Journal of Fluids and Structures 80 (2018) 275–287

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Delayed sub-optimal control for active flutter suppression of a three-dimensional wing

Qing Zhou, Zhangwei Yu, Guoping Cai *

Department of Engineering Mechanics, State Key Laboratory of Ocean Engineering, Shanghai Jiaotong University, Shanghai 200240, China

A R T I C L E I N F O

Article history:
Received 17 July 2017
Received in revised form 8 October 2017
Accepted 16 March 2018

Keywords:
Flexible wing
Flutter
Sub-optimal control
Time delay
Second-order sensitivity

A B S T R A C T

In this paper, delayed sub-optimal control based on partial-state feedback for flutter suppression system involving time-delay is investigated, and the effectiveness of the sub-optimal controller is compared with the optimal controller based on full-state feedback. Firstly, the aeroservoelastic (ASE) model of the flexible wing with control surfaces is given, and the method to dispose the time-delay in the control input is introduced. Then, the determination of the importance of each state in control feedback is studied using the second-order sensitivity of the performance index with respect to the control gain. Finally, the effectiveness of sub-optimal controller is compared with optimal controller through numerical simulations. Simulation results show that the importance of states can be effectively determined by the second-order sensitivity, and the delayed sub-optimal controller can achieve a control effect quite close to the delayed optimal controller. The order of the delayed suboptimal controller designed in this paper is lower, so it shows more engineering significance.

1. Introduction

Flutter is a self-excited vibration caused by the additional aerodynamics forces generated from the structural vibration of an aircraft during flying. Flutter will cause structural failure of an aircraft in a short time, and result in a catastrophic accident. Active Flutter Suppression (AFS) technique is an essential way to suppress the flutter of an aircraft, and with the importance of weight-minimizing in aircraft designs grows, more and more attentions have been paid to the AFS technique over the past decades. Mukhopadhyay (1995) designed a linear quadratic Gaussian (LQG) controller for the flutter suppression of a flexible wing, and the effectiveness of the controller was tested in a wind tunnel. Borglund and Kuttenkeuler (2002) investigated the ASE behavior of a thin rectangular wing with a trailing edge flap, and a fixed-structure feedback controller using numerical optimization was carried out. Huang et al. (2015a) proposed an indirect adaptive controller for the flutter suppression of a three-dimensional wing model, and the controller was schemed using LQG method and bounded-gain forgetting estimator. Gao et al. (2016) studied the finite-time H_∞ adaptive fault-tolerance control for the flutter suppression of a reentry vehicle.

Time-delay is also a critical issue needs to be considered in active flutter suppression systems. It may result in non-synchronization of control input which may cause degradation of the control efficiency and instability of the closed-loop system (Cai and Huang, 2002; Hu and Wang, 2002). Aircrafts usually travel in a high speed, and the states of aeroelastic systems will change a lot within a short time period. Even a rather small control delay involved may result in the instability of the active flutter suppression systems. Some scholars have begun to focus on the time delay in active flutter control

* Corresponding author.
E-mail address: caigp@sjtu.edu.cn (G. Cai).

https://doi.org/10.1016/j.jfluidstructs.2018.03.009
0889-9746/

systems. Zhao (2011) discussed the multiple time delays in control loop of controlled aeroelastic systems, and indicated that time delays have strong effects on the stability of the systems. Huang et al. (2015b) designed a delayed LQG controller for active flutter suppression of a three-dimensional wing model, and demonstrated the efficiency of the controller through a wind-tunnel test. Gao and Cai (2016) developed a delayed finite-time H_∞ adaptive fault-tolerance control method to deal with the two-dimensional wing flutter of a reentry vehicle. Luo et al. (2016) studied the delayed active flutter control of a two-dimensional wing using a sliding mode control method, and the controller can deal with either small or large time delay in the control input.

Time-domain modeling of a three-dimensional wing aeroelastic system will result in a state–space equation with too many states. Thus, full-state feedback controller for the aeroelastic system will be in high order, which will be difficult to be implemented in practice. Zhao (2007) introduced a partial-state feedback control method for the two-dimension wing aeroelastic system, which can use only parts of the states for feedback. Using partial-state can reduce the calculation scale. But when considering the active suppression of three-dimensional wing flutter, how to select the states used for feedback properly to stabilize the closed-loop system the most efficiently is still a problem waiting to be solved.

Considering the time delay involved in the control input, this paper studies the sub-optimal control for the active flutter suppression of a three-dimensional wing with a trailing edge control surface. The ASE model of the wing is built, and the method to dispose time-delay in the control input is introduced. A delayed sub-optimal controller based on partial-state feedback for active flutter suppression of three-dimensional wings is proposed. This paper is organized as follows: Section 2 presents the ASE modeling of three-dimensional wing flutter; delayed sub-optimal controller is discussed in Section 3; in Section 4, the results of numerical simulation are depicted; and finally Section 5 shows the conclusions of this research.

2. ASE modeling in time-domain

When n_s orders of structural modes of the three dimensional wing with n_c control surfaces are used in the analysis, the generalized aerodynamics matrixes $\boldsymbol{Q}_{ss} \in \Re^{n_s\times n_s}$ and $\boldsymbol{Q}_{sc} \in \Re^{n_s\times n_c}$ are computed via the doublet-lattice method (Albano and Rodden, 1969), where $\boldsymbol{Q}_{ss}$ is corresponding to the structural modes, and $\boldsymbol{Q}_{sc}$ is corresponding to the control surfaces deflection. Considering the coupling between the structural modes and the deflection of the control surfaces, the dynamics equation of the aeroelastic system under the actuation of control surfaces in modal-space can be expressed as (Huang et al., 2015b)

$$\boldsymbol{M}_{ss}\ddot{\boldsymbol{q}}_s(t) + \boldsymbol{D}_{ss}\dot{\boldsymbol{q}}_s(t) + \boldsymbol{K}_{ss}\boldsymbol{q}_s(t) = -\boldsymbol{M}_{sc}\ddot{\boldsymbol{\delta}}_c(t) + q_d\boldsymbol{Q}_{ss}(k)\boldsymbol{q}_s(t) + q_d\boldsymbol{Q}_{sc}(k)\boldsymbol{\delta}_c(t) \tag{1}$$

where $\boldsymbol{q}_s \in \Re^{n_s\times 1}$ is the modal coordinate vector; $\boldsymbol{M}_{ss} \in \Re^{n_s\times n_s}$, $\boldsymbol{D}_{ss} \in \Re^{n_s\times n_s}$ and $\boldsymbol{K}_{ss} \in \Re^{n_s\times n_s}$ are the modal mass, modal damping, and modal stiffness matrices respectively; $\boldsymbol{M}_{sc} \in \Re^{n_s\times n_c}$ is the coupled mass matrix between the structure and the control surfaces; $\boldsymbol{\delta}_c \in \Re^{n_c\times 1}$ is the deflection vector of the control surfaces; $q_d = \frac{1}{2}\rho_a V$ is the air dynamics pressure; and $k = \frac{\omega b_R}{V}$ is the reduced frequency, in which ρ_a is the density of air, V is the air speed, and $b_R = \frac{c}{2}$ is the reference length while c is the reference chord, ω is the oscillation frequency. Generalized aerodynamics matrixes $\boldsymbol{Q}_{ss}$ and $\boldsymbol{Q}_{sc}$ in Eq. (1) are defined in frequency-domain. Through minimum-state approximation method (Karpel and Strul, 1996), matrices $\boldsymbol{Q}_{ss}$ and $\boldsymbol{Q}_{sc}$ can be approximated into Laplace-domain as

$$\begin{aligned}\begin{bmatrix}\boldsymbol{Q}_{ss} & \boldsymbol{Q}_{sc}\end{bmatrix} &= \begin{bmatrix}\boldsymbol{A}_{ss0} & \boldsymbol{A}_{sc0}\end{bmatrix} + \frac{b_R}{U}\begin{bmatrix}\boldsymbol{A}_{ss1} & \boldsymbol{A}_{sc1}\end{bmatrix} s \\ &\quad + \left(\frac{b_R}{U}\right)^2\begin{bmatrix}\boldsymbol{A}_{ss2} & \boldsymbol{A}_{sc2}\end{bmatrix} s^2 + \boldsymbol{D}_w\left(s\boldsymbol{I} - \frac{U}{b_R}\boldsymbol{R}_w\right)^{-1}\begin{bmatrix}\boldsymbol{E}_s & \boldsymbol{E}_c\end{bmatrix} s\end{aligned} \tag{2}$$

where $\boldsymbol{R}_w$ is a diagonal matrix. The method for the values of elements in $\boldsymbol{R}_w$ and meaning of other matrices in Eq. (2) can consult Karpel and Hoadley (1991), and Karpel and Strul (1996).

Introducing aerodynamics state vector $\boldsymbol{x}_a \in \Re^{n_a\times 1}$ as

$$\boldsymbol{x}_a = \left(s\boldsymbol{I} - \frac{U}{b_R}\boldsymbol{R}_w\right)^{-1}\begin{bmatrix}\boldsymbol{E}_s & \boldsymbol{E}_c\end{bmatrix} s \begin{bmatrix}\boldsymbol{q}_s(s)\\ \boldsymbol{\delta}_c(s)\end{bmatrix}. \tag{3}$$

From Eqs. (2) and (3), aeroelastic dynamics equation in the time-domain can be derived as

$$\begin{aligned}&\boldsymbol{M}_{ss}\ddot{\boldsymbol{q}}_s(t) + \boldsymbol{D}_{ss}\dot{\boldsymbol{q}}_s(t) + \boldsymbol{K}_{ss}\boldsymbol{q}_s(t) = \\ &\quad -\boldsymbol{M}_{sc}\ddot{\boldsymbol{\delta}}_c(t) + q_d\left(\boldsymbol{A}_{ss0}\boldsymbol{q}_s(t) + \frac{b_R}{U}\boldsymbol{A}_{ss1}\dot{\boldsymbol{q}}_s(t) + \left(\frac{b_R}{U}\right)^2\boldsymbol{A}_{ss2}\ddot{\boldsymbol{q}}_s(t)\right) \\ &\quad + q_d\left(\boldsymbol{A}_{sc0}\delta_c(t) + \frac{b_R}{U}\boldsymbol{A}_{sc1}\dot{\boldsymbol{\delta}}_c(t) + \left(\frac{b_R}{U}\right)^2\boldsymbol{A}_{sc2}\ddot{\boldsymbol{\delta}}_c(t)\right) + q_d\boldsymbol{D}_w\mathbf{x}_a(t).\end{aligned} \tag{4}$$

From Eq. (3), aerodynamics term $\boldsymbol{x}_a(t)$ satisfies the equation in the time-domain expressed as

$$\dot{\boldsymbol{x}}_a(t) = \boldsymbol{E}_s\dot{\boldsymbol{q}}_s(t) + \boldsymbol{E}_c\dot{\boldsymbol{\delta}}_c(t) + \frac{U}{b_R}\boldsymbol{R}_w\boldsymbol{x}_a(t). \tag{5}$$