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강인한 관측기와 제어기를 적용한 공탄성 시스템의 응답특성 연구

A Study on the Response Characteristics of Aeroelastic Systems Applying Robust Observer and Controller

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Key Words : Aeroelastic response(공탄성 응답), Sliding mode observer(슬라이딩 모드 관측기), State estimation(상태 추정)

ABSTRACT

This paper concerns the active aeroelastic control of flapped wing systems exposed to blast and/or the sonic boom in an incompressible flow field. This is achieved via implementation of a robust estimation capability (sliding mode observer: SMO), and of the use of the deflected flap as to suppress the flutter instability or enhance the subcritical aeroelastic response to blast loads. To this end, a control methodology using LQG(Linear Quadratic Gaussian) in conjunction with SMO is implemented, and its performance toward suppressing flutter and reducing the vibrational level in the subcritical flight speed range is demonstrated. Moreover, its performances are compared to the ones provided via implementation of conventional LQG with Kalman filter.

1. Introduction

The next generation of combat aircraft is likely to operate in more severe environmental conditions that in the past. This implies that such an aircraft, in addition to gust, will be exposed, among others, to blast, fuel explosion, and sonic boom pulses.[1, 2] Under such conditions, even if the flight speed of the aircraft is below the flutter speed, the wing structure will be subjected to large oscillations that can result in its failure by fatigue. Moreover, in some special events, occurring during the operational life of the aircraft such as escape maneuvers, significant decays of the flutter speed can occur, with dramatic consequences for the further evolution of the aircraft. In this sense, robust feedback control methodology should be implemented for a stable operation, however, for aeroelastic system, due to unmeasurable aerodynamic lag states, proposing a vibration control scheme with full state feedback is not viable. In this connection, the use of a state estimator, or observer, is a more practical way of developing active controller for aeroelastic system. All these facts fully underline the necessity of the implementation of an active control capability enabling one to fulfill two basic objectives: a) to enhance the subcritical aeroelastic response, in the sense of suppressing the wing oscillations in the shortest possible time, and b) to extend the flight envelop by suppressing the flutter instability and so, contributing to a significant increase of the allowable flight speed. With this in mind, the great interest in the implementation of aeroelastic control capabilities was emphasized in the seminar papers by Mukhopadyay.[3, 4]

In this paper the active aeroelastic control of a 3-D flapped wing system exposed to an incompressible flow field will be investigated. And an LQG control strategy using sliding mode observer will be implemented, and some of its performances will be put into evidence that will be compared with conventional LQG with Kalman filter.

2. Configuration of Flapped Wing Model

Fig. 1 presents the typical wing-flap that is considered in the present aeroelastic analysis.[5, 6] The three degrees of freedom associated with the airfoil appear clearly from Fig.1. The pitching and plunging displacements are restrained by a pair of springs attached to the elastic axis (EA) with spring constants K_α and K_h, respectively. The control flap is located at the trailing edge. A torsional flap spring of constant K_β is also attached at the hinge axis; h denotes the plunge displacement (positive downward), α is the pitch angle measured from the horizontal at the elastic axis of the airfoil (positive nose-up) and β is the flap deflection measured from the control flap hinge (positive flap down).

3. Governing Equation of the System

In matrix form the aeroelastic governing equations of the 3-D flapped wing system can be written as [6, 9]:

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$$\mathbf{M}\ddot{\mathbf{y}}(t)+\mathbf{K}\mathbf{y}(t)=-\mathbf{L}(t)+\mathbf{L}_b(t)+\mathbf{L}_c(t) \quad (1)$$

where $-\mathbf{L}(t)$, $\mathbf{L}_b(t)$ and $\mathbf{L}_c(t)$ represent the unsteady aerodynamic, blast and control loads, respectively. In Eq. (1), the column vector of plunging/pitching/flapping displacement is defined as

$$\mathbf{y}(t)=\begin{bmatrix}\frac{h(t)}{b} & \alpha(t) & \beta(t)\end{bmatrix}^T \quad (2)$$

while

$$\mathbf{M}=\begin{bmatrix} bm & S_\alpha & S_\beta \\ bS_\alpha & I_\alpha & I_\beta+bcS_\beta \\ bS_\beta & I_\beta+bcS_\beta & I_\beta \end{bmatrix} \quad (3)$$

$$\mathbf{K}=\begin{bmatrix} bK_h & 0 & 0 \\ 0 & K_\alpha & 0 \\ 0 & 0 & K_\beta \end{bmatrix} \quad (4)$$

denote the mass and stiffness matrices, respectively.

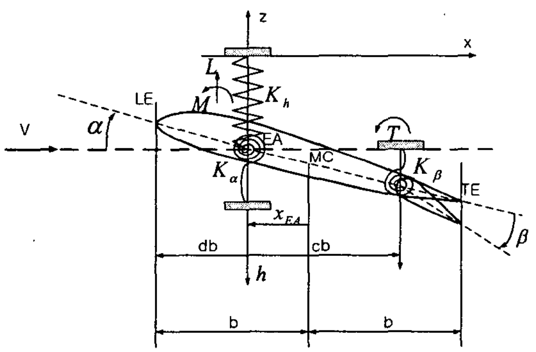


Fig. 1 Typical flapped wing section

The second order aeroelastic governing equation can be cast in a first order state-space form as:

$$\dot{\mathbf{x}}(t)=\mathbf{A}\mathbf{x}(t)+\mathbf{B}u(t)+\mathbf{G}\mathbf{w}(t) \quad (5)$$

Here $\mathbf{A}$ is the aerodynamic matrix, see Ref. 2. The state vector is given by

$$\mathbf{x}(t)=\begin{bmatrix}\dot{h}/b & \dot{\alpha} & \dot{\beta} & h/b & \alpha & \beta & B_1 & B_2 & A_1 & A_2\end{bmatrix}^T \quad (6)$$

where B_1, B_2, A_1 and A_2 denote aerodynamic lag states; $u(t)$ is control input; $\mathbf{w}(t)$ is an external disturbance represented by a time-dependent external excitation, such as blast[8], sonic-boom or step pressure pulse, etc; $\mathbf{G}$ is the disturbance-input matrix, while $\mathbf{B}$ is the control input matrix that is given by

$$\mathbf{B}=\frac{1}{I_\beta}\left[\left(\mathbf{M}^{-1}\begin{bmatrix}0 & 0 & 1\end{bmatrix}^T\right)^T 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0\right]^T \quad (7)$$

The aerodynamic load vector appearing in Eq. (1) is expressed in terms of its components as

$$\mathbf{L}(t)=\begin{bmatrix}L(t) & M(t) & T(t)\end{bmatrix}^T \quad (8)$$

where $L(t), M(t)$ and $T(t)$ denote, respectively, the aerodynamic lift (measurement positive in the upward direction), the pitching moment about the one-quarter chord of the airfoil (positive nose-down) and the flap torque applied to the flap hinge.

4. LQG Control Methodology

While the LQR design provides a robust controller, this control method is not practical due to the unmeasurable aerodynamic lag states. Furthermore, there are lots of chances when some sensors do not happen to work in a certain situation. Therefore, in general, not all of the states could be measured. In this connection, observer should be constructed in order to estimate the unmeasured states and the feedback control scheme can apply to the system via the estimated states. This leads to the following equation for the estimator dynamics.[7]

$$\dot{\hat{\mathbf{x}}}(t)=\mathbf{A}\hat{\mathbf{x}}+\mathbf{B}u(t)+\Lambda\left[\mathbf{y}(t)-\mathbf{C}\hat{\mathbf{x}}(t)\right] \quad (9)$$

$$u(t)=\mathbf{K}_c\hat{\mathbf{x}}(t) \quad (10)$$

where $\hat{\mathbf{x}}$ denotes the estimated state and $\mathbf{K}_c, \Lambda$ are the control gain matrix and the Kalman filter gain matrix, respectively. Furthermore, one needs to consider the effects of internal and external disturbances to the system. To address these issues, an LQG design, which uses noise-corrupted outputs for feedback, is used as a controller. Using LQG method with disturbance and sensor noise, the associated state-space equation corresponding to Eq. (5) is given by

$$\begin{aligned}\dot{\mathbf{x}}(t)&=\mathbf{A}\mathbf{x}(t)+\mathbf{B}u(t)+\mathbf{G}\mathbf{w}(t)\\ \mathbf{y}(t)&=\mathbf{C}\mathbf{x}(t)+\boldsymbol{\pi}(t)\end{aligned} \quad (11)$$

The plant disturbance $\mathbf{w}(t)$ and sensor noise $\boldsymbol{\pi}(t)$ are both assumed to be stationary, zero mean, Gaussian with joint correlation function

$$E\left\{\begin{bmatrix}\mathbf{w}(t)\\ \pi(t)\end{bmatrix}\begin{bmatrix}\mathbf{w}(t) & \pi(t)\end{bmatrix}\right\}=\begin{bmatrix}\Xi & 0\\ 0 & \Theta\end{bmatrix}\delta(t-\tau) \quad (12)$$

where $E\{\cdot\}$ denotes the expected value, which is known as mean square value, δ denotes the Kronecker delta, while Ξ and Θ denote the intensities of the disturbance and the sensor noise. For the present case, Ξ and Θ are defined as positive definite, and positive, respectively.

$$\Xi=\left[\mathbf{I}_{10\times10}\right],\quad \Theta=\left[\mathbf{I}_{6\times6}\right] \quad (13\text{ a, b})$$

The associated control input is obtained such that the system is stabilized and the control minimizes the cost function

$$J_{LQG}=E\left\{\int_0^\infty\begin{bmatrix}\mathbf{x}^T & u^T\end{bmatrix}\begin{bmatrix}\mathbf{Z} & 0\\ 0 & \mathbf{R}\end{bmatrix}\begin{bmatrix}\mathbf{X}\\ u\end{bmatrix}\right\}dt \quad (14)$$

The optimal feedback gain matrix $\mathbf{K}_c$ and the Kalman filter gain matrix Λ are obtained from

$$\mathbf{K}_c=-\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P},\quad \Lambda=-\Pi\mathbf{C}^T\Theta^{-1} \quad (15)$$

where $\mathbf{P}$ an Π are the positive definite solutions of the following Riccati equations:

$$\mathbf{A}^T\mathbf{P}+\mathbf{PA}-\mathbf{PBR}^{-1}\mathbf{B}^T\mathbf{P}+\mathbf{Z}=\mathbf{0} \quad (16)$$

$$\mathbf{A}\Pi+\Pi\mathbf{A}^T-\Pi\mathbf{C}^T\Theta^{-1}\mathbf{C}\Pi+\mathbf{G}\Xi\mathbf{G}^{-1}=\mathbf{0} \quad (17)$$

5. Robust State Observer

The controller and the observer are designed based on the mathematical model that considers both measured states and estimated ones. Since unmeasured states are not considered in the controller and observer design, their neglect may cause both control spillover and observation spillover. Spillover effects are undesirable and may cause system instability[11] and reduction in performance.[12] Although the effects of control and observation spillover do not always produce instability, it is desirable to reduce the observation spillover as to remove the potential to generate any instability. To this end, we introduce a sliding mode observer that reduces the effect of observation spillover from the unmeasured states, which is known to have the robustness property and disturbance decoupling property. In this sense, a sliding mode observer is designed to provide robust state estimation.[12] The sliding mode observer has the form[13]

$$\dot{\hat{\mathbf{x}}}=\mathbf{A}\hat{\mathbf{x}}+\mathbf{B}u+\mathbf{G}_l(\mathbf{y}-\mathbf{C}\hat{\mathbf{x}})+\mathbf{G}_{nl}\nu \quad (18)$$

where ν represents a discontinuous switching component defined as

$$\nu=\begin{cases}-\rho\dfrac{\mathbf{T}e}{\|\mathbf{T}e\|} & e\neq0\\ 0 & e=0\end{cases} \quad (19)$$

The matrix $\mathbf{T}$ is a positive definite symmetric matrix, and $\mathbf{A}_0=\mathbf{A}-\mathbf{G}_l\mathbf{C}$ satisfies

$$\mathbf{TA}_0+\mathbf{A}_0^T\mathbf{T}=-\mathbf{Q} \quad (20)$$

for some positive definite design matrix, $\mathbf{Q}$ and ρ is a positive scalar function. The objective is to induce a sliding motion in the error space

$$S_0=\left\{e\in\mathbb{R}^n : \mathbf{C}e=0\right\} \quad (21)$$

that consequently drives the error $e=\hat{\mathbf{x}}-\mathbf{x}$ to zero in finite time despite the presence of the uncertainties in modeling and disturbances. The error dynamics become

$$\dot{e}=\mathbf{A}_0e+\mathbf{G}_{nl}\nu+\mathbf{G}_l\mathbf{C}_R\nu_R \quad (22)$$

Note that the residual modes appear as disturbances in the error dynamics. With the given form of additional discontinuous input ν, the sliding mode observer can estimate the states of the system as decoupling the effect of residual modes, $\mathbf{G}_l\mathbf{C}_R\nu_R$. For the stability of observation error dynamics considering residual modes, using the Lyapunov stability theory, it can be shown that the error dynamics Eq. (22) is asymptotically stable.[12, 13]

6. Discussion of Results

The considered geometrical and physical parameters of the flapped wing system are identical to the ones in the work by Edwards [6]

Parameter	Value
$b=0.3048(m)$	$c=1.0$
$x_{EA}=-0.3$	$m=128.7(kg/m)$
$K_\alpha=0.2\times100^2I_\alpha$	$I_\alpha=0.25\times26.9(kg-m^2/m)$
$K_\beta=0.2\times300^2I_\beta$	$I_\beta=0.25\times0.6727(kg-m^2/m)$
$K_h=0.2\times50^2m$	$S_\alpha=0.3\times8.946(kg)$
$\rho=1.225(kg/m^3)$	$S_\beta=0.3\times1.471(kg)$

Table 1 Geometrical Parameters of Wing Model

The geometrical parameter values of the flapped wing system to be used in the present numerical simulations are presented in Table 1. The flutter speed for this model is V_F =139.3m/s. In order to validate the present result in this paper, a comparison is done using the parameters shown in Refs.[6, 14], for which the calculated flutter speed is V_F =271.3m/s. The critical value of the flutter speed is obtained herein via the solution of both the complex eigenvalue problem and from the subcritical aeroelastic response analysis and an excellent agreement with Refs.[6, 14] is reached. As remarked in Ref.15, from mathematical point of view, it can be assumed that, instead of moving the flap with a required deflection, an equivalent control hinge moment can be incorporated into the open-loop aeroelastic governing equation (5). This is analytically valid since this external moment acts on the flap-hinge and affects only β DOF. The following numerical simulations are based on initial conditions $\tilde{h}(=h/b)$ and with flight speed V_f =131m/s.

6.1 Performance of observer in terms of number of states available

In general, all of the states are not available online due to either initial configuration or malfunctions. We can consider the case where it is possible to measure only both velocity and displacement of $\tilde{h}$ and α as a function of time, respectively. The associated output equation is given by

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)\,,\ \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{23}$$

We may also invoke more terrible situations where it is possible to measure only plunging displacement $\tilde{h}$, which can be represented by output equation

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)\,,\ \mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{24}$$

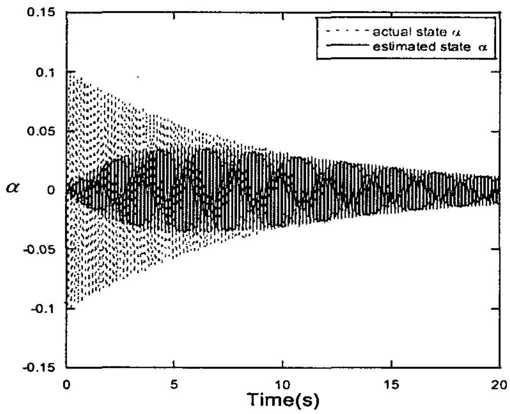


Fig.2 Performance of estimation of pitching state based on plunging measurement via Kalman filter

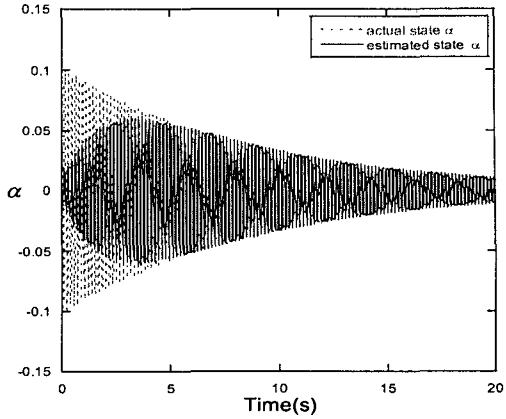


Fig. 3 Performance of estimation of pitching state based on four states, $\dot{\tilde{h}}, \dot{\alpha}, \tilde{h}$ and α via KF

Fig. 2 represents the Kalman filter's performance of estimation of pitching state using measurement of plunging displacement. Finally, the stable estimation is reached in 10 seconds, which takes more than twice of the case of plunging estimation case. Fig.3 is pitching state estimation based on four state measurements such as $\dot{\tilde{h}}, \dot{\alpha}, \tilde{h}$ and α . As expected, performance of recovering estimation of state is excellent compared to the one based on only one measurement of plunging.

6.2 Performance of observers using one measurement

As mentioned before, many harsh situations may occur when only one state is available. However, at that, situations, the observer should estimate the other states with one measurement,[16] and the feedback control scheme should be implemented via the estimated states. In this connection, the sliding mode observer is introduced and performances will be put into evidence that will be compared to conventional Kalman filter (KF).

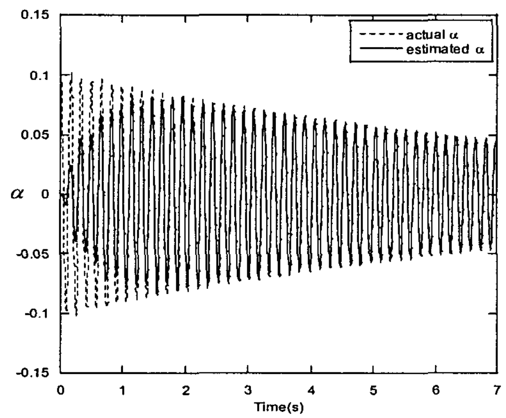


Fig. 4 Performance of estimation of pitching state based on plunging measurement via SMO

Fig. 4 represents the performance of estimation of pitching state using sliding mode observer (SMO), which is based on plunging measurement. The result shows that SMO successfully recover the plunging state $\tilde{h}(= h / b)$ in 3 seconds. The performance of sliding mode observer is excellent compared to the one of KF. The other case of estimation performances of plunging state based on pitching measurement are similar each other.

6.3 Performance of observers subjected to model uncertainty and disturbance

The robustness of the observers and the performance of the state estimation were tested by changing mass of the mathematical model on which the observers are based, and by passing sinusoidal disturbance. It gives us the robustness of the observer under harsh situations. We simulated estimation performances for both Kalman filter and sliding mode observer in case there was model uncertainty and disturbance, respectively.

Figs. 5-6 show the state estimation as a function of time with 10% mass reduction for a Kalman filter and sliding mode observer, respectively. Kalman filter produced a stable estimation in 10 sec, but sliding mode observer obtained a stable estimation in 5 sec. Figs. 7-8 depict estimation performance of only one measurement under sinusoidal disturbance of 44.72 rad/s. While it takes more than 10 sec for recovering the state via Kalman filter, satisfactory state estimation is acquired in 2 sec under sinusoidal disturbance when the sliding mode observer was used. In a certain sense, Kalman filter cannot work as observer in a current mission.

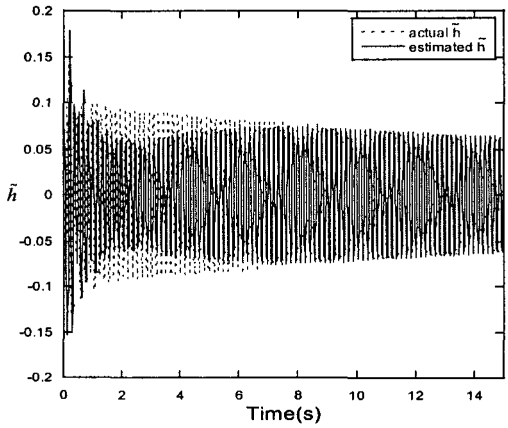


Fig. 5 Performance of estimation of state based on only one measurement via KF with 10% mass reduction

6.4 Control performance to disturbance loads

Figs. 9, 10 display the uncontrolled/controlled plunging/pitching aeroelastic time-histories of flapped wing system operating at $V_f = V_F$ subjected to a blast pulse and sonic-boom pressure. In this case, a stable response of feedback control using sliding mode observer is experienced. Although a little extent unstable response is lasting at first, it gives good control results due to working of robust state observer, sliding mode observer.

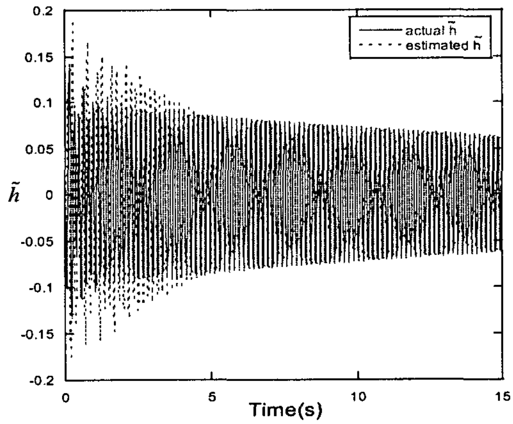
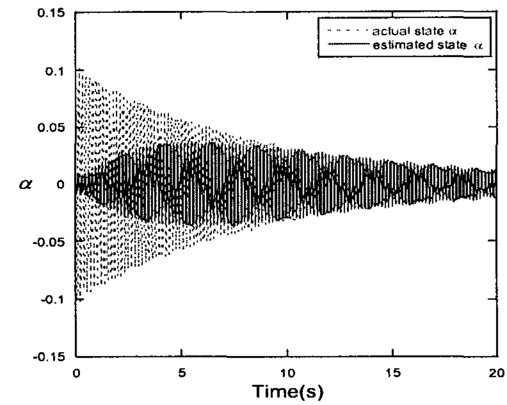
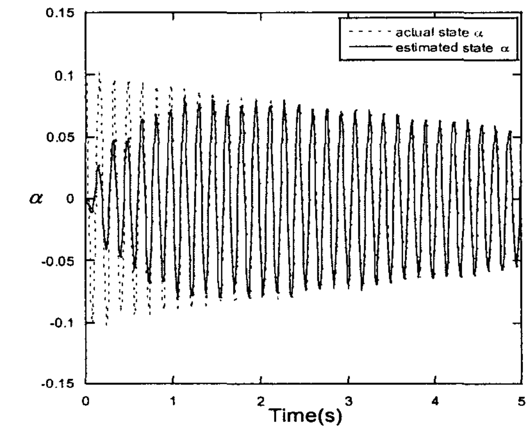


Fig. 6 Performance of estimation of state based on only one measurement via SMO with 10% mass reduction



Figs. 7 Performance of estimation of state based on only one measurement via KF with sinusoidal disturbance



Figs. 8 Performance of estimation of state based on only one measurement via SMO with sinusoidal disturbance

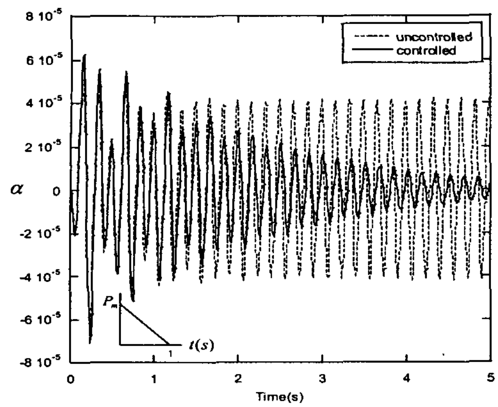


Fig. 9 Uncontrolled/controlled pitching time-histories of flapped wing flying at $V_f = V_F$ subjected to a blast pulse (t_p=1 sec)

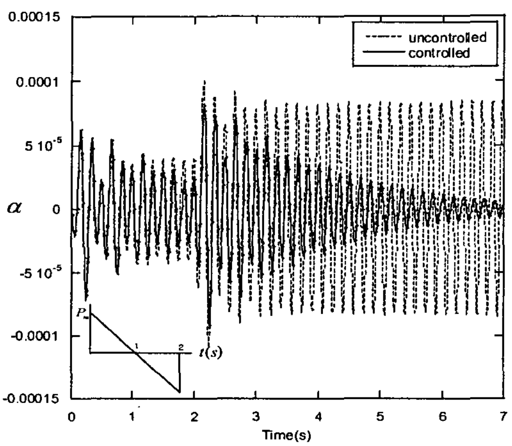


Fig. 10 Uncontrolled/controlled pitching time-histories of flapped wing system flying at $V_f = V_F$ subjected to a sonic boon. (t_p=1)

7. Conclusions

There are many severe situations where next combat aircrafts frequently will experience. In this connection, the present research shows the excellent estimation performance of the sliding mode observer in comparison with Kalman filter under restricted measurement, which is very desirable due to a less computational effort and applying worst case which may happen with only one sensor alive. In addition, the robustness of sliding mode observer is presented with operating mass reduction and sinusoidal disturbance on our aeroelastic system.

The feedback control system which is based on the robust sliding mode observer using only one measurement shows high efficient control performance in external disturbances.

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References

(1) Marzocca, P., Librescu, L., and Chiocchia,G, "Aeroelastic Response of a 2-D Lifting Surfaces to Gust and Arbitrary Explosive Loading Signatures," *International Journal of Impact Engineering*, Vol. 25, No. 1, 2001 ,pp. 41-65.

(2) Librescu, L. Na, S. Marzocca, P. Chung, C. Kwak, M. "Active Aeroelastic Control of 2-D Wing-Flap Systems Operating in an Incompressible Flowfield and Impacted by a Blast Pulse," *Journal of Sound and Vibration* (in press)

(3) Mukhopadyay, V., "Flutter Suppression Control Low Design and Testing for the Acting Flexible Wing," *Journal of Aircraft*, (Special Adaptive Flexible Wing Issue), Vol. 32, No. 1, pp. 45-51, 1995

(4) Mukhopadyay, V., "Historical Perspective on Analysis and Control of Aeroelastic Responses," *Journal of Guidance, Control and Dynamics*, Vol. 26, pp. 673-684, 2003

(5) Scanlan, R.H., and Rosenbam,R., "*Introduction to the Study of Aircraft Vibration and Flutter*," The Macmillan Co.,1951

(6) J.W. Edwards, "Unsteady Aerodynamic Modeling and Active Aeroelastic Control, SUDARR 504, Standford Univ. 1977. Also available as NASA CR-148019.

(7) P. Dorato, C. Abdallah, and V. Cerone, "*Linear-Quardratic Control : An Introduction*," Prentice-Hall, 1995.

(8) Na, S., and Librescu, L. "Optimal Vibration Control of Thin-Walled Anisotropic Cantilevers Exposed to Blast Loading," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 3, 2000, pp. 491-500.

(9) E. H. Dowell, E. F. Crawley, H. C. Curtiss Jr., D. A. Peters, R. H. Scanlan, and F. Sisto, "*A Modern Course in Aeroelasticity*," Sijthoff and Noordhoff, 1978.

(10) Balas, M. J. "Feedback Control of Flexible Systems," *IEEE Transactions on Automatic Control* AC-23(4), 1978, pp.673-679

(11) D. J. Inman, "Active Modal Control for Smart Structures," *Philosophical Transaction: Mathematical, Physical & Engineering Sciences* 359(1778), 2000, pp.205-219

(12) Edwards, C. and Spurgeon, S., "*Sliding Mode Control: Theory and Applications*," The Taylor & Francis, 1998

(13) M. H. Kim and D. J. Inman, "Reduction of Observation Spillover in Vibration Suppression Using a Sliding Mode Observer," *Journal of Vibration and Control*, 7, 2001, pp.1087-1105

(14) Olds, S. D., "Modeling and LQR Control of a Two-Dimensional Airfoil," MS Thesis, Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, VA, April 1997.

(15) Djayapertapa, L. and Allen, C.B. "Numerical Simulation of Active Control of Transonic Flutter," *Proc. Of the 23rde ICAS Congress*, Toronto 2002, 411.1-411.10

(16) Tadi, M. "State-Dependent Riccati Equation for Control of Aeroelastic Flutter," *J. of Guidance, Control and Dynamics*, Vol.26, No.6, 2003, pp. 914-917