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Nonlinear Disturbance Observer-Enhanced Dynamic Inversion Control of Missiles

Wen-Hua Chen
Loughborough University, Loughborough, Leicestershire, England LE11 3TU, United Kingdom

Nonlinear dynamic inversion control (NDIC) is one of the most promising nonlinear control methods in aerospace engineering. For longitudinal dynamics of a missile, a nonlinear disturbance observer-based approach is proposed to enhance its disturbance attenuation ability and performance robustness against uncertain aerodynamic coefficients. Stability of the proposed nonlinear disturbance observer-enhanced NDIC is established. Its flexibility and efficiency are demonstrated by two different choices of the nonlinear gain function in the observer. Simulation results show that the nonlinear disturbance observer-based technique can significantly improve disturbance attenuation ability and performance robustness of dynamic inversion control.

I. Introduction

THERE has been wide interest in the application of nonlinear control in aerospace engineering, and several nonlinear control methods have been developed and tried on aircraft, missiles, and space satellites. Among them, nonlinear dynamic inversion control (NDIC) is a promising candidate, which provides a systematic alternative approach to the well-known gain scheduling technique (for example, see Refs. 1–4). The basic idea in NDIC is to cancel nonlinear dynamics of a nonlinear system using its nonlinear inversion and to embed desired linear dynamics.

Because unknown disturbances widely exist in aerospace engineering including wind, friction, coupling effects from other subsystems, and environmental and electromagnetic noise, to achieve successful application in aerospace engineering it is crucial for a nonlinear control method to have the ability to handle unknown disturbances. Another important property required for a good control method in aerospace engineering is robustness against unmodeled dynamics and variation of various aerodynamic derivatives. It has been recognized that the NDIC may have poor performance robustness.[4] As will be shown, its performance may significantly degrade under unknown disturbances and uncertain aerodynamic coefficients.

A nonlinear disturbance observer-based control (DOBC) approach is introduced in this paper to enhance the disturbance attenuation ability and performance robustness of the NDIC. A longitudinal autopilot for a missile is designed using this concept. The disturbance observer-based technique has been applied in the control of nonlinear systems or systems with unknown disturbances for two decades,[5–8] where an observer is designed to estimate external disturbances or ignore nonlinear dynamics and then compensate for them. A typical example is the widely used independent joint control in industrial robots (for example, see Refs. 9 and 10), 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 DOBC method has also found its applications in other industrial systems including machining centers, motors, disc/CD-ROM drives, and pulse width modulation (PWM) inverters.

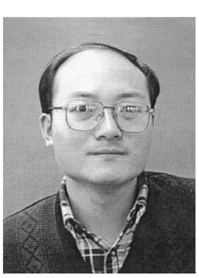
The longitudinal autopilot of a missile developed in this paper consists of a nonlinear disturbance observer and a conventional NDIC. The structure of the composite controller is investigated, and its properties such as stability are established. It is shown that the DOBC approach provides a general way to handle unknown disturbances in nonlinear systems. Different from the linear case where the disturbance observer approach is considered as an alternative approach to design of controllers with integral action, due to the complexity of nonlinear systems, in general, the nonlinear disturbance observer approach does not necessarily lead to a controller with integral action. However, it still has the offset removal ability, which can be considered as generalized integral action for nonlinear systems. Discussion then is focused on the choice of the nonlinear gain function in the disturbance observer, and two choices of the nonlinear gain function, which lead to two disturbance observer-enhanced NDIC schemes, are presented. It is shown that the DOBC provides a flexible way to handle unknown disturbances or uncertainties of nonlinear systems. Simulation study shows that the DOBC significantly enhances the disturbance attenuation ability and robustness of the NDIC.

II. Longitudinal Dynamics of a Missile

The model of the longitudinal dynamics of a missile under consideration is taken from Refs. 11 and 12, described by

$$\dot{\alpha} = f_1(\alpha) + q + b_1(\alpha)\delta + d_2 \tag{1}$$

$$\dot{q} = f_2(\alpha) + b_2\delta + d_1 \tag{2}$$



Wen-Hua Chen holds a Lectureship in Flight Control Systems in the Department of Aeronautical and Automotive Engineering at Loughborough University, England, United Kingdom. He received his M.Sc. and Ph.D. degrees from the Department of Automatic Control at Northeast University, the People's Republic of China, in 1989 and 1991, respectively. From 1991 to 1997, he was a Lecturer in the Department of Automatic Control at Nanjing University of Aeronautics and Astronautics. He held a research position and then a Lectureship in Control Engineering in Center for Systems and Control at University of Glasgow, Scotland, United Kingdom from 1997 to 2000. He has published one book and published or presented more than 40 papers in journals and at conferences. His research interests include robust control, nonlinear control, and their applications in aerospace engineering. He may be contacted at w.chen@lboro.ac.uk.

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where α is the angle of attack (degrees), q the pitch rate (degrees per second), and δ the tail fin deflection (degrees). The disturbances d_2 and d_1 represent all disturbance torques that may be caused by unmodeled dynamics, external wind, and the variation of aerodynamic coefficients, etc. The nonlinear functions $f_1(\alpha)$, $f_1(\alpha)$, $b_1(\alpha)$, and b_2 are determined by aerodynamic coefficients. For instance, when the missile travels at Mach 3 at an altitude of 6095 m (20,000 ft) and the angle of attack $|\alpha| \leq 20$ deg, they are given by

$$f_1(\alpha) = \frac{180 g Q S}{\pi W V} \cos\left(\frac{\pi \alpha}{180}\right)(1.03 \times 10^{-4}\alpha^3 - 9.45 \times 10^{-3}\alpha|\alpha| - 1.7 \times 10^{-1}\alpha) \quad (3)$$

$$f_2(\alpha) = \frac{180 Q S d}{\pi I_{yy}}(2.15 \times 10^{-4}\alpha^3 - 1.95 \times 10^{-2}\alpha|\alpha| + 5.1 \times 10^{-2}\alpha) \quad (4)$$

$$b_1(\alpha) = -3.4 \times 10^{-2} \frac{180 g Q S}{\pi W V} \cos\left(\frac{\pi \alpha}{180}\right) \quad (5)$$

$$b_2 = -0.206 \frac{180 Q S d}{\pi I_{yy}} \quad (6)$$

The tail fin actuator dynamics are approximated by a first-order lag,

$$\dot{\delta} = (1/t_1)(-\delta + u) \quad (7)$$

where u is the commanded fin defection (degrees) and t_1 the time constant (seconds). The significance of the parameters in Eqs. (3–6) and their values for the missile under consideration are listed in Table 1.

To emphasize the main contribution of this paper, only the disturbance/uncertainty in Eq. (2) is considered in this study. This is justified based on two reasons. One is that in simulation study, for this particular plant, it is found that its performance under NDIC is much more sensitive to the variation of aerodynamic derivatives in Eq. (2) than that in Eq. (1). The other is that if there are any unknown disturbances in Eq. (1) that should be taken into account, by repeating the design procedure of the nonlinear disturbance observer for d_1 in Eq. (2) developed in this paper, it is easy to design a nonlinear observer to estimate them.

III. NDIC

In the absence of the disturbance d_1, an autopilot for the missile to track a reference $w(t)$ can be designed using the NDIC.[3] When the output is chosen as

$$y = \alpha + k_q q \quad (8)$$

where k_q is a chosen constant, the resultant control law is given by

$$u = \delta - [t_1/(b_1 + k_q b_2)]\{k_1[y - w(t)] + k_2[f_1 + q + b_1(\alpha)\delta + k_q(f_2 + b_2\delta) - \dot{w}] + m - \ddot{w}\} \quad (9)$$

Table 1 Parameters in longitudinal dynamics of the missile

Parameter	Symbol	Value
Weight	W	4410 kg
Velocity	V	947.6 m/s
Pitch moment of inertia	I_{yy}	247.44 $\text{kg} \cdot \text{m}^2$
Dynamic pressure	Q	293,638 N/m^2
Reference area	S	0.04087 m^2
Reference diameter	d	0.229 m
Gravitational acceleration	g	9.8 m/s^2
Time constant of tin actuator	t_1	0.1 s

where

$$m = \left[\frac{\partial f_1(\alpha)}{\partial \alpha} + \frac{\partial b_1(\alpha)}{\partial \alpha}\delta + k_q \frac{\partial f_2}{\partial \alpha}\right][f_1(\alpha) + q + b_1(\alpha)\delta] + f_2(\alpha) + b_2\delta \quad (10)$$

and k_1 and k_2 are constant gains to be designed according to desired closed-loop behaviors.

When the command signal ω_{cmd} is filtered by a low-pass prefilter

$$G(s) = \omega_n^2 \big/ \left(s^2 + 2\zeta\omega_n s + \omega_n^2\right)$$

the structure of the closed-loop system is shown in Fig. 1.

After substitution of the NDIC law (9) into the longitudinal dynamics of the missile, the closed-loop error dynamics are given by

$$\ddot{y}(t) - \ddot{\omega}(t) + k_2[\dot{y}(t) - \dot{\omega}(t)] + k_1[y(t) - \omega(t)] = 0 \quad (11)$$

In the following study, these parameters are chosen as

$$\zeta = 0.7, \qquad \omega_n = 10\ \text{(rad/s)} \quad (12)$$

$$k_q = 0.06\ \text{(s)} \quad (13)$$

$$k_1 = 15(1/\text{s}^2), \qquad k_2 = 6(1/\text{s}) \quad (14)$$

Because, as shown in Eq. (11), the longitudinal dynamics of the missile is feedback linearized by NDIC, the closed-loop poles under NDIC is given by $-7.0 \pm 7.14j$. After linearizing the nonlinear longitudinal dynamics and the NDIC around the origin, the Bode diagram of the linearized open-loop system is shown in Fig. 2. It can be seen that the open-loop gain crossover frequency is 7.38 rad/s with good phase margin of about 60 deg. With a loop rolloff slope of about 20dB/decade, a good-high frequency attenuation can be achieved. The closed-loop frequency response is also given in Fig. 3, which shows that the bandwidth of the closed-loop system is about 10 rad/s.

In the absence of disturbances, as shown in Fig. 4, quite good tracking performance is achieved under this control law, where the dashed–dot line denotes the reference signal and the dashed line the output response under the designed NDIC.

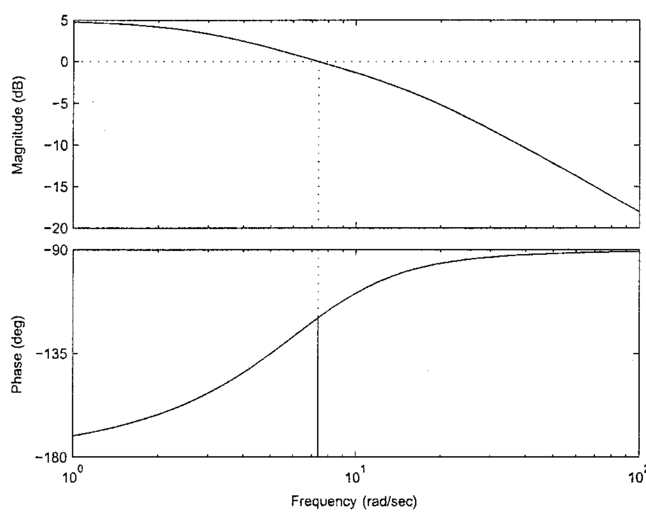

Fig. 2 Bode diagram of the linearized open-loop system under NDIC: phase margin = 60.615 deg at 7.384 rad/s.

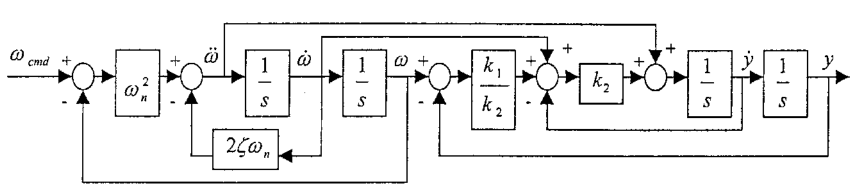

Fig. 1 Closed-loop system under NDIC.

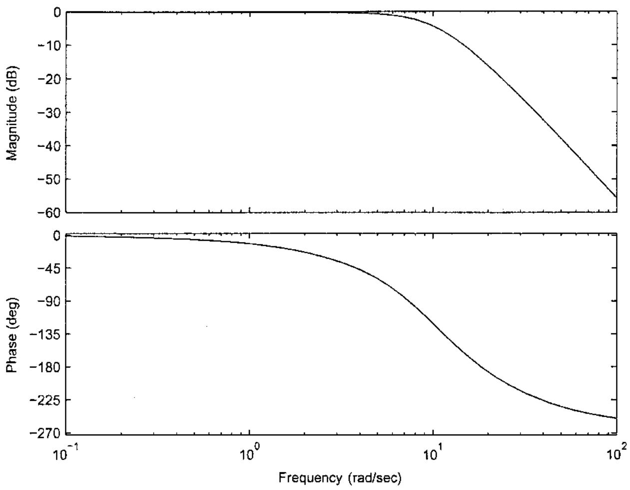

Fig. 3 Bode diagram of the closed-loop system under NDIC.

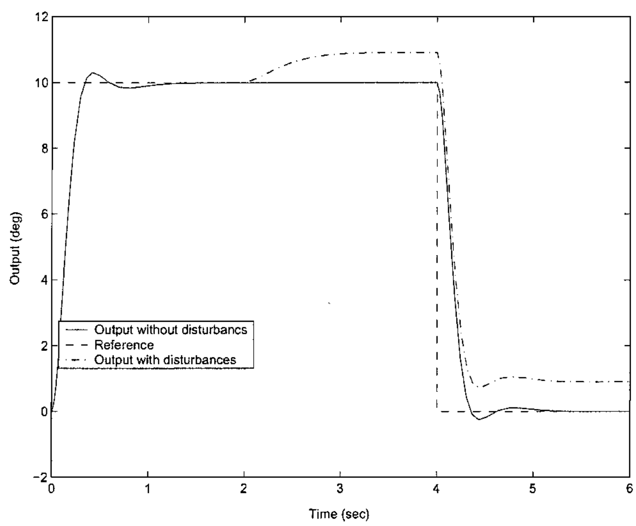

Fig. 4 Performance of NDIC with and without unknown disturbances.

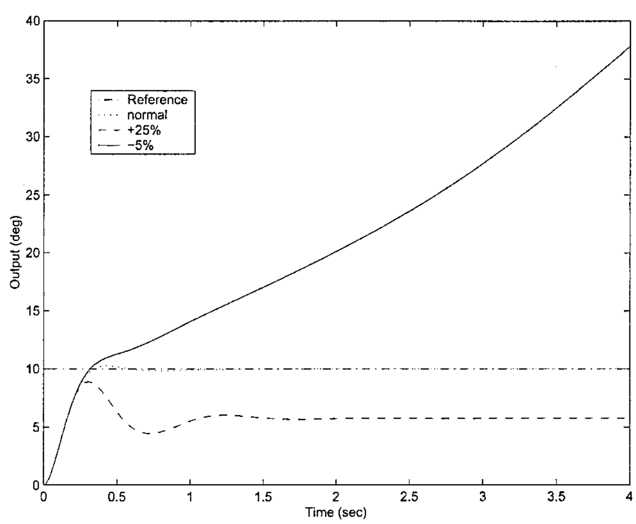

Fig. 5 Poor robust performance of NDIC under different aerodynamic coefficients.

However, this NDIC scheme has poor disturbance attenuation ability. When a constant disturbance occurs at 2 s, the time history of the output is plotted by the dashed–dot line in Fig. 4. Furthermore, this control system is very sensitive to the variation of aerodynamic coefficients. This is evident in Fig. 5 where +25 and −5% denote the tracking performance of the autopilot based on the NDIC technique when the real $f_2(\alpha)$ varies +25 and −5% from its nominal value, respectively. As can be seen from Fig. 5, the NDIC cannot tolerate only −5% variation of the aerodynamics derivative of $f_2(\alpha)$.

IV. Nonlinear Disturbance Observers

The longitudinal dynamics of the missile [Eqs. (1), (2) and (7)] can be put into the general description of a single input/single output affine system as

$$\dot{x}(t) = f(x) + g_1(x)u + g_2(x)d_1, \qquad y = h(x) = \alpha + k_q q \quad (15)$$

where

$$f(x) = \begin{bmatrix} f_1(\alpha) + q + b_1(\alpha)\delta \\ f_2(\alpha) + b_2\delta \\ -(1/t_1)\delta \end{bmatrix} \quad (16)$$

$$g_1(x) = \begin{bmatrix} 0 \\ 0 \\ 1/t_1 \end{bmatrix} \quad (17)$$

$$g_2(x) = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad (18)$$

and

$$x = \begin{bmatrix} \alpha \\ q \\ \delta \end{bmatrix} \quad (19)$$

In this paper, a nonlinear disturbance observer is designed to estimate the unknown disturbance d_1, given by

$$\hat{d}_1 = z + p(x)$$
$$\dot{z} = -l(x)g_2(x)z - l(x)(g_2(x)p(x) + f(x) + g_1(x)u) \quad (20)$$

where $\hat{d}_1$ and z are the estimate of the unknown disturbance and the internal state of the nonlinear observer, respectively, and $p(x)$ is a nonlinear function to be designed. The nonlinear observer gain $l(x)$ is defined as

$$l(x) = \frac{\partial p(x)}{\partial x} \quad (21)$$

It can be shown that, under the assumption that the disturbances are slowly time varying, $\hat{d}_1(t)$ approaches $d_1(t)$ exponentially if $p(x)$ is chosen such that

$$\dot{e}_1(t) + \frac{\partial p(x)}{\partial x} g_2(x) e_1(t) = 0 \quad (22)$$

is globally exponentially stable for all $x \in R^n$, where the estimation error is defined as

$$e_1 = d_1 - \hat{d}_1 \quad (23)$$

As far as stability of the estimation error is concerned, any nonlinear vector-valued function $l(x) = \partial p/\partial x$ such that Eq. (22) is asymptotically stable can be chosen. After $l(x)$ has been chosen, $p(x)$ is found by integration. An alternative method is to start from $p(x)$ and choose $p(x)$ such that the estimation error approaches zero. As will be discussed in Sec. VI, there exist considerable degrees of freedom in the choice of $p(x)$ or $l(x)$.

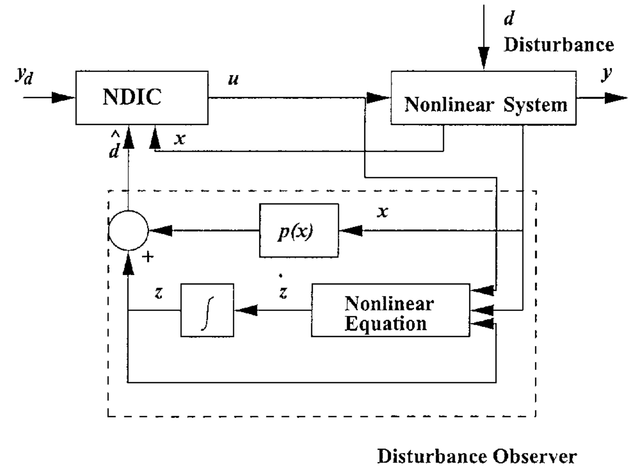

Fig. 6 Nonlinear disturbance observer-enhanced dynamic inversion control.

V. Nonlinear Disturbance Observer-Based NDIC

This section will show that the closed-loop system under the NDIC (9) with the observer (20), as shown in Fig. 6, is also globally exponentially stable with an appropriate choice of the design function $p(\boldsymbol{x})$.

After the disturbance is estimated by the observer (20), the disturbance observer-based NDIC law is given by

$$u^* = u - \{t_1/[b_1(\alpha) + k_q b_2]\}(1 + k_2 k_q)\hat{d}_1 \tag{24}$$

where u is given by the NDIC as in Eq. (9).

When the control law in Eq. (24) is applied to the missile, the whole closed-loop system consists of the nonlinear observer (20), the NDIC (9), and the nonlinear system (15). When the NDIC (9) is substituted into the nonlinear system (15) and a series of manipulations is executed, the closed-loop system error equation is given by

$$\ddot{e}(t) + k_2\dot{e}(t) + k_1 e(t) - (1 + k_2 k_q)e_1(t) = 0 \tag{25}$$

where the tracking error is defined by

$$e = y - w \tag{26}$$

Remember that the observer error is governed by Eq. (22). It is ready to establish the following result.

Theorem: The closed-loop system under the nonlinear disturbance observer-based dynamic inversion control in Fig. 6 is globally exponentially stable if the following conditions are satisfied:

1) The closed-loop system under the NDIC is globally exponentially stable in the absence of disturbances.

2) The observer is exponentially stable under an appropriately chosen design function $p(\boldsymbol{x})$ for any $\boldsymbol{x}$ varying within the state space.

3) The solutions of the preceding composite system are defined and bounded for all $t > 0$.

The proof of the theorem follows from the crucial observation that the convergence of the observer does not depend on the variation of the state $\boldsymbol{x}$. It can be derived from Ref. 13 or Chapter 10 in Ref. 14.

VI. Nonlinear Observer Gain Study

An autopilot for the missile in Eqs. (1), (2) and (7) is designed using the preceding nonlinear disturbance observer-enhanced dynamic inversion control technique. Two choices of the design function $p(\boldsymbol{x})$, which result in two different nonlinear disturbance observer-based NDIC schemes, are proposed and compared.

A. DOBC1: Linear Gains

For the missile in Eqs. (1–7), $\boldsymbol{g}_2(\boldsymbol{x})$ is given by Eq. (18), which is independent of the state α, q, and δ. When the gain $\boldsymbol{l}$ is chosen as a constant matrix, that is,

$$\boldsymbol{l} = [l_1 \quad l_2 \quad l_3] \tag{27}$$

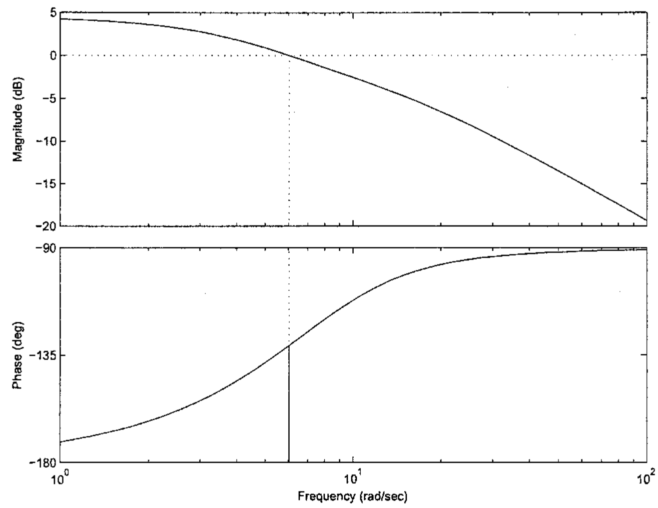

Fig. 7 Open-loop frequency response under DOBC1: phase margin = 48.972 deg at 6.0387 rad/s.

the error dynamics (22) of the disturbance observer is linear and can be written as

$$\dot{e}_1 + l_2 e_1 = 0 \tag{28}$$

It is stable for any $l_2 > 0$. In this case, $p(\boldsymbol{x})$ is given by

$$p(\boldsymbol{x}) = l_1\alpha + l_2 q + l_3\delta \tag{29}$$

where the units for l_1, l_2 and l_3 are degrees per degree, degrees per degrees per second, and degrees per degree, respectively. The observer with the gain $\boldsymbol{l}(\boldsymbol{x})$ and the variable $p(\boldsymbol{x})$ are then integrated with the NDIC of Eqs. (9) and (12). The composite controller is referred to as DOBC1 hereafter. Following the theorem, the missile under the DOBC1 is asymptotically stable.

To investigate the frequency response of the open-loop system and closed-loop system under the DOBC1, they are linearized around the origin. It is found that the linearized closed-loop system has total six stable poles. Compared with the closed-loop poles of the linearized system under NDIC, one extra pole at -10 is introduced by the nonlinear disturbance observer. Actually, this pole depends on the gain l_2 and can be directly determined from Eq. (28). Because of the cancellation of poles and zeros, only two poles, $-7 \pm 7.14j$, remain, which are the same as that under the pure dynamic inversion control. The closed-loop frequency response under DOBC1 is the same as that under the NDIC, thus, is not given. As shown by the Bode diagram of the linearized open-loop system under DOBC1 in Fig. 7, there is a little change in the open-loop crossover frequency, that is, now at 6.0 rad/s with a reasonable phase margin about 50 deg.

Under the same disturbances as in Fig. 4, the performance of the proposed disturbance observer-based NDIC is shown in Fig. 8, where $l_1 = l_2 = l_3 = 10$ and the gains in the NDIC are same as that in Eq. (12). It is evident that good dynamic disturbance attenuation ability is achieved and there is no steady-state error.

B. DOBC2: Nonlinear Gains

This section further demonstrates the efficiency and the flexibility of the proposal disturbance observer-based NDIC. It is well known that appropriate nonlinearity in the closed-loop system introduced by controller design could result in better performance. That is, after canceling undesired nonlinearity of the controlled plant, it may be useful to embed not only linear dynamics but also desired nonlinear dynamics by choosing appropriate nonlinear gains.

Because disturbances and uncertainties may cause the variation of the pitch rate, it may be desired that the observer gain is chosen as a function of the pitch rate q.

When $p(\boldsymbol{x})$ is chosen as

$$p(\boldsymbol{x}) = l_2(q + cq^3) \tag{30}$$

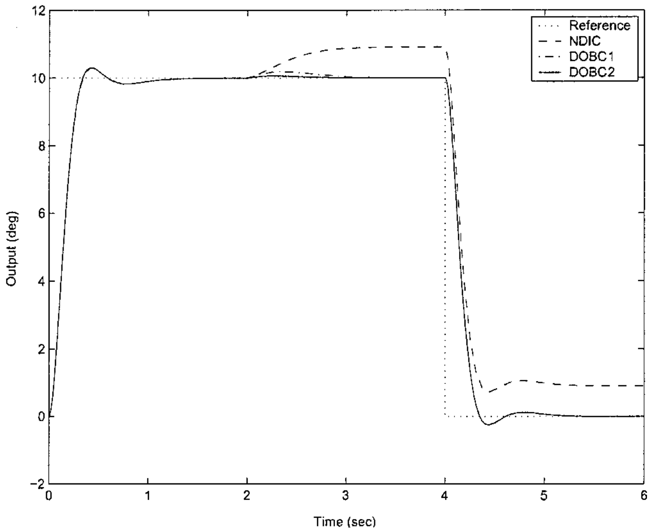

Fig. 8 Performance of disturbance observer-enhanced NDIC with different nonlinear observer gain functions; comparison of disturbance attenuation.

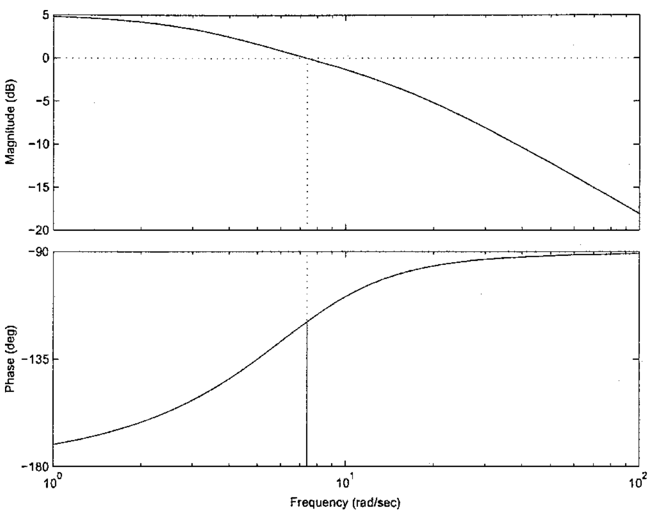

Fig. 9 Open-loop frequency response under DOBC2: phase margin = 60.615 deg at 7.384 rad/s.

it implies that

$$l(x) = \begin{bmatrix} 0 & l_2(1 + 3cq^2) & 0 \end{bmatrix} \tag{31}$$

where the coefficient c is chosen as

$$c = \tfrac{1}{3}(\mathrm{s}^2/\,\mathrm{deg}^2) \tag{32}$$

Then the error dynamics is given by

$$\dot{e}_1 + l_2(1 + q^2)e_1 = 0 \tag{33}$$

It is easy to show that the disturbance observer and, hence, the whole system is stable for all q when $l_2 > 0$.

When l_2 is chosen the same as the earlier case, as shown in Fig. 8, this controller, referred as DOBC2, has even better disturbance attenuation ability than DOBC1, although their tracking performances are indistinguishable.

Note that after linearizing the DOBC2 and the longitudinal dynamics around the origin, the closed-loop poles are the same as those under DOBC1. Figure 9 shows that the open-loop frequency response is the same as that under NDIC. Therefore, the nonlinear disturbance observer technique significantly improves the disturbance attenuation ability of NDIC but does not degrade its tracking performance and high-frequency attenuation ability.

One variable of interest in missile control is actuator rate because due to energy limitation, there is a restriction on the actuator rate. To this end, the time histories of the tail fin rate under NDIC, DOBC1, and DOBC2 are investigated. Under the same reference signal, as shown in Fig. 10, they are indistinguishable. This also verifies that the DOBC does not significantly change the bandwidth of the system under NDIC. It can be seen that the tail fin rate is reasonable for all of the proposed control schemes.

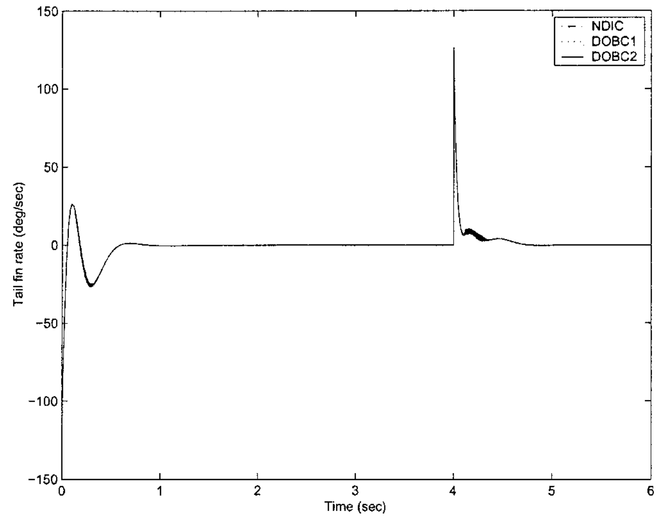

Fig. 10 Time histories of the tail fin rate under different control schemes.

VII. Robustness of Disturbance Observer-Enhanced NDIC

In addition to external disturbances, the term d_1 can represent uncertainties or unmodeled dynamics. That is, in the disturbance observer-enhanced NDIC approach, the uncertainties can be considered as a part of disturbances, and the observer can estimate and then compensate for them. Although the stability result in the theorem is not valid because it is established on the assumption that the disturbances are slowly time varying, the efficiency of the proposed technique is validated by the simulation study. Rigorous robust stability analysis for such an uncertain nonlinear system remains a challenging problem and beyond the scope of this paper. The improvement of the performance robustness against disturbance and uncertainties is mainly due to the introduction of the nonlinear disturbance observer in the loop that tries to estimate the influence of disturbances and uncertainties and then compensate for it.

As shown in Sec. III, the performance of the NDIC significantly degrades when $f_2(\alpha)$ varies within the range from +25 to −5% of its normal value. To test the robust performance of the proposed disturbance observer-based NDIC, a larger range of uncertainties is considered. When it is supposed that $f_2(\alpha)$ varies from +25 to −10% of its normal value, the resultant performance of DOBC1 is shown in Fig. 11. It is shown that the DOBC1 exhibits satisfactory performance robustness against the uncertainty. When the variation of the aerodynamic derivative increases from −10 to −20%, the closed-loop system under DOBC1 is still stable, although poor performance is obtained. When DOBC2 is applied, it is found that excellent robustness is achieved where the aerodynamic derivatives in $f_2(\alpha)$ varies from +25 to −25%, as shown in Fig. 12. Compared with Fig. 5, it can be seen that the nonlinear disturbance observer technique significantly improves performance robustness of the NDIC. This also highlights the flexibility and efficiency of the disturbance observer-based NDIC technique proposed in this paper and the possible benefits of embedding desired nonlinearity in the closed-loop dynamics.

Notice that, as shown in Figs. 2, 7 and 9, adding the nonlinear disturbance observer on the NDIC does not significantly change the low-frequency gain and the open-loop crossover frequency. Therefore, the disturbance observer-based technique achieves good robustness against aerodynamic derivatives and good disturbance attenuation ability but without an increase in the loop bandwidth or using high gain.

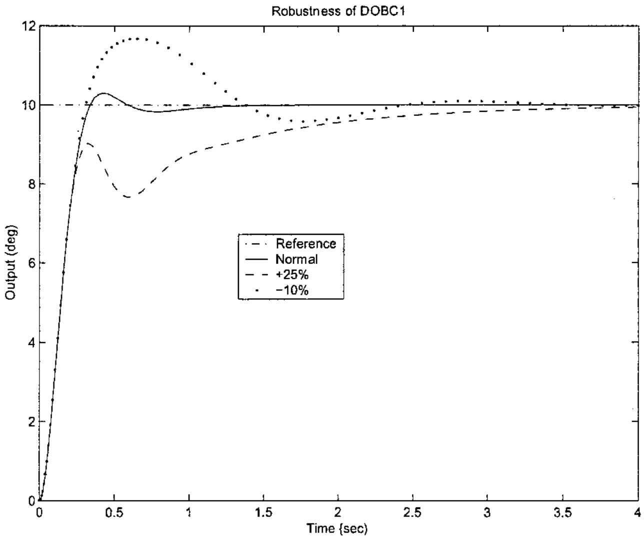

Fig. 11 Robust performance of DOBC1 under different aerodynamic derivatives.

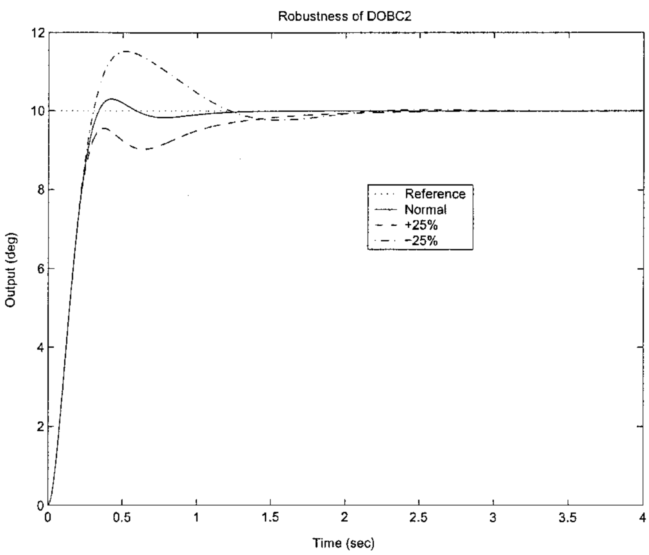

Fig. 12 Tracking robust performance of DOBC2 under different aerodynamic derivatives.

VIII. Conclusions

Disturbance attenuation ability and robustness against the variation of aerodynamic derivatives are two important properties required for control methods to be successfully used in aerospace systems. Investigation shows that the NDIC methods may exhibit poor performance under unknown disturbances and uncertainties in aerodynamics. This paper proposes a nonlinear disturbance observer-based approach to enhance these properties of the current NDIC methods. Two design schemes are proposed. Both of them, in particular the second one, exhibit good disturbance attenuation ability and robustness against uncertainties. It is shown that the nonlinear disturbance observer-based approach provides considerable degrees of freedom in the controller design. As shown in the second disturbance observer-enhanced scheme, excellent performance may be achieved by appropriately choosing nonlinear gain and, thus, deliberately introducing desired nonlinearity in the closed-loop systems.

Acknowledgments

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