsilon(x,t) = -z_0P'(x)A\eta(t)
\]

If the current instantaneous mode coordinate \( \eta(t) \) is obtained, the acceleration, velocity and displacement of the respective beam node are able to be achieved by polynomial \( P(x) \) and matrix \( A \) of feature coefficient, as shown below:

\[
y(x,t) = P(x)A\eta(t)
\]

\[
v(x,t) = P(x)A\dot{\eta}(t) = \frac{1}{\Delta t} P(x)A(\eta_t - \eta_{t-\Delta t})
\]

\[
a(x,t) = P(x)A\ddot{\eta}(t) = \frac{1}{\Delta t^2} P(x)A(\eta_t - 2\eta_{t-\Delta t} + \eta_{t-2\Delta t})
\]

Through the insertion of the Legendre polynomials \( P(x) \) to (13), angular velocity \( \dot{\theta} \), the beam deflection angle \( \theta \), and the angular acceleration \( \ddot{\theta} \) attributed to vibration is yielded as follows:

\[
\dot{\theta}(x,t) = P'(x)A\eta(t)
\]

\[
\dot{\theta}(x,t) = P'(x)A\dot{\eta}(t)
\]

\[
\ddot{\theta}(x,t) = P'(x)A\ddot{\eta}(t)
\]
3. HIGH-PRECISION ATTITUDE CONTROLLING APPROACH OF ROCKET BY COMPLYING WITH DEFORMATION RECONSTRUCTION

3.1 Dynamic Modeling of Attitude and Vibration of Vehicle for launching

The vibration of the pitch plane of vehicle for launching is a key object of investigation in the system design and flight controlling. The present study mainly models the vibration and deformation of the pitch plane. The model adopted in the present study is shown in Fig 3. The linearized dynamics equation of the vehicle for launching pitch channel given elastic vibration is shown:

\[
\begin{align*}
\Delta \dot{\theta} &= c_1 \Delta \alpha + c_2 \Delta \theta + c_3 \Delta \phi + \sum_{i=1}^{n} c_i \eta_i + \sum_{i=1}^{n} c_i \eta_i + \mathbf{F}_{he} \\
\Delta \dot{\phi} &= b_1 \Delta \phi + b_2 \Delta \alpha + b_3 \Delta \eta + \sum_{i=1}^{n} b_i \eta_i + \sum_{i=1}^{n} b_i \eta_i + \mathbf{M}_{he} \\
\Delta \dot{\alpha} &= \Delta \phi - \Delta \alpha \\
\eta_i &= 2 \zeta \omega_i \eta_i + \omega_i \eta_i = D_i \Delta \phi + D_i \Delta \alpha + D_i \delta_\phi + D_i \delta_\alpha - Q_i
\end{align*}
\]  

(15)

where  \( c_1, c_2, c_3, c_i, b_1, b_2, b_3, b_i, b_{ij}, b_{ij}, b_{ij}, b_{ij}, D_i, D_i, D_i, D_i, D_i \), and  \( D_i \) represent the pitching dynamics coefficients, \( \Delta \alpha \) represents the attack angle, \( \mathbf{F}_{he}, \mathbf{M}_{he} \) and \( Q_i \) denote the perturbed force, torque, and generalized disturbance force coefficients, separately \( \Delta \phi \) expresses the vehicle axis direction, \( \delta_\phi \) represents the angle of gimbal deflection, \( \eta_i \) is vibration mode’s generalized coordinate, \( \omega_i \) and \( \zeta_i \) represent the damping ratio and bending mode natural frequency, separately, \( \Delta \theta \) expresses the angle of flight path, and \( n \) denotes the number of bending modes.

![Figure 3. Disturbance coefficient of elastic rocket in pitch plane.](image)

The mathematical model of vehicle for launching is regarded as an object with disturbance parameters and uncertain disturbances attributed to vibration, slosh, and structural disturbances. The nominal model of the attitude controlling system is yielded.

\[
x = A_p x + B_p u + D_p,
\]

(16)

where  \( A_p, B_p, \) and  \( D_p \) are the system, control, and disturbance matrices, separately, and the state vector  \( x = [\theta, \phi, \alpha, \eta, \dot{\eta}]^T \). As the control command refers to the gimbals deflection angle,  \( u = \delta_\phi \).

Given (3), the deformation at any body point of the vehicle for launching is able to refer to the integration all modes’ linear superposition, and the deflection angle attributed to vibration is:

\[
\theta(x, t) = \sum_{i=1}^{n} w_i(x) \eta_i(t)
\]

(17)

In the mentioned equation,  \( w_i(x) = \frac{d\phi_i(x)}{dx} \). The pitch angle rate and measured pitch angle are:
\[
\begin{align*}
\varphi_M &= \varphi + \dot{\varphi}(x_{gyro}, t) \\
q_M &= q + \dot{q}(x_{gyro}, t) \\
\ddot{q}_M &= \ddot{q} + \dddot{q}(x_{gyro}, t)
\end{align*}
\] (18)

where \(\varphi_M\), \(q_M\), and \(\ddot{q}_M\) are the actual measured pitch angle, pitch angle rate and pitch angle acceleration, separately, and \(x_{gyro}\) expresses the attitude sensing device’s position.

3.2 Increment-based dynamic inversing control Law

To facilitate the description of increment-based dynamic inversing control, the following affine nonlinear systems are considered:

\[
\begin{align*}
\dot{x} &= f(x) + G(x,u) \\
y &= h(x)
\end{align*}
\] (19)

In the mentioned equation, \(y\) expresses a \(p\)-dimensional output, \(G(x,u)\) expresses an \(n\times m\) dimensional state-dependent control matrix, \(f(x)\) expresses the system dynamics, \(u\) expresses the \(m\times 1\) control input, and \(x\) denotes the \(n\)-dimension state quantity. For obtaining the approximate dynamics within increment-based form, the first-order Taylor-series expansion of \(\dot{x}\) regarding \((x_0,u_0)\):

\[
\begin{align*}
\dot{x}_0 &= f(x_0) + G(x_0,u_0) \\
&\quad + \frac{\partial}{\partial x} (f(x)+G(x,u))_{x_0,u_0} (x-x_0) \\
&\quad + \frac{\partial}{\partial u} G(x,u)_{x_0,u_0} (u-u_0).
\end{align*}
\] (20)

The equation of state at the point \((x_0,u_0)\) is

\[
\dot{x}_0 = f(x_0) + G(x_0,u_0).
\] (21)

The definition of partial derivative is:

\[
\begin{align*}
\bar{A} &= \frac{\partial}{\partial x} (f(x)+G(x,u)) \\
\bar{B} &= \frac{\partial}{\partial u} G(x,u)
\end{align*}
\] (22)

The outputting equation regarding time is yielded:

\[
\dot{y} = \frac{\partial h(x)}{\partial x} \dot{x} \approx h_x \left( \dot{x}_0 + \bar{A}(x_0,u_0) \Delta x + \bar{B}(x_0,u_0) \Delta u \right)
\] (23)

In terms of a high enough control update (so, a small-time incremental result), \(x\) is approaching to \(x_0\). The state variable increment \(\Delta x\) refers to a high-order small quantity regarding the control input’s increment \(\Delta u\). Thus, it is able to be ignored. The expected closed-loop dynamic feature refers to \(\nu\). This study develops increment-based dynamic inversing control law for endowing the system output dynamic feature with the capability of tracking the expected feature, i.e., \(\nu = y\). Introducing the mentioned to (21), the control input is:

\[
u = u_0 + \Delta u = u_0 + \left( h_x \bar{B}(x_0,u_0) \right)^{-1} (\nu - h_x \dot{x}_0)
\] (24)

where \(u_0\) is a nominal (or reference) control.
### 3.3 Design of Control Law By complying with Deformation Information Remedy

The flexible rocket controlling mechanism is by complying with the increment-based dynamic inversing control law. This section first introduces the basic principle of the increment-based dynamic inversing control law, and then designs a high-precision attitude controlling system of the flexible vehicle for launching by complying with the increment-based dynamic inversing control law, which considers the attitude and deformation information at the same time.

From (24), the corresponding increment-based dynamic inversing control law is obtained as follows:

\[
\Delta u = B^{-1} (v - \dot{q}_0),
\]

where \( \dot{q}_0 \) is the angular acceleration in the pitching direction of the rocket at the current moment, and the inverse matrix of \( h, \hat{B}(x, u) \) is equal to \( B^{-1} \).

According to the characteristics of the rocket attitude control, a dual-loop control law is designed by complying with the increment-based dynamic inversing control law. The outer loop includes the attitude angle loop (slow loop) and angular velocity loop (fast loop). The desired angular velocity of the outer loop \( q_{des} \) is yielded by a proportional–integral–derivative (PID) or more complex control law. In this analysis, a simple proportional control is used:

\[
q_{des} = K_{x,out} \Delta \phi.
\]  

(26)

The desired angular acceleration can also be obtained from a proportion control law:

\[
v = K_{q,out} q = K_{q,out} (q_{des} - q),
\]

where \( K_{x,out} \) and \( K_{q,out} \) are the proportional gain coefficients of the slow loop and the fast loop, separately. The inner loop is the angular acceleration loop, which adopts an increment-based dynamic inversing control law:

\[
u_c = u_0 + \Delta u = u_0 + B^{-1} [v - \dot{q}_0].
\]

where \( u_0 \) is the control input at the last sampling time, and the subscript \( c \) represents the instruction.

The attitude angle and the attitude angular rate obtained by the measuring device contain the elastic vibration information for the body of the rocket, which cannot provide accurate measurement information of the guidance, navigation, and control (GNC) system. When the vibration information for the body of the rocket receives the measurement with the FBG sensing device, the attitude Angle and angular rate faults attributed to the rocket vibration can be compensated by the feedback loop, as shown in Fig 4.

![Figure 4. Block diagram of incremental dynamic inversion control by complying with deformation remedy.](image)

According to (18), the deflection of a flexible rocket can be estimated using an FBG sensing device array. FBG measurements can be used to compensate for the pitch angle and pitch rate \( \phi_M, q_M \), and \( \dot{q}_M \):

\[
\begin{align*}
\dot{\phi}_M &= \phi_M - \phi, \\
\dot{q}_M &= q_M - q, \\
\dot{q}_M &= \dot{q}_M - \dot{q}_0.
\end{align*}
\]  

(29)
where $\hat{\phi}_M$, $\hat{q}_M$ and $\hat{\dot{q}}_M$ are the pitch angle, pitch angle rate and pitch angle acceleration after remedy, separately, and $\varphi_b$, $q_b$ and $\dot{q}_b$ are the rocket vibration information obtained by the FBG measurement, which are yielded with Equation.

4. Modeling and Fault Analysis of FBG Measuring Mechanism within Flight Environments

4.1 FBG System Measurement fault

The transient response of the rocket in the controlling mechanism simulation is used as the "measurement data" of the FBG to reconstruct the overall deformation. However, the actual rocket flight is affected by the complex flight environment. In addition to the measurement fault, there are complex noises in the output strain data, as well as transmission delays between the sensing device and the controlling mechanism. These factors need to be comprehensively analyzed and considered in FBG modeling and controlling device simulation.

4.1.1 Sensing device Measurement fault Analysis: The measurement fault is mainly composed of strain transfer coefficient, sensing device packaging quality and environmental change. At present, the strain measurement fault of the corrected strain optical fiber sensing device can be reduced to less than 5% [10].

4.1.2 FBG Measuring mechanism Noise and Time Delay Analysis: After investigation, it is found that the noise of mechanism for measuring FBG is mainly composed of light source, FBG sensing device and demodulation system. Due to the hardware characteristics, each unit may introduce noise sources, and these noises are superimposed on each other. Produce complex additional effects, which will affect the output of the FBG sensing device signal, resulting in unstable measurement performance of the FBG.

To simulate the real output signal noise of the mechanism for measuring FBG, we investigated and tested the actual mechanism for measuring FBG (Fig 5). The technical parameters are shown in Table 1.

| FBG measuring system model | The main technical parameters |
|----------------------------|------------------------------|
| FT1611                     | Working wavelength: 1529~1569 nm |
|                            | Number of optical channels: 16 |
|                            | Measurement wavelength range: 40 nm |
|                            | Resolution: 2 pm |
|                            | Scanning frequency: 1000Hz |

Figure 5. mechanism for measuring FBG.
By analyzing the data of the static FBG sensing devices (Fig 6), we found that there was background noise with an amplitude of 1.6 pm and a frequency of 1000 Hz in the wavelength signal output by the mechanism for measuring FBG. After processing the wavelength variation, the background noise of the strain signal was obtained, the amplitude was about 2με, the frequency was about 1000Hz, and the measuring mechanism had a time delay of about 1.5ms.

The above operation is an experiment performed when the mechanism for measuring FBG was in a static state. However, due to the effect exerted by the complex mechanical and acoustic environment during the flight of the rocket, there may be noise of multiple frequencies. To simulate the strain value output by the mechanism for measuring FBG during flight, we mixed white noise with amplitude limit to 2με and sample time of 0.01s, 0.001s, and 0.0001s, and added them into the control loop to test the stability of the controlling mechanism. To simulate the response time delay phenomenon of the sensing device, a time delay fault of 1.5ms is introduced into the control loop.

![Figure 6. Background noise of the strain signal.](image)

### 4.1.3 Effect exerted by Flight Environments on FBG Measuring mechanism

In the course of the rocket flight, the environment temperature and pressure with the sensing device intalled vary as the flight altitude change. For changes in external pressure and temperature, an approach termed as reference grating exploits one separate reference grating to be the device sensing temperatures and pressures by complying with the path of fiber, i.e., grating within thermal and pressure contact with local configuration yet shield according to strain change [11]. As the identical physical characteristics exhibited by the strain grating and the reference grating, the deviation of strain attributed to the environment parameter change is able to be effectively remedied. Thus, the measurement fault attributed to variations of pressures and temperatures within simulation was temporarily neglected.

### 4.2 Deformation Reconstruction Fault

"FBG deformation reconstruction fault" refers to the difference between the reconstructed shape and the actual shape of the rocket. This is attributed to the strain measurement fault $e$ and the accuracy of the reconstruction algorithm. Their specific relationship can be explained by the following figure:

![Figure 7. Rocket reconstruction process and faults.](image)

From the Fig 7, the reconstruction fault value refers to the fault value of rotation Angle and rotation angular velocity obtained by the shape reconstruction algorithm in chapter 2 of the present study and is closely related to the accuracy of FBG sensing device and reconstruction algorithm.
5. SIMULATION ANALYSIS

Taking a vehicle for launching with a large slenderness ratio as an example (details of the rocket parameters are in [12]), the increment-based dynamic inversing controlling device and the rocket pitch direction dynamics model designed in the present study are used to verify the performance of the designed controlling mechanism in the MATLAB simulation environment, and a comparison is drawn between the traditional notch filter PID control and PID control with FBG remedy. Lastly, this study analyzes the effect exerted by FBG reconstructing precision on the developed controlling mechanism.

The rocket height of the reference point is set to 11.26 km (43.5 Kpa at the peak dynamic pressure), the mass of the launcher is 7972kg, the velocity is 522.3m/s, and the pitch Angle is 41.2°.

- Set the fast loop gain $K_f = 5$ as well as slow loop gain $K_q = 4$ in INDI controlling device;
- Set PID control parameter $K_p = 4, K_d = 3, K_i = 0$. The notch filter parameter $\omega_n$ was set to the first-order vibration frequency for the body of the rocket, $\xi_s$ and $\xi_r$ were set to 0.012 and 0.57, separately.
- For increasing the effect exerted by the elastic influence on controlling mechanism, and the attitude sensing devices received the placement at the forward end at the 2nd phase, right under the payload adapter.
- The control command was set to a 1° step command and suppose the strain measurement fault was 4%.

The increment-based dynamic inversing control law by complying with FBG remedy developed in the present study is used to simulate the flight of carrier rocket, and the control effects of PID control without remedy, traditional notch filter and PID control with FBG remedy are compared. The results achieved based on the simulation of the pitch Angle and the rocket elastic deformation coordinate at $x_{geo}$ are shown in Fig 8 and Fig 9.

According to Fig 8, for the flexible body rocket model without remedy PID control, the system output gradually diverges at 2 s due to the impact of elastic effect, and the control instruction cannot be tracked. After adopting notch filter or adding FBG remedy, despite the measurement fault attributed to the

![Figure 8. Pitch angle response curves.](image-url)
vibration of the body of the vehicle for launching, the system can still track the command attitude and stabilize the rocket to the desired control command in a certain time.

![Figure 9. Modal coordinates response.](image)

However, when the notch filter PID control is adopted, the maximum overshot is 14.1%, which is greater than the two control approaches using FBG remedy, and the adjustment time and steady-state fault of FBG+INDI control are the smallest, as shown in Fig 8. The elastic deformation attributed to the FBG+INDI control scheme is obviously smaller than that attributed to the traditional notch filter and the FBG+PID control scheme.

In conclusion, for large flexible rocket, after introducing FBG remedy or adopting notch filter, the system is capable of tracking the command attitude despite the measurement fault attributed to the vibration achieved by the body of the vehicle for launching. However, from the perspective of the control effect, the notch filter has a low control accuracy and cannot achieve good stable convergence. In comparison, the INDI approach using FBG remedy has a higher control accuracy and less rocket vibration.

6. CONCLUSION
To deal with the problem that the curvature information of the large flexible rocket body affects the attitude controlling for the body of the rocket while improving the controlling precision achieved by the controlling device, the present study proposes an approach of reconstructing deformation and highly precise attitude controlling of the vehicle for launching by complying with strain measurement. The data of the test of vibration is incorporated into the increment-based dynamic inversing control for designing the controlling mechanism. Moreover, the modeling and fault analysis of the mechanism for measuring FBG within flight environments are carried out, and the developed scheme receives the simulation and verification. According to the results achieved based on the simulation, the controlling mechanism with deformation information remedy could be more accurately tracked with the instruction attitude than the conventional filtering approach. In addition, the incremental dynamic reverse and FBG remedy architecture reduced the rocket vibration amplitude to a certain extent. The FBG measurement fault fell to a particular range, the controlling mechanism was capable of still precisely tracking attitude of instruction. The developed control scheme provides an effective approach for high precision attitude controlling of flexible rockets.

ACKNOWLEDGMENT
The authors of this study would like to express gratitude to LetPub (www.letpub.com) for its linguistic assistance and science-based consultation when the present study was being prepared.

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