International Workshop on Automobile, Power and Energy Engineering

Research on Whole-spacecraft Vibration Isolation based on Predictive Control

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Abstract

Launch vehicles will impart high levels of vibration to satellite during launch. Whole-spacecraft vibration isolation is a better choice to reduce the magnitude of launch dynamic loads. In this paper, active vibration isolation technology based on predictive control for whole-spacecraft vibration isolation is studied.

Considering the special environment of the rocket, pneumatic isolation system is applied. In order to improve the dynamic characteristics of the isolation system, a cascade control with double loop structure and predictive control algorithm for pressure tracking control of inner loop are proposed. A pneumatic servo system exhibits strong non-linearity. To resolve this problem, the control method of multi-models combined with MPC is put forward and applied in this paper, where piecewise linear models, on which controllers are built, are obtained by integrating the models with data at the work points. To enhance the tracking speed, a strategy of switching ahead is proposed, whose feasibility and effectiveness are proved by experiments. In addition, by resetting the predictive horizon and the weighting matrices of the MPC algorithm, influences of the considerable time delay, which is caused by a long pipeline, on the control system performance are effectively suppressed. With these newly proposed approaches, the pressure tracking performance is significantly improved. Thus with this design, the real-time pressure tracking can be guaranteed and so that the active control system can work at higher frequency range. The experiment results of isolation system with the double loop controller showed that the overshoot appears near the natural frequency was decreased greatly.

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Keywords: Whole spacecraft vibration isolation; Predictive control; Nonlinearity; Time delay; active control

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doi:10.1016/j.proeng.2011.08.1112
1. Introduction

To a satellite, launch environment is the worst-case loading condition, although it takes only several ten minutes. This results in an over design of the satellite structure and increment of the launch cost. A lot of efforts have been devoted to investigating an approach to minimize launch loads to satellites in the form of a whole-spacecraft vibration isolation system since 1993[1-4]. The objective of such effort is to reduce the launch-induced vibration of a satellite by inserting an isolation system between the launch vehicle and the satellite. To date, many types of whole-spacecraft isolation systems have been designed and successfully applied for many times [5].

In our research project, a kind of isolation platform with eight struts for the whole-spacecraft vibration isolation is being investigated. This system integrates passive and active isolation function together. As a part of the whole project, active control technique with single isolator is developed in detail in this paper.

The active isolation system with double loop is showed in Fig.1. By adding inner loop specialized for the pressure control, the control system can suppress the disturbance quickly and improve the dynamic characteristics of pressure tracking effectively. Most importantly, the real-time pressure tracking can be guaranteed, and thus the active control system can still work well at the higher frequency range.

2. Nonlinearity

In order to resolve the nonlinearity problem of pressure tracking, a nonlinear MPC algorithm based on the multi-model method is suggested. In this method, the whole nonlinear model is neared by several
piecewise linear models. Then MPC controllers are designed according to these models, and by switching among controllers, the closed loop control is realized.

2.1. Piecewise linear model building

Choosing \( N \) output \( y_0 \leq y_1 \leq \cdots \leq y_{N-1} \) in the output space \( Y \), and calculating the corresponding work points \((x_i, u_i, y_i)\), then piecewise linear models \( \Sigma_i \) at these \( N \) work points can be built by the linearized method:

\[
\Sigma = \{\Sigma_0, \cdots, \Sigma_i, \cdots, \Sigma_{N-1}\}
\]

where \( \Sigma_i \) is

\[
\begin{align*}
\dot{x} &= A_ix + B_iu \\
y &= C_ix
\end{align*}
\]

The number and position of the work point \( y_i \) are decided by the output curve of the real plant. But usually it is better using much fewer linear models for quickly tracking and simplifying the controller design.

The experiment data of the real pressure tracking system in wide range is showed in Fig. 2.

![Fig. 2. Multi-model division](image)

By simplifying the flow equation of valve’s orifices and pressure differential equation of the chambers, the linear pneumatic model around pressure work point \( P_0, P_1, \cdots P_i \) can be gotten [6]:

\[
G_i = \frac{R_i}{1 + T_i s}
\]

This model express the relationship between the input of voltage and output of pressure, and can be changed to the state space description \( \Sigma_i \). According the model data, three linear models are simplified nearly, they are \( \Sigma_1, \Sigma_2 \) and \( \Sigma_3 \) (Fig. 2).
2.2. Multi-model controller design

N linear models \( \Sigma_i \) have been built in section 2.1. According to the MPC, the predictive output of a linear model can be written as

\[
Y_p^{(i)}(k) = \Psi^{(i)}x(k) + \Upsilon^{(i)}u(k-1) + \Theta^{(i)}\Delta U(k)
\]  

(4)

The goal of predictive control is for output \( Y \) to follow the setpoint \( \Gamma \). Suppose the setpoint of every output subspace is \( \Gamma_i \), then performance index is

\[
J^{(i)}=(\Gamma_i(k)-Y_p^{(i)}(k))^T Q^{(i)}(\Gamma_i(k)-Y_p^{(i)}(k))+\Delta U^{(i)}(k)^T R^{(i)} \Delta U^{(i)}(k)
\]  

(5)

The control input increment and the controller gain are acquired by minimizing the above performance index, and they are

\[
\Delta U^{(i)}(k) = K^{(i)}(\Gamma_i(k)-Y_f^{(i)}(k))
\]  

(6)

\[
K^{(i)} = (\Theta^{(i)^T} Q^{(i)} \Theta^{(i)} + R^{(i)})^{-1} \Theta^{(i)^T} Q^{(i)}
\]  

(7)

thus \( N \) controllers are obtained

\[
C = \{C_0, \ldots, C_i, \ldots, C_{N-1}\}
\]  

(8)

Fig. 3 shows the principle sketch with the multi-model MPC. \( N \) setpoints, \( N \) linearized models and \( N \) controllers are switched at the same time according to the given rules.

![Fig. 3 Principle sketch with multi-model MPC](image)

2.3. Multi-model switching

Using piecewise linear models \( \Sigma_i \) for control means that the output is controlled from \( y_0 \) to the steady state \( y_1 \), then to \( y_2 \), ..., \( y_N \). Simulation results of a nonlinear system with three piecewise models are showed in Fig. 4(a). Obviously due to the difference between the local setpoint \( \Gamma_i \) and the global setpoint \( \Gamma \), the system response reaches to the setpoint \( \Gamma \) slowly. In every stage, the response speed will be fast at the beginning of the control process, and decreases greatly when the output nears the steady state. If we
switch model $\Sigma_i$ and controller $C_i$ to $\Sigma_{i+1}$ and $C_{i+1}$ before the response arriving to the steady state $y_i$, namely switching ahead, the response speed can be improved significantly (Fig. 4(b)).

![Fig. 4](image_url)

Fig. 4. (a) Multi-model switching normally; (b) Multi-model switching ahead

2.4. Experiment study

It is found from experimental results that there are little difference between two model ($\Sigma_1$ and $\Sigma_2$) switching and three model ($\Sigma_1$, $\Sigma_2$ and $\Sigma_3$) switching. Therefore, switching with two models is used in the real experiment, with a consideration of the system reliability and the controller simplification.

Two switching methods are compared in Fig. 5(a). Switching positions of the two curves are $P = 4kgf/cm^2$ and $P = 3.5kgf/cm^2$ respectively. The system response speed with $P = 3.5kgf/cm^2$ increases greatly compared with $P = 4kgf/cm^2$. The tracking curve in a wide range with multi-model switching method is showed in Fig. 5(b). By the proposed method of multi-model MPC, the pressure tracking system is realized effectively in real time.

![Fig. 5](image_url)

Fig. 5(a). System response with multi-model switching; (b) System response in a wide range
3. Time Delay

Time delay caused by a long pipeline is another problem need to be resolved in the pressure tracking system.

3.1. Time delay performance analysis

Gas pipeline of active control system is showed in Fig. 6. Pipeline will generate a time delay in the gas transmission. The relationship of the time delay versus the pipeline length is showed in Table 1.

![Gas pipeline of active control system](image)

Table 1. Pipeline length versus transmission time delay

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time delay (ms)</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

The overshoots of response will add gradually with the increasing of delay time, even lead the system to unstable with a large enough delay step. So time delay must be considered in the pressure tracking system.

3.2. MPC with time delay

A single-input single-output system with time delay is

\[
x(k+1) = Ax(k) + Bu(k) \\
y(k) = z^{-d}Cx(k)
\]

where \( d \) is the step of time delay.

According to the MPC algorithm, predictive step \( H_p \) is added to \( H_p + d \). Then the predictive output \( Y_p(k+d+1) \) of \( d+1 \) step at \( k \) instant is

\[
Y_p(k+d+1) = z^{-d}Cx(k+d+1) \\
= Cx(k+1) \\
= \ldots \\
Y_p(k+d+H_p) = Cx(k+H_p)
\]
It is known from (10) that the predictive output \( Y_p(k + d + i) \) of \( d+i \) step corresponds to the real output of \( i \) step, thus input horizon \( H_p \) should be added to \( H_p + d \). The setpoint \( \Gamma(k) \) becomes:

\[
\Gamma(k) = [\hat{r}(k+1|k) \quad \ldots \quad \hat{r}(k+i|k) \quad \ldots \quad \hat{r}(k+H_p+d|k)]^T
\]

(11)

Performance index now is

\[
J = \sum_{i=d+1}^{H_p+d} \|r(k+i) - \hat{y}(k+i|k)\|_Q^2 + \sum_{i=0}^{H_p-1} \|\Delta u(k+i|k)\|_R^2
\]

(12)

Where \( Q = \text{diag}[0 \quad \ldots \quad 0 \quad Q(d+1) \quad \ldots \quad Q(H_p+d)] \), \( R = \text{diag}[R(0) \quad R(1) \quad \ldots \quad R(H_u-1)] \).

In the performance index, only the error of model prediction and input command from \( d+1 \) to \( H_p + d \) are considered which reduces the effect of the time delay, namely \( Q(i) = 0, \ 1 \leq i \leq d \). The weighting matrix \( R \) is not changed.

3.3. Experiment results

To demonstrate the capabilities of predictive controllers, a pipeline with 1m is used to connect the cylinder and the valve in experiment. Fig. 7 shows the experiment results of pressure tracking. When considering the time delay in the MPC algorithm, the overshoot of up tracking response reduces 4% compared with the response without considering the time delay.

Fig. 7. System response with time-delay
When a wide range of pressure tracking is required, the method of multi-model switching and time delay introduced before are considered in controllers design. Fig. 8 shows the system response in a wide range. The overshoot is reduced 4.4% compared with the system without considering the time delay. The experiment results demonstrate that the MPC algorithm with multi-model and time delay is feasible and effective in the real control system.

![System response with multi-model switching and time delay](image)

**Fig. 8. System response with multi-model switching and time delay**

### 4. Active Isolation Control

Using nonlinear MPC and time delay method introduced before, pressure tracking control in a wide range is realized. As the inner loop of the active vibration isolation system for providing the energy, the respond bandwidth of the pressure tracking is enlarged sufficiently such that it is qualified as the control input to the isolation control system.

The isolation system performance with double loop control is examined by means of sinusoidal sweeping. Frequency changes from 5Hz to 30Hz, which is controlled by LMS Test Model Analysis System. Excitation is created by a vibration table. Fig.9 is the photo of active isolation experiment system. Transmissibility curve of isolation system is showed in Fig.10. With active control, the overshoot appears near the natural frequency decreases greatly.

![Active isolation experiment system](image)

**Fig. 9. Active isolation experiment system.**
5. Conclusion

In this paper, a theoretical and experimental investigation is presented into such problems as nonlinearity and time delay associated with the pressure tracking system. And results of vibration isolation experiment have proven the proposed method is valuable.

In order to resolve the problem of strong nonlinearity, a nonlinear MPC based on the multi-model is suggested. In this method, a nonlinear space is divided into several linear subspaces, and in which piecewise models at work points are built. According to these models, controllers are obtained. With the strategy of switching among controllers, the closed loop control is realized. At the same time, the method of switching ahead is successfully used to significantly raise the speed of response. The experimental study showed that the presented method is feasible and effective.

The time delay of the pressure system produced by a long pipeline can not be ignored. By resetting the predictive horizon and the weighting matrices of the MPC algorithm, affection of the time delay on the control system can be suppressed effectively and this has been proved by the results from experiment.

The isolation system experiment results with double loop control show that the overshoot appears near the natural frequency decreases greatly.

References


