ROBUST CONTROL OF UNCERTAIN FLEXIBLE SPACECRAFT USING DISTURBANCE OBSERVER BASED CONTROL STRATEGIES

Wen-Hua Chen

Department of Aeronautical and Automotive Engineering, Loughborough University
Loughborough, Leicestershire, LE11 3TU, UK, W.Chen@lboro.ac.uk

ABSTRACT

Spacecraft with large flimsy structures impose an interesting and challenging design problem for on-board Guidance, Navigation and Control Systems (GNC) due to their flexible modes and possible significant uncertainties. This paper presents a new approach to this problem, namely disturbance observer based control (DOBC), where a disturbance observer is employed not only to estimate and cancel external disturbances but the influence of flexible modes and uncertainties. A two stages design procedure is proposed. It is shown that three design objectives, i.e. attenuation of external disturbance, suppression of flexible modes and robustness against uncertainties, can be achieved by the proposed scheme. The proposed technique is easy to implement and transparent to practitioners, and it shall have significant potential for AOCS of spacecraft with flexible structures and other space systems.

Keywords: Flexible structure, attitude and orbit control systems, robust control, disturbance attenuation

1. INTRODUCTION

A number of future spacecraft missions have been identified for possible use of large flimsy structures to avoid a prohibitive mass. These large light weight structures have intrinsically very low stiffness. Examples of them include large inflatable antenna for space radio telescopes, solar sail for interplanetary flight and inflatable solar reflector for future orbital transfer vehicles.

One of the main concerns in the control of spacecraft with large flimsy appendages is that the flexible modes are moving towards the critical frequencies or the bandwidth of the control systems. A very widely method to reduce the influence of the flexible modes is the notch filter technique, which provides required gain reduction at the flexible mode frequencies. However, there are significant uncertainties in spacecraft with large flexible structures such as the change of structure damping, which causes the variations of flexible mode frequencies and mode shaping and makes the use of the notch filter technique difficult. It is evident that due to the phase lag introduced by the notch filter, it is possible to destabilise the spacecraft when the flexible frequencies change. The combination of flexible modes, high uncertainties, and external force/torque disturbance that might have unknown magnitude and frequency range poses a great challenge for Attitude and Orbit Control System (AOCS) design for spacecraft with large flimsy appendages. To address this issue, robust control methods in particular Quantitative Feedback Theory (QFT) and H^∞ control have been investigated [1].

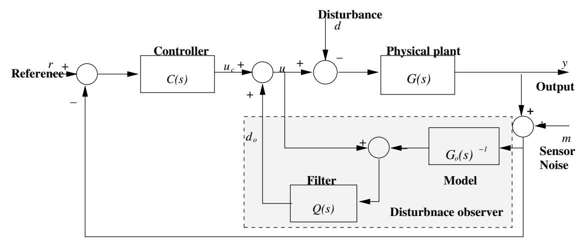

Figure 1. A block diagram configuration of disturbance observer based control technique

2. DISTURBANCE OBSERVER BASED CONTROL TECHNIQUE

This paper proposes a new approach for the AOCS of spacecraft with large flimsy appendages, namely disturbance observer based control (DOBC) technique. A schematic configuration of the DOBC concept is shown in Figure 1, where $G_0(s)$ is the nominal model chosen for the controller design, $G(s)$ the real spacecraft dynamics, d the external disturbance and m the sensor noise. It can be seen that in addition to a conventional feedback controller $C(s)$, there is an inner feedback loop with a filter

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$Q(s)$ that is introduced to estimate the influence of the external disturbance and uncertainties. The control action consists of two parts: control action generated from the primal controller, u_c, and the estimated equivalent disturbance d_0. It can be shown that when there is no mismatching between the physical plant and the model and no external disturbances, the inner loop does not take effect and this configuration is equivalent to a conventional feedback controller.

Bock diagram manipulations of the inner disturbance observer loop give

$$d_0(s) = Q(s)[\left(G^{-1}(s) - G_0^{-1}(s)\right) y(s) + d(s) - G_0^{-1}(s)m(s)] \tag{1}$$

and

$$\begin{aligned} y(s) &= \left(Q(s)G_0^{-1}(s) + (1 - Q(s))G^{-1}(s)\right)^{-1} \\ &\quad \left(u_c(s) + Q(s)G_0(s)^{-1}m(s) - (1 - Q(s))d(s)\right) \end{aligned} \tag{2}$$

The following observations can be made based on Eq. (1) and (2):

- Not only the external disturbance d but also the mismatch between the model $G_0(s)$ and the plant $G(s)$ can be estimated in d_0 (see Eq.(1)).
- Within a specified frequency range of $|Q(s)| \approx 1$, the real plant of $G(s)$ behaves as the nominal model $G_0(s)$ in spite of the presence of d and uncertainties. Actually, it follows from Eq. (2) that

$$\begin{aligned} y(s) &\approx G_0(s)u_c(s) - m(s) \\ &\qquad \text{in the frequency range of } |Q(j\omega)| \approx 1 \end{aligned} \tag{3}$$

Therefore DOBC provides not only a promising means of external disturbance attenuation but also for robust control.

The disturbance observer based control (DOBC) technique has been applied in the control of systems with unknown external disturbances and uncertainties for two decades [2, 3, 4, 5], where an observer is designed to estimate external disturbances or the influence of uncertainties and then compensate for them. A typical example is the widely used independent joint control in industrial robots (for example see [6, 7]), where a controller is designed based on a simplified linear model for each individual link. The nonlinear dynamics and the coupling effects from the other links are considered as disturbances and a linear disturbance observer is designed to estimate and then compensate for them. In addition to robotics, the disturbance observer based control method has also found its applications in other industrial systems including machining centre, motors, disk/CD-ROM drives and PWM inverters, and it is now regarded as a promising robust control methods for practitioners in Japan.

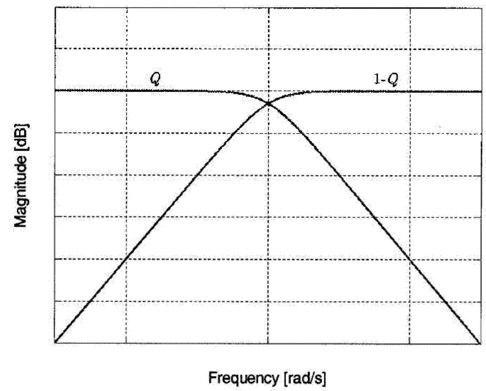

Figure 2. Trade-off for Q filter design where 1-Q(s): robustness and disturbance attenuation; Q(s): sensor noise attenuation

It must be noticed that the similar technique has been applied in aerospace and space systems under another terminology 'Disturbance accommodating control technique' [8] [9] [10] although it was developed independently. Attempt has been made to applying this technique to the Hubble space telescope and missiles [8] [9]. Most recently, the disturbance observer was employed to estimate and cancel the combined effects of nonlinear terms and uncertainties for reusable launch vehicles in [10], and a nonlinear DOBC technique was developed for highly manoeuvrable missiles with quite promising robust performance and disturbance attenuation ability in [11].

The design of the filter $Q(s)$ is critical for the success of DOBC techniques. It has been mentioned that a good robustness and external disturbance rejection can be achieved in the frequency range of $|Q(j\omega)| \approx 1$. However it shall be noticed from Eq. (1) that within this frequency range, the sensor noise cannot be attenuated. Fortunately in most of engineering systems, the external disturbance and sensor noise have different characters in their spectral energy content. In general, the filter $Q(s)$ is designed as a low pass filter. Fig. 2 illustrates the frequency response of a low pass filter where $1 - Q(s)$ indicates the external disturbance attenuation and robustness while $Q(s)$ represents the sensor noise attenuation. Furthermore, to make the control scheme implementable, the relative degree of $Q(s)$, i.e. the difference between the order of the denominator and the numerator, shall be larger than that of the nominal model $G_0(s)$.

3. TWO STAGE DESIGN PROCEDURE

In the view of the above features, the DOBC technique is applied to design AOCS for spacecraft with large flexible structures. A two stages design procedure is proposed. First a primal controller is designed based on the nominal model of the rigid body of the spacecraft, according to the frequency domain specifications such as gain and phase margin, bandwidth, and transient performance requirements such as overshoot, while ignoring external disturbances, flexible modes and uncertainties. Traditional design methods for AOCS of spacecraft such as Proportional and Derivative (PD) controller can be used. Certainly, if necessary robust control methods also can be employed. The second stage is mainly about attenuation of disturbances, flexible modes and possible uncertainties, and the disturbance observer, or the filter $Q(s)$, is designed and employed to estimate the external disturbance and the differences between real spacecraft dynamics and the simplified model $G_0(s)$ used for the primal controller design. The whole composite controller is obtained by integrating the primal controller with the disturbance observer as in Fig. 1. It shall be noticed that the distinguishing feature of DOBC structure is that if there are no uncertainties and external disturbances the disturbance observer does not take affect and the composite controller behaves like the primal controller. This is in contrast with other robust control methods where robustness is usually achieved at the price of the nominal performance. This is because most of the robust control methods are essential the 'worst case' design, to achieve good performance at the worst case, the controller has to be de-tuned from the nominal performance. In this application, the disturbance observer is designed to suppress the flexible modes and the uncertainties, and makes the real spacecraft behave like the simplified model without flexible modes and uncertainties in the required frequency domain.

4. CASE STUDY AND RESULTS

The case study was developed based on a latest telecommunication satellite [1] with significantly enlarged solar arrays and inflatable antenna. Significant uncertainties including 10% perturbation in damping ratio and 15% perturbation in mode frequencies are also considered. The frequency response of the roll axis dynamics described by a 18th order transfer function was plotted in Fig, 3 by dashed lines, where three typical cases are considered: the nominal case, the worst case and the best case under all perturbations (the worst case and best case are determined based on the shift of the flexible modes and their magnitude). It is interesting to notice that due to coupling, the first two cantilever (anti-resonance) frequencies are not located at the mode frequencies.

Design specifications

1. Control performance specifications
    - a bandwidth of 0.015Hz
    - minimisation of the controller order
    - good rejection of high frequency noises including measurement and actuation
    - Final pointing accuracy: ± 0.09 deg

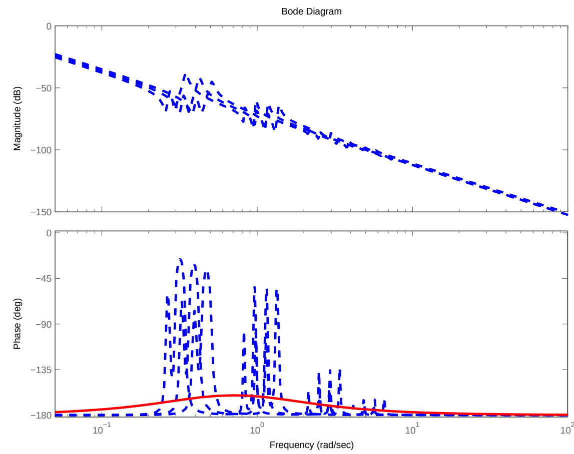

Figure 3. Frequency response of spacecraft with flexible structure and significant uncertainties; Dashed line: the typical cases of the spacecraft; Solid line: a third order nominal model for controller design

2. Robust performance specifications
    - gain margin of at least 6 dB
    - phase margin of at least 30 deg

    or

    - $\max |T(j\omega)| < 2$ where $T(s)$ stands for closed-loop transfer function form the roll reference to the roll output

First a third order model is chosen for the controller design whose frequency response is given by the solid line in Fig. 3,

$$G_0 = \frac{2.8 \times 10^{-4}(2s+1)}{2s^3 + 2s^2} \tag{4}$$

It can be seen from Fig. 3 that this simplified model provides a quite satisfactory approximation of the real satellite dynamics in most of the frequency domain. For this simplified model, a PD like controller is designed to achieve design specifications such as gain and phase margin, bandwidth, and sensor noise attenuation. It consists of two parts: a phase lead filter and a low pass filter.

A phase lead filter is designed to provide enough phase/gain margins and the required bandwidth for the nominal plant using classic design method, for example see [12].

To reduce high frequency noise of the sensors, a low pass noise rejection filter is then added which is connected to the phase lead filter in series,

$$F_0 = \frac{1}{2 * \pi * 0.04s + 1} \tag{5}$$

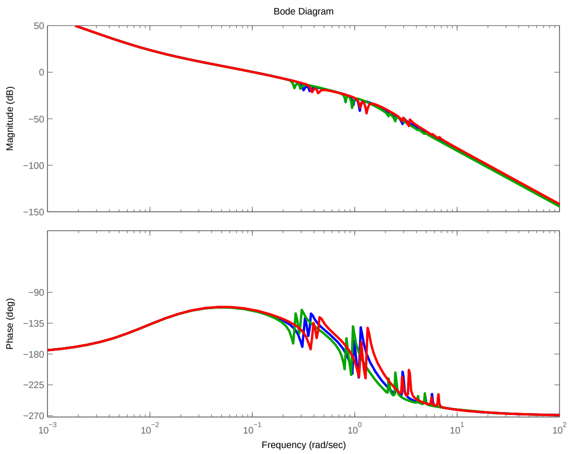

Figure 4. Frequency response of spacecraft with flexible structure and significant uncertainties after disturbance observer is applied; Dash-dot line: nominal model for controller design; Solid line: the typical cases

However, the requirement on the external disturbance attenuation is not considered in this stage and is left to the disturbance observer design. Under a third order low pass filter $Q(s)$, the dynamics of these three typical cases of the spacecraft are shown in Fig. 4 by solid lines. It is evident that the flexible modes and the uncertainties are significantly suppressed. Actually, the real spacecraft dynamics under the disturbance observer technique in particular in terms of the gain of the frequency response are very much similar to the simplified model used for the controller design, i.e. the dash-dot line in the plot.

The disturbance observer is then integrated with the designed primal controller in the DOBC structure, Fig. 1. When the composite DOBC is applied, the complementary sensitivity functions and sensitivity functions of these typical cases under uncertainties are shown in Fig. 5 and 6, respectively. Quite good robustness and disturbance attenuation is exhibited. The complementary sensitivity function is less than 2dB (i.e. 1.6) over all the frequency range. There is no explicit requirement on the the sensitively function and the maximum magnitude of the sensitively function for all uncertain cases is about 5.7dB (i.e 1.92) under the current design. More detail of the gain and phase margin and bandwidth under typical uncertain cases are given in Tab. 1. For all uncertain cases, the gain margin and phase margin are above the the specifications of 6dB and 30deg respectively. The required bandwidth of 0.015Hz is also achieved for almost all the cases.

A series of simulations is conducted for various conditions and uncertainties. The implementation of the proposed DOBC on AOCS of satellite is shown in Fig. 7, where the explicit inverse of the nominal plant is avoided and, $Q_1(s) = Q(s)$ and $Q_2(s) = Q(s)G_0^{-1}(s)$. It shall be noticed that the DOBC configuration in Fig. 7 is only suitable for a system with minimum phase. There are a number of other implementations of DOBC which are

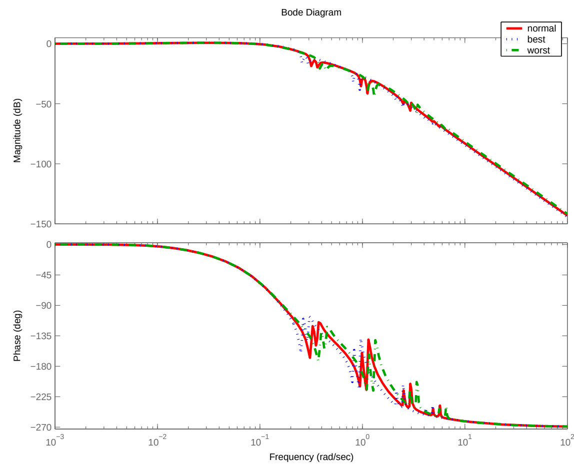

Figure 5. Complementary sensitivity function of spacecraft with flexible structure and significant uncertainties after the disturbance observer is applied; Dash-dot line: nominal model for controller design; Solid line: the typical cases

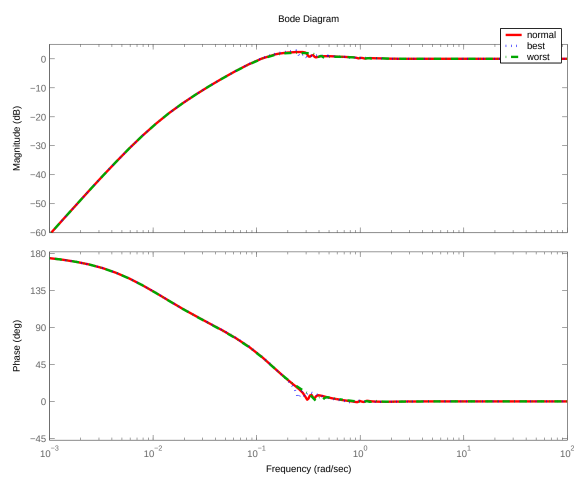

Figure 6. Sensitivity function of spacecraft with flexible structure and significant uncertainties after the disturbance observer is applied; Dash-dot line: nominal model for controller design; Solid line: the typical cases

Table 1. Gain and phase margin and bandwidth under DOBC

Typical case	Gain Margin (dB)	Phase margin (deg)	Bandwidth (Hz)
Nominal	6.9	54.6	0.0152
Best	7.1	58.3	0.0155
Worst	6.5	51.1	0.0149

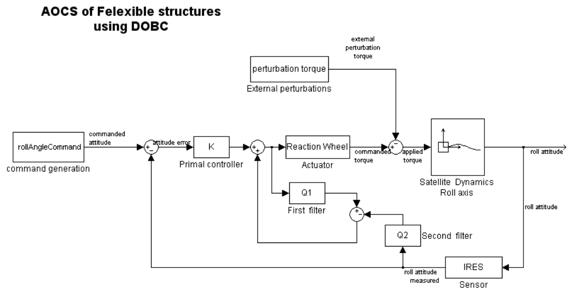

Figure 7. simulation implementation of DOBC for the benchmark

suitable for non-minimum phase plants.

In the simulation, two forms of external disturbances are considered: magnetic momentum and radio frequency disturbance torque. The noise of the actuator reaction wheel is modelled by stochastic noise. Only roll axis is considered in this simulator and the sensor error is represented by white noise with sampling frequency $f_s = 1.25$Hz. Simulations confirm that good time response is achieved under various external disturbances and uncertainties for the spacecraft with flexible structure, as shown in Fig. 8. The requirement of final pointing accuracy of 0.09deg is achieved. Actually under various conditions, the maximum error is about 7×10^{-4}rad=0.02(deg). The high frequency noise from the sensor and the actuation is well rejected. It shall be noticed that compared with other robust control methods, it is relatively easy to control the order of the controller. In this work, a simple PD controller with a first order low pass filter is used as the primal controller, and a third order disturbance filter is then designed. All of them are with quite low order and easy to implementation.

5. CONCLUSIONS

For the robust control of spacecraft with uncertain flexible structure, three objectives are successfully achieved by the DOBC technique simultaneously, namely

- attenuation of external disturbance
- suppress of flexible modes
- improvement of robustness.

It is shown that DOBC provides a simple, transparent, effective and easy to be implemented control technique for spacecraft with uncertain and flexible structure, and also has significant potential in other space system applications.

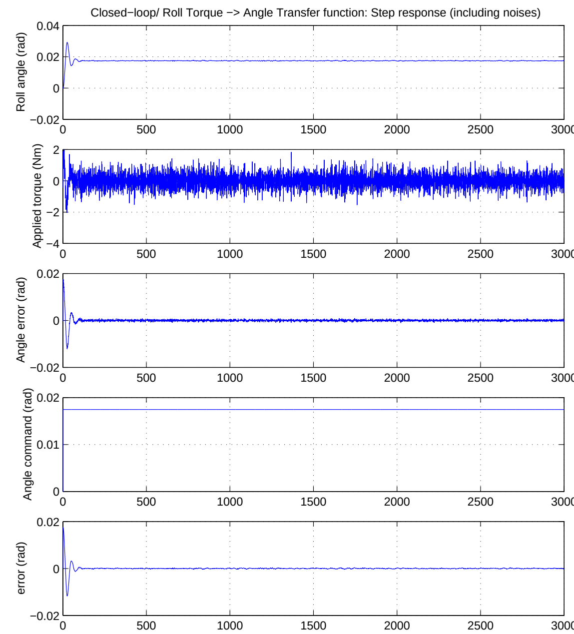

Figure 8. Typical time response under DOBC

6. ACKNOWLEDGEMENT

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