Design of a Variable Stability Flight Control System

Sungsu Park*
Department of Aerospace Engineering
Sejong University, Seoul, Korea

Joon Soo Ko**
Agency for Defense Development
Daejeon, Korea

Abstract

A design objective for variable stability flight control system is to develop a controller of in-flight simulation capability that forces the aircraft being flown to follow the dynamics of other aircraft. This paper presents a model-following variable stability control system (VSS) for in-flight simulation which consists of feedforward and feedback control laws, the aircraft dynamic model to be simulated, and switching and fader logics to reduce the transient effect between two aircraft dynamics. The separate design techniques for feedforward and feedback control law proposals are based on model matching and augmented linear quadratic (LQ) techniques. The system allows pilots to select and engage VSS mode, and when deselected, the aircraft reverts to the baseline flight control system. Both the baseline flight control laws and VSS control laws are computed continuously during flight. Initialization of the state values are necessary to prevent instability, since VSS control laws have integrators and filters in longitudinal, and lateral/directional axes. This paper demonstrates and validates the effectiveness and quality of VSS with F-16 models embedded in T-50 in-flight simulation aircraft.

Key Word : VSS, In-Flight Simulation, Model-Following Control

Introduction

An in-flight simulation is a technique to change an aircraft's stability and flying characteristics to match those of another aircraft, the simulated aircraft. Since the in-flight simulation environment safely provides the realism of an actual flight, this tool, combined with ground-based simulation, has essential roles in the aircraft development process [1,2]. The objective for in-flight simulation design is to develop a controller that forces the aircraft dynamics to behave like dynamics of other aircraft. This paper developed a variable stability control system (VSS) model that provides such an in-flight simulation capability. This system is composed of a model-following control, a model to simulate aircraft dynamics, and switching and fader logic to reduce transient effects that may occur when changing between the baseline and VSS modes.

This paper presents a model-following control design technique for in-flight simulation, in which feedforward and feedback control laws are designed independently of each other. The proposed design technique also uses linear quadratic (LQ) regulator concepts with proportional plus integral (PI) control. Fader logics are required to reduce undesirable transients during engagement and disengagement of variable stability system (VSS) mode, and initialization of the state values in control laws are necessary to prevent instability since VSS control laws have integrators and filters in longitudinal and lateral/directional axes. Stability issues are also discussed during transition between VSS on and off modes.

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* Associate professor, Sejong University
E-mail : sungsu@sejong.ac.kr Tel : 02-3408-3769 Fax : 02-3408-3333
** Principal researcher, Agency for Defense Development

This paper utilizes simulations to demonstrate the stability and quality of the model-following technique and to investigate VSS performance of F-16 models embedded in T-50 in-flight simulation aircraft.

Design of Control Laws

There are two methods available to achieve in-flight simulation capability: response-feedback and model-following techniques. A response-feedback technique modifies the dynamics of the aircraft through the response feedback loops and gains, but it is limited in its capacity to model dissimilar aircraft dynamics. A model-following control system forces the in-flight simulation aircraft to respond according to a pre-programmed aircraft dynamic model, and it allows high accuracy of simulation over widely dissimilar aircraft dynamics [3]. Most advanced in-flight simulations are, therefore, based on model-following systems [4]. Given the equation of the motion for an in-flight simulation aircraft, the model-following control algorithms are formalized as follows:

$$\dot{x}_p = A_p x_p + B_p u_p \tag{1}$$

and the equation of motion for a model aircraft,

$$\dot{x}_m = A_m x_m + B_m u_m \tag{2}$$

determine the control law u_p such that the exact model-following is achieved,

$$x_p = x_m \text{ and } \dot{x}_p = \dot{x}_m \tag{3}$$

where A_p and A_m are state matrices, B_p and B_m are control matrices, x_p and x_m are the n state variables, u_p and u_m are the m control variables, and the subscripts p and m denote the corresponding in-flight simulation aircraft and model aircraft states and parameters, respectively. The proposed control system in this research for achieving the goal of in-flight simulation consists of feedforward and feedback control laws, the aircraft dynamic model to be simulated, baseline and model flight control systems, and switching and fader logics. Fig. 1 shows the architecture of this control system.

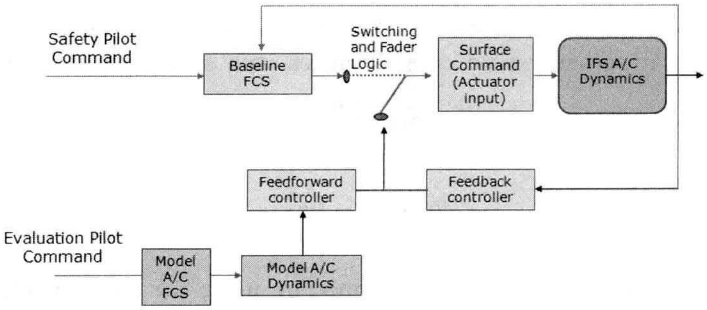

Fig. 1. Model-following variable stability control system

Feedforward Control

Equation 3 can be accomplished if the control law u_p is chosen as follows:

$$u_p = B_p^{-1}(\dot{x}_m - A_p x_m) \tag{4}$$

Conceptually, this controller cancels the bare airframe dynamics and elicits the model aircraft dynamics as the model would to a given model input u_m. However, the solution of Equation 4 is not acceptable because typical dimensions of state variables are larger than the degrees of freedom of input variables. One possible solution for this problem is to replace the inverse of B_p in Equation 4 as the pseudo-inverse, defined as:

$$B_p^+ = (B_p^T B_p)^{-1} B_p^T \tag{5}$$

Use of Equation 5 means that exact model-following is not achievable in this case, and additional feedback control is needed to reduce the model-following errors. The feedforward gains depend only on the parameters of in-flight simulator aircraft, and thus, controller gains do not need to change according to the aircraft model to be simulated. Since these gains act on the model aircraft states and their rates, the model aircraft dynamics must be used in the forward path.

Feedback Control

The objective of feedback control is to reduce the model-following error, which is defined as follows:

$$e_p = x_p - x_m \tag{6}$$

Choosing the control law as a combination of feedforward and feedback control u_{fb},

$$u_p = B_p^+(\dot{x}_m - A_p x_m) + u_{fb} \tag{7}$$

the model-following error dynamics become:

$$\dot{e}_p = A_p e_p + B_p u_{fb} + \Delta f \tag{8}$$

where $\Delta f = (B_p B_p^+ - I)(A_m - A_p)x_m + (B_p B_p^+ - I)B_m u_m$. If the exact matching condition is satisfied, the term Δf will be zero, Otherwise the magnitude of Δf is minimized in the sense of least square by feedforward control Equation 4. The feedback control law should be selected to minimize the model-following error. To improve the performance of model-following capability further, it is desirable for the control law to be a proportional plus integral (PI) feedback control.

Defining augmented error states is:

$$\bar{x} = [w^T \ \ \dot{e}_p^T]^T \tag{9}$$

where $w = De_p$ is some linear combinations of the error elements with selection matrix D, the state space representation of an augmented error dynamics with states calculated by Equation 9 is:

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}\dot{u}_{fb} + \begin{bmatrix} 0 \\ \Delta\dot{f} \end{bmatrix} \tag{10}$$

where

$$\bar{A} = \begin{bmatrix} 0 & D \\ 0 & A_p \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} 0 \\ B_p \end{bmatrix}$$

The design of feedback control is performed by using the standard LQ synthesis on the dynamics, defined by Equation 10, with the following performance index:

$$J = \int_0^\infty w^T Q w + \dot{u}_{fb}^T R \dot{u}_{fb}\, dt \tag{11}$$

The elements in Q and R determine the relative importance of the selected errors and the expenditure of the feedback control rates.

The resulting feedback control is given by [5]:

$$u_{fb} = K_1 e_p + K_2 D \int e_p \, dt \tag{12}$$

where $[K_2\ \ K_1] = -R^{-1}[0\ \ B_p^T]\,\bar{P}$, and $\bar{P}$ is a symmetric positive definite solution of the following algebraic Riccati equation with the existing conditions that (A_p, B_p) is controllable, A_p is nonsingular and $DA_p^{-1}B_p$ is also nonsingular.

$$\overline{A^T}\bar{P}+\bar{P}\bar{A}+\bar{Q}-\bar{P}\bar{B}R^{-1}\overline{B^T}\bar{P}=0 \tag{13}$$

where

$$\bar{Q}=\begin{bmatrix} Q & 0 \\ 0 & 0 \end{bmatrix}$$

This feedback scheme has two advantages. First, the feedback gains depend only on the parameters of in-flight simulation aircraft, so it does not need to change the controller gains according to the aircraft model to be simulated. Second, the design of feedback control is performed independently from that of feedforward control.

Switching and Fader Logic

The system allows the pilot to specify VSS on-mode, and both the pilot and the automatic limit-monitoring system may revert to the baseline flight control system upon mission completion or to ensure flight safety. The baseline flight control system is used when the VSS mode is not engaged, and both types of control laws are computed continuously during flight. Because the baseline and the model-following control laws work concurrently, actuator commands from the model-following control law and the baseline flight control law of in-flight simulation aircraft also feed into the switching and fader logic, to prevent the aircraft from becoming transient during mode transitions. Typical fader logic structure is expressed as follows:

$$\delta_{FADER}(t) = (1-\alpha(t))\delta_{IFS}(t) + \alpha(t)\delta_{VSS}(t) \tag{14}$$

where $\delta_{IFS}(t)$ and $\delta_{VSS}(t)$ are actuator commands calculated by the baseline flight control law and the model-following control law, respectively, and $\alpha(t)$ is a fading factor having a value between 0 and 1. One simple example of a fading factor may be given by the first order delay system.

Stability Issues

Because model-following control laws have integrators and filters in each control axis, the state values in control laws must be initialized to prevent undesirable transitions and potential instability during switching between VSS on and off modes. Although it is well-documented that improperly switching between stabilizing controllers can lead to an unstable time-varying system [6], the concept of smooth changes of controllers using fader logic and state value initialization ensure the stability of systems no matter how switchings are performed between the two controllers [7].

Simulation Results

Simulations were conducted to evaluate the model-following capability and performance of the system across mode transitions. The linear 6-degrees of freedom (DOF) uncoupled F-16 aircraft [8] was used as a model to produce the desired aircraft dynamics in a T-50 in-flight simulation aircraft. The resulting system produced a model-following simulation scheme where the T-50 aircraft recreated F-16 flight dynamics. The baseline and model flight control laws were designed only for longitudinal axis for simplicity. These are normal acceleration (N_z) command trackers which are used to give a good flight path control in the mid to high dynamic pressure flight regime.

Since it is desirable for a system to show model-following characteristics for multiple inputs in longitudinal and lateral/directional axes, aileron and rudder doublets, and 2-g normal acceleration command were incorporated into the system in succession. Figure 2 illustrates these inputs and associated controller commands. Note that VSS was disengaged after 25 seconds of being selected on at 2 second. The red lines show the pilot doublets and commands as applied to the F-16 model, and the blue lines show the resulting surface commands of the controller required for the T-50 to simulate the F-16.

Figures 3 and 4 show the dynamic response of the system with the multi-axis pilot inputs, revealing that acceptable model-following qualities are obtained, and there are no significant transients when VSS is disengaged at 27 second.

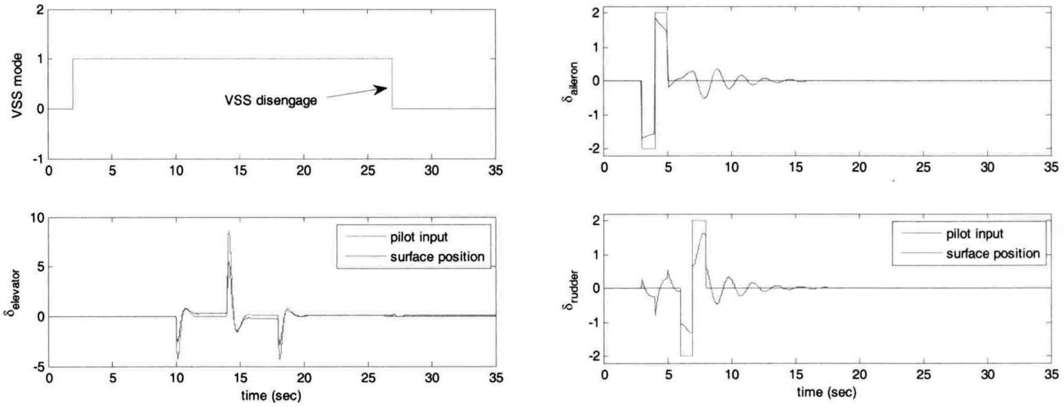

Fig. 2. Pilot inputs for the model aircraft and controller inputs required for in-flight simulation

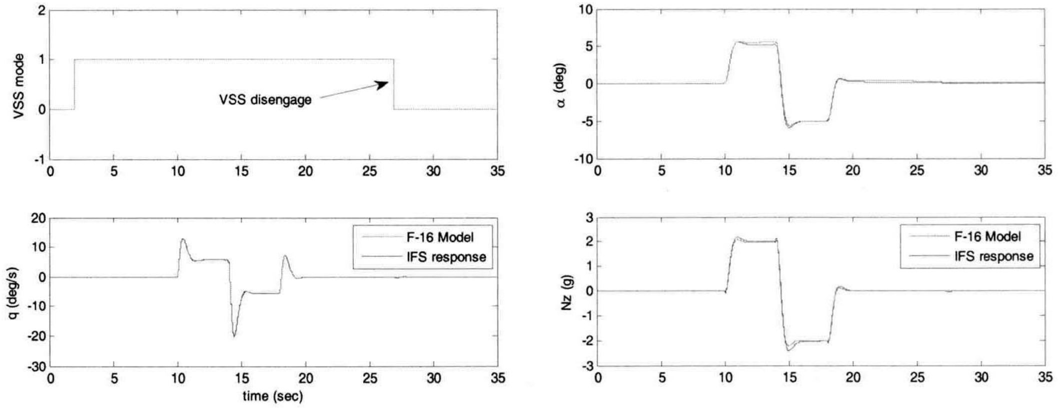

Fig. 3. In-flight simulation (longitudinal) time responses (Mach=0.6, h=10,000ft)

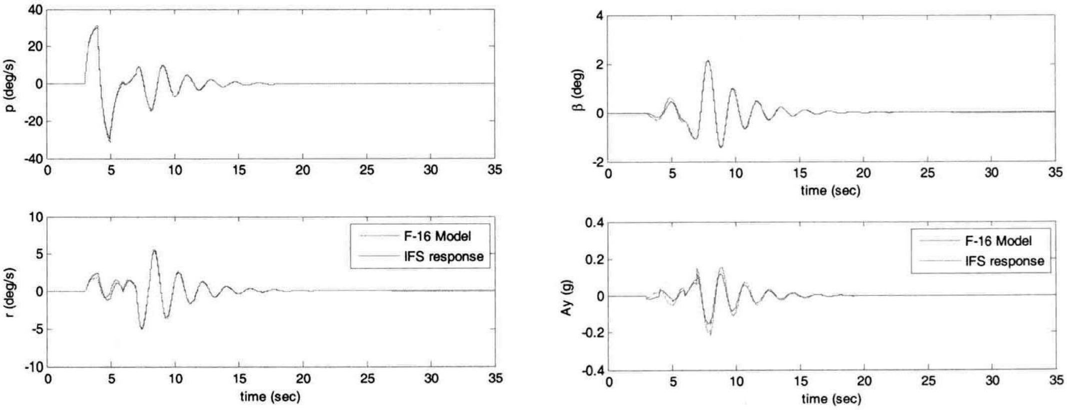

Fig. 4. In-flight simulation (lateral/directional) time responses (Mach=0.6, h=10,000ft)

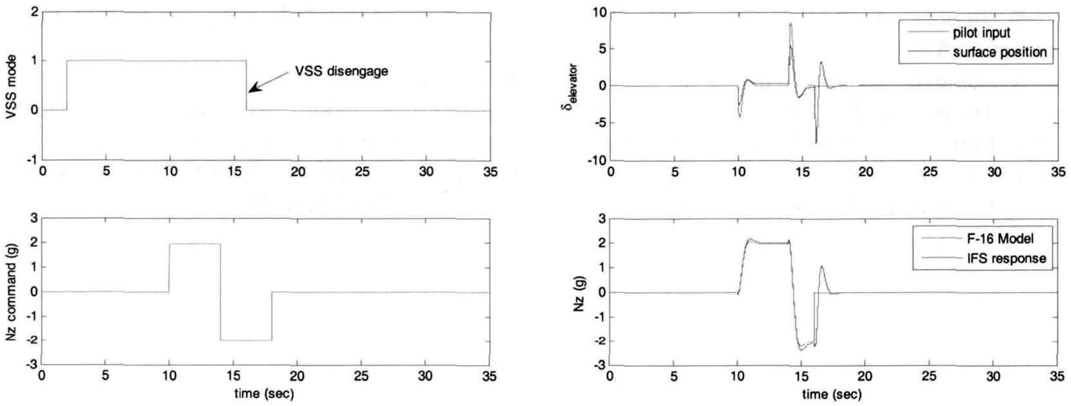

Fig. 5. In-flight simulation time responses (abrupt disengagement)

In order to further investigate stability and transient effects during the engagement and disengagement of the VSS mode, VSS was forced to be disengaged abruptly at 15 second. This may happen by the automatic limit monitoring system and the safety pilot for ensuring flight safety. Figure 5 shows that the overall system is stable and there are no significant transients during the abrupt disengagement of the VSS mode.

Conclusions

A model-following variable stability control system has been presented for an in-flight simulation. This system consists of feedforward and feedback control laws, the aircraft dynamic model to be simulated, a baseline and model flight control system, and switching and fader logics.

The feedforward and feedback control laws are designed independently of one another, and feedforward and feedback gains depend only on the parameters of in-flight simulation aircraft. They need not change controller gains according to the aircraft model to be simulated. In the design of feedback gains, a linear quadratic regulator technique with PI control was utilized.

Fader logics are required to reduce undesirable transients during engagement and disengagement of variable stability system (VSS) mode, and initialization of the state values in control laws are necessary to prevent instability since VSS control laws have integrators and filters in each control axis.

Simulations demonstrated the stability and quality of the model-following control system, and verified and validated VSS extremely well. Acceptable simulation quality was obtained overall, at a finer grain of analysis, no significant transients were observed during mode switches at the time of VSS disengagement. These paper findings suggest that simulations may be used to verify dissimilar aircraft dynamics and flight control systems safely, while reducing both development time and development costs.

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