공학석사학위논문

Handling Quality and PIO Analyses with State Space Predictor Considering Time Delay of UAV

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비행성 및 PIO 분석 연구

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Abstract

Handling Quality and PIO Analyses with State Space Predictor Considering Time Delay of UAV

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Modern digital flight control systems have the time delay due to various sources including the data-link transport time delay between a vehicle and a ground pilot. Time delay not only degrades HQ (Handling Quality) but can also induce PIO (Pilot-Induced Oscillation), which may cause mission failure or critical accident during performing complicated missions such as precision approach, air refuel, and combat maneuver.

This study analyzes HQ and PIO considering time delay of the UAS (Unmanned Aircraft Systems). Predictive pitch compensation is applied to improve the HQ degraded by the time delay.

Even though the autonomous level of UAS becomes higher, a ground pilot is still required for safety and mission control. Therefore, UAS should be able to satisfy military requirements of HQ.

In this study, the state space predictor is applied to the UAS to compensate for the effect of time delay. Neal-Smith, Bandwidth, and Ralph-smith criteria are used to evaluate the HQ and PIO. Numerical simulation is performed to demonstrate the performance of the time-delay compensation; the state space predictor improves the HQ of the UAS and reduces the PIO tendency compared to the lead compensator.

Keywords: Handling Quality (HQ), Flying Quality (FQ), Time Delay, Compensation (Predictor), UAS (UAV), PIO (Pilot-Induced Oscillation)

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To the Lord my God

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Chapter 1

Introduction

1.1 UAS Pilot

In 1910s, there was an attempt to develop a powered UAV (Unmanned Aerial Vehicle). Also a lot of attempts had been made to develop remote-controlled airplanes during and after two World War. However, during the Vietnam War, the United States (U.S.) was finally able to develop the technology needed for UAS (Unmanned Aircraft System) [1]. Yom Kippur War in 1973 by Israel and the U.S, and by the Gulf War of 1991, during which the multi-role armed UAS, General Atomics MQ-1 Predator was used, the advantages of UAS had been conclusively proven. Furthermore, it showed the increasing role of air power and how it could influence an entire battle. UAS have also been developed to replace manned aircraft for a wide variety of roles. For example, the U-2; which is a high-altitude reconnaissance aircraft, has been replaced by the Global Hawk; high-altitude UAS, and fighter aircraft such as the F-18 will be replaced by a stealth type UCAV (Unmanned Combat Air Vehicle) such as the X-47 Pegasus. The autonomy level of the UAS has increased gradually from the RPV (Remotely Piloted Vehicle) to the fully autonomous level of today. For instance, the Global Hawk is able to perform automatic take-off and landing. Nevertheless, recent cases such as the RQ-3 Dark Star and the Korean Medium-altitude UAV showed that the role of a ground pilot is still required for ‘Safety’ and ‘Mission Control’, and especially during the development phase for a project to progress successfully. ‘Autonomous Flight Control System’ is still designed based on the linear equations of motion whose parameters are estimated from wind-tunnel tests and/or computational fluid dynamic data. For this reason, the difference between the assumed linear dynamics and the real nonlinear dynamics can cause serious problems, especially during emergency conditions.

The ‘Unmanned Systems Integrated Roadmap FY2011-2036’ recommends that the UAS pilot (or operator) should engage in the control loop in the case of an emergency or a mission change situation, although the UAS is at the highest level of autonomy [2]. Because it is hard to predict future abnormal situations, a skillful pilot is required, who can make decisions in complicated situations based on abundant experience and multiple cognitive skills. The X-36 project that McDonnell-Douglas and NASA (National Aeronautics and Space Administration) worked together on demonstrated just how important the ground pilot can be, even when highly automatic UAS are used [3].

1.2 Handling Quality

‘Handling Quality’ of the airplane is very important for the UAS pilot, because it has been developed to satisfy military specifications concerning safety and performance. Sometimes, Flying Quality (FQ) and Handling Quality (HQ) are confused and used interchangeably [4].

‘FQ’ considers basic aircraft stability and controllability. To avoid confusion, the following definitions are used. In Ref. [5], “Flying Qualities are defined as the stability and control characteristics which affect ease of safely flying an airplane during steady and maneuvering flight during the total mission.” Etkin [6] defines stability as “…the tendency or lack of it, of an aircraft to fly with wings level” and control as “…steering an aircraft on an arbitrary flight path”, respectively.

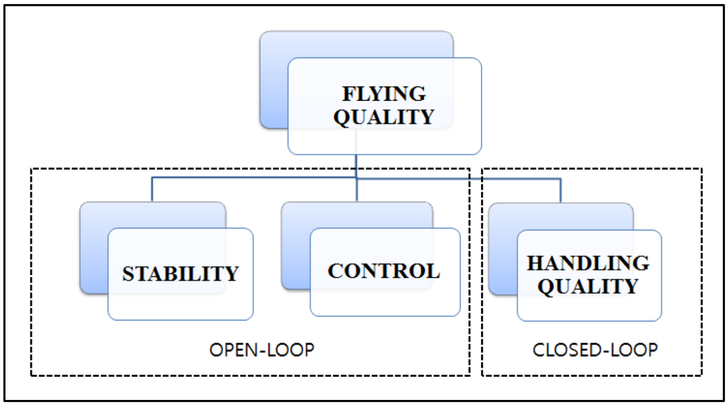

Figure 1.1 Flying Quality Breakdown [8]

Cooper and Harper [7] define Handling Quality as "…those qualities or characteristics of an airplane that govern the ease and precision with which a pilot can perform the mission required in support of an aircraft role." Fig. 1.1 shows how FQ, stability, control, and HQ are related to each another [8]. In Fig. 1.1, control and HQ are all subgroups of FQ. Stability and control analysis deals with the interaction of the control surfaces with the external forces and each moment on the aircraft. Generally, stability and control analysis primarily deals with systems that are still in the design phase, as shown in Fig. 1.2 as an open-loop system without a pilot [8]. On the other hand, HQ evaluation deals with the pilot and aircraft performing as a closed-loop system, as shown in Fig. 1.3 [8]. If the pilot wants a desired pitch angle (θ), the stick force input of the pilot goes through the control system and aircraft dynamics. The resulting pitch angle is fed to the Stability Augmentation System (SAS) and then back to the pilot, at which point the pilot determines if more input is needed. The main point is that stability and control require analysis without a pilot, while HQ analysis is carried out with a pilot in the loop. In this study, the term open-loop is used to signify that there exists no pilot in the analysis of the aircraft transfer function, whereas the term closed-loop is used to signify that a pilot model is considered in the analysis.

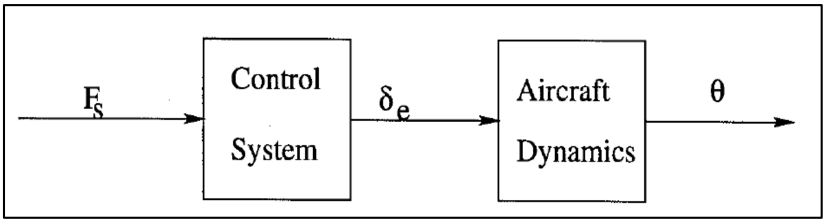

Figure 1.2 Open-Loop System [8]

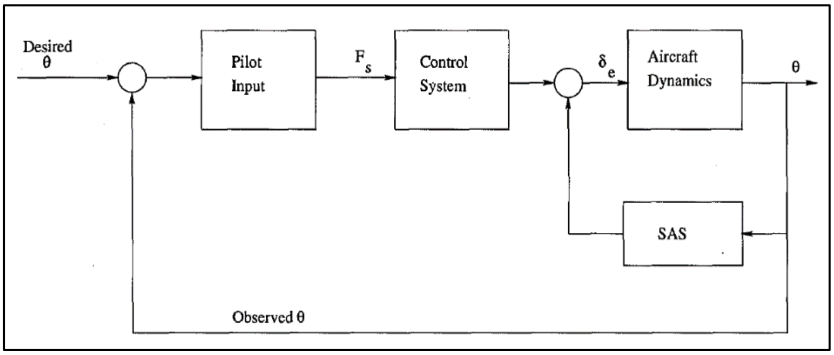

Figure 1.3 Closed-Loop System [8]

The MIL-SPEC (Military Specification) that specifies HQ criteria has been modified along with the development of aircraft technology [9]. 'MIL-F-8785C' was replaced by the 'MIL-STD-1797A', because the mechanical control system has evolved into the 'Fly-By- Wire' system. For the UAS, there was the 'RPV FQ design criteria' proposed by the Air Force Flight Dynamics Laboratory (AFFDL) in 1976 [10]; however, it was too old to apply to modern technology. Especially, the longitudinal short-term pitch response criteria were adopted from the 'MIL-F-8785C [11]', piloted aircraft criteria. Therefore, HQ criteria of the UAS have been developed by taking into account the piloted aircraft criteria.

The six methods offered by the 'MIL-STD-1797A [12]' are widely used to predict HQ. The MIL-SPEC strongly suggests that all or several criteria should be simultaneously applied because it is very hard to assess complex modern aircraft HQ by only one criterion. Therefore, it does not always provide the same results when different criteria are used.

In this study, 2 HQ criteria are considered; ‘Neal-Smith (Pilot In-the-loop) criterion’ and ‘Bandwidth criterion’ that are both suitable for the high maneuverability aircraft for the UCAV application. Also, one effective criterion, ‘Ralph Smith criterion’ that was developed including the PIO criterion in 1995, is also applied. The Ralph Smith (or Smith-Geddes) criterion is a good method to evaluate not only HQ but also PIO tendency. Therefore, in this study, the UAS is analyzed by three criteria, which will be explained in Section 2.2 and 3.3.

1.3 Literature Survey

Following the development of UAS, UAS HQ studies have been done actively [13, 14]. Research applying the HQ criteria to evaluate test aircraft flight control systems such as the F-16XL have been carried out continuously [15]. Also, studies applying the HQ criteria to evaluate UAS flight control systems have been performed recently [16].

Time delay occurring in the inner-loop for controlling the multi-variable and the high-order dynamic model requires complex analysis. Hodkinson and Johnston [17] studied time delay problems, since PIO tendencies were observed during the approach and landing flight tests of the space shuttle. The X-36 design team avoided the time delay problem by making the system have sufficient bandwidth to keep delays of the data-link and control system within the MIL-STD-1797A requirements [3]. The UAS can avoid the time delay problem by using a sufficient bandwidth; however it is difficult to handle precision control missions such as air-refueling, air-to-air gunnery, bombing, and precision approach. Therefore, time delay compensation algorithms have been studied via numerous flight simulations for aircraft with flight control system. Cardullo, George [18], McFarland [19], and Crane [20] studied the time delay compensation algorithm, and flight simulators have been used successfully. Guo et al. [21] confirmed that the time delay reduces the phase margin and causes PIO, which leads to a bad influence on system performance and HQ.

To date, many compensation techniques have been developed to mitigate the time delay in the flight simulator. The Lead compensator [20, 22], the McFarland Velocity Predictor [19], and the Sobiski/Cardullo State space predictor [18, 23] are the most prominent current techniques.

If the UAS has a data-link delay, t_d, a pilot must wait $2t_d$ to see the effects of his control inputs on the UAS performance. This is essentially similar to the flight simulator delay problem in that the UAS pilot would not be able to distinguish between delay due to data-link latency and control system delay. Thurling [24] applied delay compensation algorithms of the flight simulator system to the UAS and obtained successful flight test results. However, it could not focus on the PIO tendency due to the scarcity of literature concerning PIO of UAS.

In this study, the PIO tendency is predicted by using the Ralph Smith method [39], and the effectiveness of the proposed compensation algorithms are evaluated by Neal-Smith [30], Bandwidth [32], and Ralph Smith criteria.

1.4 Contributions

The contributions of this study are summarized as follows.

- Time Delay Compensation using state space predictor is performed. The ground pilot (or operator) can handle the UAS easily with the compensated flight control system even if there exists a time delay problem by several sources. Especially the High Maneuverability UAS can be applied by the predictive compensator.

- Handling Qualities of the UAS evaluated by Neal-Smith, Bandwidth and Ralph Smith method. The UAS model considered in this study has high maneuverability, and the HQ criteria are based on the fighter data. Therefore, the HQ methods can be also applied to UCAV systems.

- PIO Tendency is studied and compensated by the state space predictor. The PIO tendency is predictable by the Ralph Smith method, and it could be reduced by using the proposed the state space predictor.

1.5 Thesis Overview

This thesis is organized as follows.

Chapter 1 describes the background including the necessity of the UAS pilot and HQ. The relevant research works on the time delay compensation are summarized.

In Chapter 2, the characteristics of time delay systems are discussed with a focus on how time delay affects human control behavior and aircraft HQ. Current methods for estimating pilot rating of HQ using a mathematical model of the aircraft are discussed. Furthermore, compensating methods for time delay is presented.

In Chapter 3, PIO is defined and the necessity of PIO tendency study based on predictive PIO method and Ralph-Smith criterion is explained.

In Chapter 4, the lead compensator and the stat space predictor are designed to demonstrate the effectiveness of the compensation in improving the HQ and PIO tendency of the delayed system.

Finally, conclusions and further research are presented in Chapter 5.

Chapter 2

Handling Quality &
Time Delay Compensation

2.1 Time Delay Effect on Human Control Behavior

2.1.1 Cooper-Harper Rating Scale

Handling Quality evaluated by test pilot can be used as the engineering data to design an aircraft or to evaluate the aircraft. Cooper-Harper Rating (CHR) Scale [7] was made by this necessity. In 1966, Harper at the Cornell Aeronautical Laboratory and Cooper at the NASA Ames research center presented their cooperative works that were accumulated their experiences and knowledge. After that, the CHR scale was adopted as the MIL-SPEC criteria for evaluating HQ, and it has been widely used. As shown in Fig. 2.1, the CHR scale is made up of simple 'Yes or No' questions. The total scales are 10, from 1 to 10 points, and each points belong to the below 3 HQ levels in calm air or in light atmospheric disturbances [12].

1. Level 1: "Clearly adequate for the mission flight phase. Desired performance is achievable with no more than minimal pilot compensation." And median CHR must not be worse than 3.
2. Level 2: "Adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists." And median CHR must not be worse than 6.
3. Level 3: "Aircraft can be controlled in the context of the mission flight phase, even though pilot workload is excessive or mission effectiveness is inadequate, or both." And median CHR must not be worse than 9.

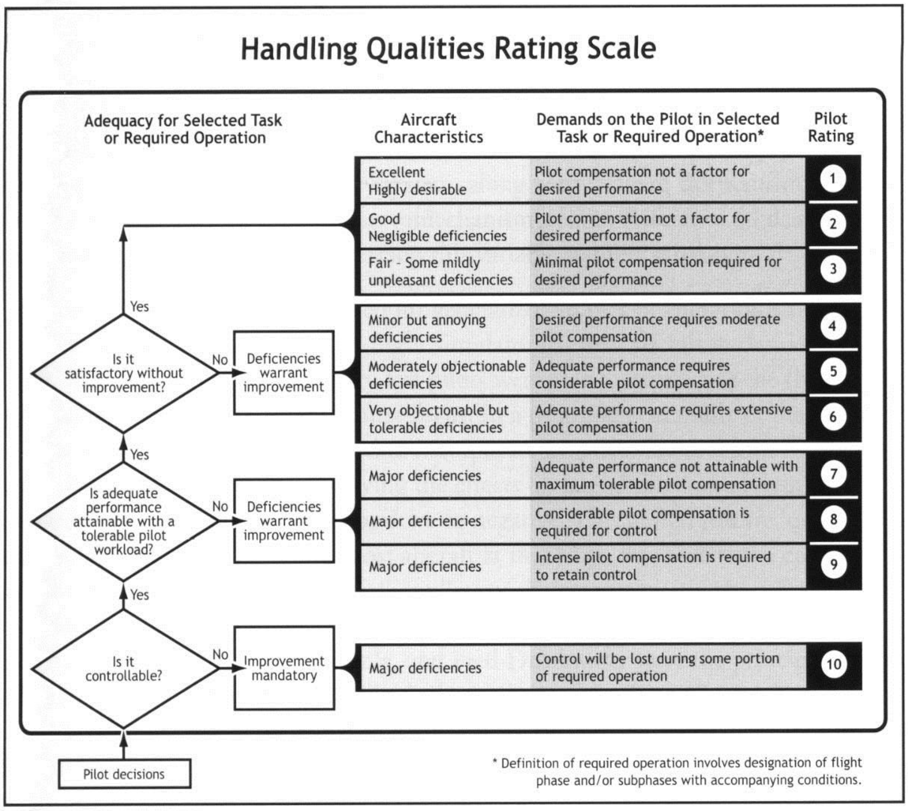

Figure 2.1 Cooper-Harper HQ Rating Scale [7]

A CHR of '10' or sometimes called 'Level 4' indicates that aircraft control will be lost at some point in the mission profile**.** It is evaluated as 'Acceptable' up to Level 2, however it should be corrected if it is evaluated as Level 3 that includes major deficiencies. In this study, this CHR is used.

The CHR was made by median rating of three or more (odd number) test pilots. The criteria (or methods) that could estimate HQ rating were developed by CHR data as well as mathematical methods, which are explained in Section 2.2.

2.1.2 Time Delay

To a pilot, time delay can be considered as a 'Dead time' between the pilot's force input and the onset of any aircraft response. These delays can be caused by various sources within the flight control system. Transport delays are induced by computational latency when control laws are computed. System delays may come from analog portions of the flight control system. Higher order effects from high frequency poles in complex control laws or from aircraft stick dynamics and actuators also contribute to the time delay. And, there exist pilot input delay and data-link delay especially for the UAS.

Typically, the complexity of modern control system design results in numerous dynamic elements which can introduce a perceived delay in the initial response of the aircraft to a pilot input. This form of time delay is often referred to as 'Equivalent' or 'Effective' time delay, depending on the measurement method. Each method represents an approximation of the dead time sensed by the pilot [25].

Equivalent time delay inherent to the controlled elements can be derived from frequency response analysis, and is used to make a 'Low Order Equivalent System (LOES)' [26, 27] matching to the actual frequency response of the system. The equivalent time delay inherent to the pilot can be modeled as the e^{-ST} delay term in a pilot model transfer function [13].

Effective time delay is a time domain analysis method can be calculated from the response of the system using a step input, as shown in Fig. 2.2, which is a difference between the application time of a step input and the time axis intersection of the maximum slope tangent to the response.

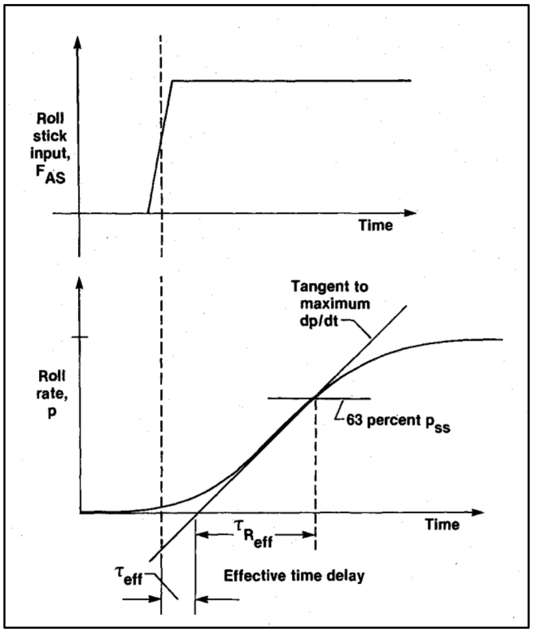

Figure 2.2 Computing Effective Time Delay [25]

It should be noted that effective and equivalent time delay for the same system may not be the same. Systems that cannot be accurately modeled in LOES form generally show poor correlation between equivalent and effective delay [25].

2.1.3 Time Delay Effect on Handling Quality Rating

Some aircrafts including F-16, F-18, Tornado, and Space Shuttle vehicles showed potentially dangerous PIOs during flight test. These initiated substantial study for the effects of time delay on HQ.

A flight test program was conducted in 1978 on the Dryden Flight Research Center F-8 DFBW airplane to study the relationship between time delay and HQ [28]. In 1979, Hodgkinson and Johnston at the McDonnell aircraft company studied time delay effect on pilot HQ rating using the U.S. Air Force

(USAF) / Calspan variable stability NT-33 aircraft. HQ of several high order systems and their analytically derived LOES were compared [17]. And in 1987, Bailey and Knotts at the Calspan advanced technology center and researchers at the USAF Human Resources Laboratory tested both NT-33 In-flight simulator aircraft and ground-based simulator to study allowable time delay for pilot. Especially, Bailey applied small and large size transport aircraft models besides F-16 fighter model to compare data. The CHR became worse and fell from Level 1 to Level 2 as time delay increased in common [29]. Therefore it was cleared that time delays give negative effects on HQ rating regardless of the type of aircraft, because there does not exist any big differences among different aircraft models. As shown in Fig. 2.3, the F-16 model CHR become worse (higher) as time delays increase from 100 msec. The CHR above ‘5’ means that quite patience is required for the pilot and it could cause the PIO when aircraft response has continuous latency. Therefore, it can be stated that time delay is also closely related to the PIO, and it needs to be compensated.

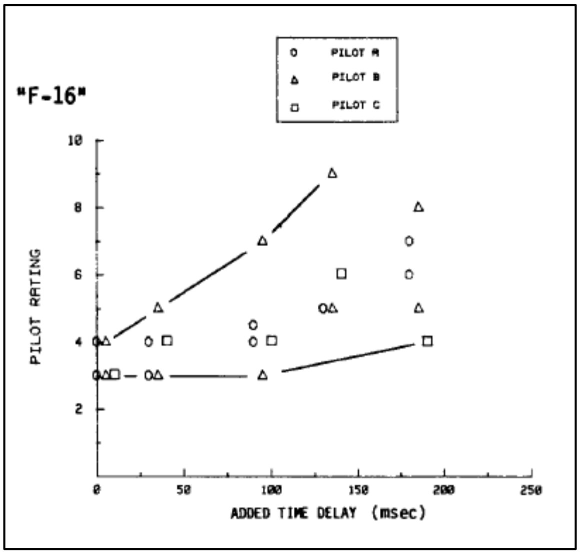

Figure 2.3 Effect of Time Delay on HQ using F-16 Model [28]

2.2 Mathematical Methods for Estimating Handling Quality

Numerous studies have investigated the mathematical methods for estimating HQ using accumulated CHR data and experiences. Especially, several methods were developed, and six of them were adopted as the 'MIL-STD-1797A' longitudinal short term HQ criteria. The longitudinal motion is more important than the lateral-directional when the aircraft is maneuvering and approaching precisely. Therefore, in this study, the longitudinal short term motion analyzed. Two of six MIL-SPEC criteria, 'Neal-Smith' and 'Bandwidth (BW)' criteria are adopted because these criteria are constructed based on the fighter aircraft data, which is useful for the evaluation of the high maneuverability aircraft.

2.2.1 Neal-Smith Criterion

The Neal-Smith criterion [30, 31] made by Neal and Smith is analytical procedure to evaluate the HQ of fighter type aircraft with augmented short period pitch dynamics. It is based on the assumption that accurate pitch attitude control is essential for good FQ. FQ boundaries were developed through correlation with NT-33 in-flight simulation data. Note that the closed-loop pitch tracking performance is related to the dynamic compensation generated by the pilot to achieve the required closed-loop BW. Thet BW requirements are summarized in Table 2.1 [12].

Since Neal-Smith is a closed-loop criterion, it requires a pilot model which is assumed to consist of a fixed delay, variable gain, and variable first-order compensation network. The model is represented by Eq. (2.1) [30] where τ_{p1} and τ_{p2} are the pilot lead and lag compensation time constants respectively.

Table 2.1 Bandwidth Requirements in Neal-Smith Criterion

Flight Phase	Bandwidth (rad/s)
Category A (Air-to-Air Combat, Ground attack, etc.)	3.5
Category B (Climb, Cruise, Descent, etc.)	1.5
Landing	2.5
Other Category C (Takeoff, Approach etc.)	1.5

$$Y_P = K_P \ e^{-0.3s} \frac{\tau_{p1}s+1}{\tau_{p2}s+1} \tag{2.1}$$

MIL-STD-1797A [11] modifies the original Neal-Smith model. The pilot delay is defined as 0.25 seconds, and a low frequency integration term, (5s+1)/s, is added to the model if there is no free ‘s’ in the denominator of the plant model. However, in this study, the original Neal-Smith method, Eq. (2.1), is needed. This method assumes that the pilot attempts to achieve three objectives which will result in good tracking performance [30].

1. The pilot tries to achieve a particular value of the open-loop gain-crossover frequency, w_C $(|\theta/\theta_C| = 0\,dB)$.
2. The pilot tries to minimize any low-frequency, closed-loop ‘droop’ (hold $|\theta/\theta_C|$ as near 0 dB as possible, for $w \le w_C$).
3. The pilot tries to maintain good high-frequency stability by keeping the damping ratio of any closed-loop oscillatory modes greater than 0.35, and by maintaining a phase margin of 60 to 110 degrees.

A pilot adjusts his gain to achieve the required BW while minimizing ‘droop’ and closed-loop resonance as shown in Fig. 2.4.

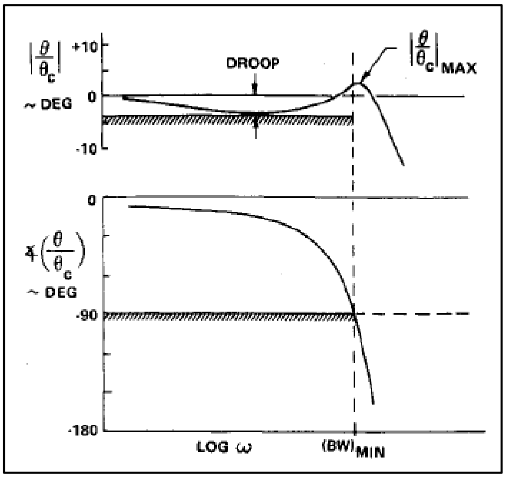

Figure 2.4 Neal-Smith Tracking Performance Standards [31]

A detailed study of the pilot comments showed that the trends in the pilot comments, for various combinations of short-period and control-system dynamics, could be nicely explained in terms of the parameters $\angle(\theta/\theta_C)$, phase angle of the pilot compensation, and $|\theta/\theta_C|_{\max}$, resonance peak. Fig. 2.5 shows the pilot comments associated with various combinations of the parameters.

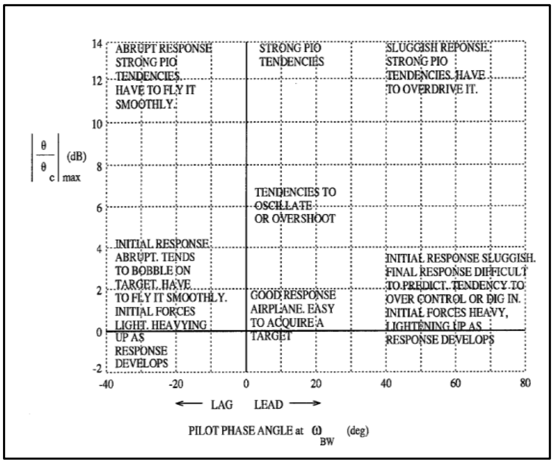

Figure 2.5 Summary of Pilot Comment Data, Neal-Smith Graph [31]

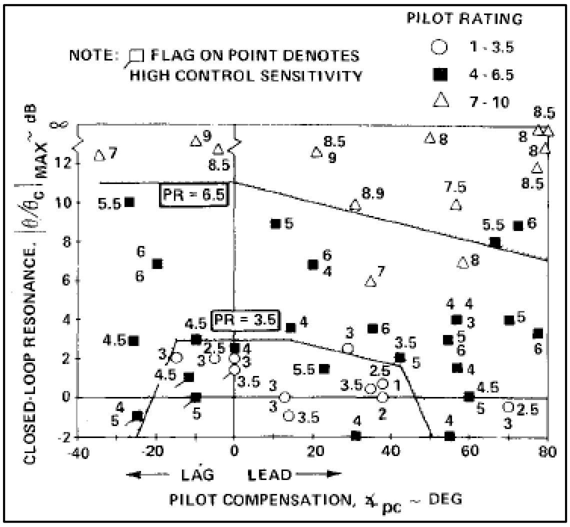

Figure 2.6 Neal-Smith Handling Quality Level Boundaries [31]

The pilot rating data from the present experiment are shown in Fig. 2.6 (for one pilot). The 3.5 and 6.5 pilot rating boundaries shown in the figure are based primarily on the ratings of both pilots. In the original Neal-Smith analysis, the values of closed-loop resonance and pilot compensation provided by the pilot model fulfilling the three criteria previously discussed are plotted versus one another.

2.2.2 Bandwidth (BW) Criterion

The Bandwidth criterion [32] was developed as a response to the inaccuracy with which classical methods evaluated highly augmented control systems, and it has been referred to as a 'pilot-in-the-loop' criterion. However, the analysis does not involve a dynamic pilot model. Therefore, it is listed in MIL-STD-1797A as an 'open-loop' technique. In summary, it may be considered a classical method of HQ rating prediction. MIL-SPEC suggests employing the bandwidth criterion when aircraft response dynamics do not have classical characteristics such as short period and phugoid longitudinal modes. Thus, it is perhaps the only 'classical' method that is capable of making an accurate assessment in the face of a pure transport delay and non-classical aircraft dynamics, which are likely to be found in UAS.

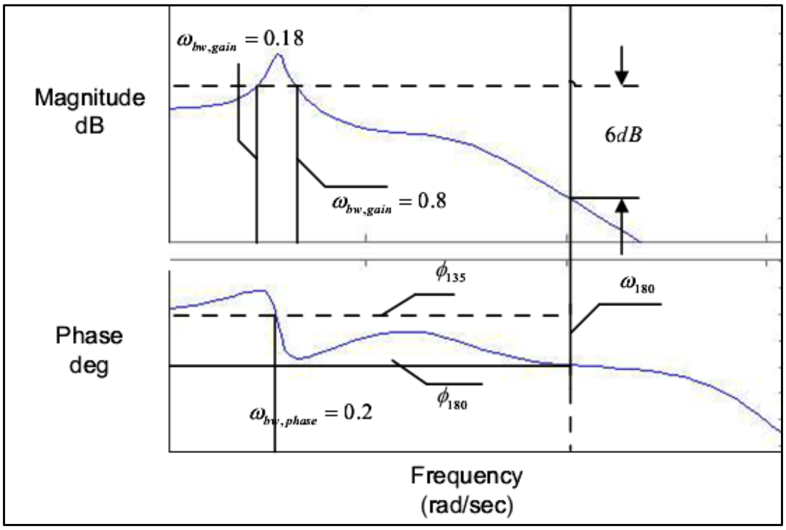

Figure 2.7 Definition of Bandwidth for Pitch Angle Response [16]

The BWs at the phase or gain margin, $\omega_{BW_{Gain}}$ or $\omega_{BW_{Phase}}$, are defined as the highest frequency if the phase margin is at least 45 degrees whereas the gain margin is at least 6 dB. The BW is the lesser of the two frequencies as shown in Fig. 2.7 (ω_{BW} is 0.18), and systems are defined as either 'gain-margin-limited' or 'phase-margin-limited' depending on which criterion is used to specify the BW.

The shape of the phase curve is also important for pilot HQ rating prediction. A rapid phase roll-off at frequencies above ω_{BW} results in a large decrease in the phase margin for a small increase in pilot gain. The gain margin limit of 6 dB makes a pilot double his gain and still not cause instability. Systems with rapid phase roll-off are most often 'gain-margin-limited'. Because rapid phase roll-off is well represented by pure time delay, $e^{-j\omega\tau}$, a parameter τ_p representing phase delay is calculated as follows from MIL-STD-1797A [12].

$$\tau_p = -\frac{\left(\Phi_{2\omega 180} + 180\deg\right)}{57.3} \tag{2.2}$$

where ω_{180} is the frequency corresponding to -180 degree phase shift, and $\Phi_{2\omega 180}$ is the phase angle at twice that frequency.

When τ_p and ω_{BW} are plotted versus one another, regions of the plot have been shown through numerous studies to correlate with different levels of HQ rather than a specific numerical HQ rating as shown in Fig. 2.8.

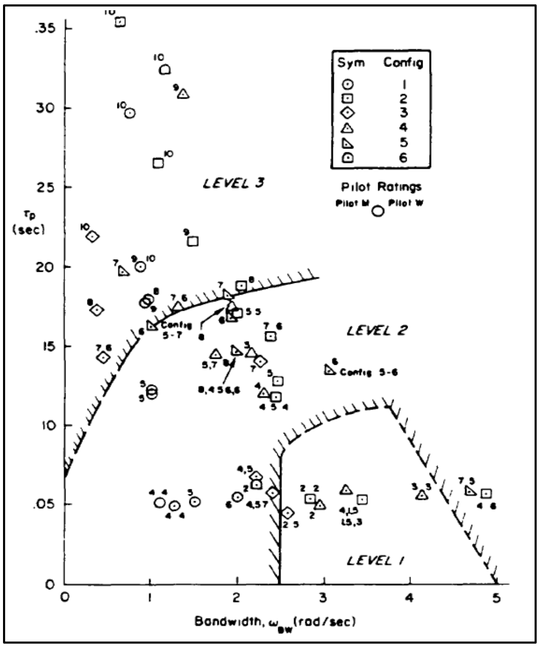

Figure 2.8 Bandwidth Criterion Pilot Ratings for Category C [12]

2.3 Time Delay Compensation Methods

The purpose of time delay compensation is to predict to mitigate the system latency in view of the time-domain perspective, which is to provide phase lead to compensate the lag in system phase margin from a frequency-domain perspective. This compensation is to predict the future system state by using the current state information [21].

Therefore, an effective compensator should meet the following two criteria:

1. It should be able to give enough phase lead to compensate the phase lag induced by the time delay.
2. It should have minimum ‘gain distortion’ defined as the ratio $|G_c(\omega_n)| / |G_c(\omega_d)|$, which is also proportional to filter pole-zero separation.

Additionally, the compensation should have sufficient simplicity, because it does not cause delay due to computation. Therefore, a third criterion is:

3. The computational workload should be minimal.

Numbers of methods have been introduced to compensate the time delay. The ‘Lead compensator’, the ‘Velocity Predictor’, and the ‘State space predictor’ are the three most prominent methods.

2.3.1 Lead Compensator (LC)

The transfer function of the Lead compensator [21, 22] is represented on

$$G_c(s) = \frac{Y_p(s)}{Y(s)} = k\frac{s+\omega_n}{s+\omega_d},\ (\omega_n < \omega_d) \tag{2.3}$$

$$\frac{Y_p(s)}{Y(s)} = k\frac{\tau_n s+1}{\tau_d s+1} = k\frac{\tau_n s+1}{\alpha\tau_n s+1},\ (0<\alpha<1) \tag{2.4}$$

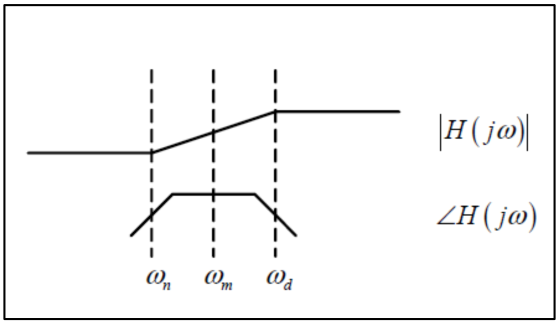

Figure 2.9 Bode asymptotes of the Lead Compensator [21]

where $Y_p(s)$ and Y(s) are the Laplace transforms of the predicted state and the undelayed state, respectively. Pole and Zero, ω_d and ω_n, are the two corner frequencies of the compensator. If $\omega_n < \omega_d$, Eq. (2.3) leads to the Bode asymptotes of the magnitude, $|H(j\omega)|$, and the phase, $\angle H(jw)$, as shown in Fig. 2.9. The top of phase asymptote in $[\omega_n \ \omega_d]$ gives the phase lead. The maximum phase lead is at a frequency ω_m, the medium frequency; which is the geometric mean of the two frequencies. And the maximum phase lead is

$$\sin\phi = \frac{1-\alpha}{1+\alpha} \tag{2.5}$$

The phase lead is acquired instead of the gain distortion, since the magnitude $|H(j\omega)|$ is not unity and the high-frequency gains are increased. The system using phase lead compensation may have high-frequency noise problem. Nevertheless, as Crane stated [20], the increased frequency, which is larger than crossover frequency (ω_c), usually does not cause a problem. Since the power of the input including the disturbance and the system amplitude ratio normally decreases immediately at the increased frequency. Note that ω_c is used for measuring the bandwidth or responsiveness.

The frequency-domain technique can satisfy the design requirements precisely. However, the real aerodynamic models are usually nonlinear, while the classical method assumes linearity. Hence, the classical lead compensator has natural limitation for mitigating the delay problem.

The ideal design is to make the medium frequency, ω_m, place at the pilot crossover frequency, ω_c, because ω_c region has been presented to be the most critical for pilot control. However, ω_c is normally hard to know. One practical approach is to assume an estimated crossover frequency, $\hat{\omega}_c$, and let $\omega_m = \hat{\omega}_c$. Then, the maximum phase lead is calculated to compensate the phase lag caused by time delay t_d as follows.

$$\phi = t_d \, \hat{\omega}_c \tag{2.6}$$

Now, the ratio α is calculated using Eq. (2.5), and finally the transfer function can be determined. However, this practical approach has following two problems [21].

1. The $\hat{\omega}_c$ is not the real crossover frequency ω_c, which may be changed in a simulation owing to various factors. The further $\hat{\omega}_c$ (ω_m) departs from ω_c, the less phase lead at ω_c.
2. Due to Eq. (2.5) ($0 < \alpha < 1$), ϕ would be less than $\pi / 2$. For a long delay t_d, the estimated $\hat{\omega}_c$ become very small by Eq. (2.6), and it diverges from ω_c, resulting in insufficient phase lead.

The above two problems explain why the lead compensator could not be used for long time delay. Today with these problems, two approximate methods were introduced by Ricard and Harris [33], and Crane [20]. However, in all cases, the lead compensator could not compensate the entire delay, especially for a large delay.

2.3.2 Velocity Predictor Algorithm

Another technique that has been employed for mitigating time delay is the velocity predictor algorithm [19] originated by McFarland, which has been proven successful on both research and training simulators. The technique uses the past two values of velocity as well as the current position to predict the future position,

$$U_{n+1} = U_n + b_0 V + b_1 V_{n-1} + b_2 V_{n-2} \tag{2.7}$$

where U is a position, and V is a velocity. The algorithm assumes a bandwidth of two to three hertz for high gain tasks. Sinusoidal inputs are applied to the compensation delay model in order to tune it at the proper frequency. The values of constants b_0, b_1, and b_2 are found as functions of delay, update rate, and bandwidth [18].

Apparently, the problem of the Velocity Predictor is the spikes. If the delay becomes longer, the magnitude of the spikes would be larger. The Velocity Predictor algorithm is a special integrator or an extrapolator. The simplest extrapolator to provide a prediction of t_d is as follows.

$$U_{n+1} = U_n + t_d V \tag{2.8}$$

If the rate changes slowly (low frequency), then the extrapolation works well. However, if the rate changes rapidly, the prediction causes error, because the rate might be much different t_d later.

The McFarland Velocity Predictor is the exclusive extrapolator given by Eq. (2.8), because it uses three sequential steps of rates that can extrapolate the future rate better than a single rate. For moderate frequency (around 1 Hz), let the average of these three rates be $\bar{V}$, then Eq. (2.7) becomes to $U_{n+1} = U_n + t_d \bar{V}$, which is similar to Eq. (2.8). By using average rate, more accurate prediction can be obtained. However, if the rate changes abruptly (high frequency), then spikes would occur [21].

2.3.3 State Space Predictor (SSP)

Sobiski and Cardullo [34] proposed a State Space Predictor (SSP) for compensating the transport time delay based on the following equation.

$$x(t+t_d) = e^{At_d} x(t) + \int_0^{t_d} e^{A(t_d-\tau)} Bu(t+\tau) d\tau \qquad (2.9)$$

Where A is a system matrix, B is an input matrix of the linear system. $y = Cx$, and x and u are state vector and input vector, respectively.

Equation (2.9) can be derived from the solution of the state space linear differential equation. This equation shows that the predicted state vector $x(t+t_d)$ at time $t+t_d$ may be calculated from the current state vector $x(t)$ and the future input u, between t and $t+t_d$, is provided. Unfortunately, this is an obviously impossible condition considering stochastic operator's control input u. Therefore, Sobiski and Cardullo made some assumptions about the form that the input might take piece-wise constant, sinusoidal, exponentially decaying, etc., so that the future input may be approximated by the current input. Then, the prediction is represented as

$$x(t+t_d) = [e^{At_d}x(t)] + \left[\int_0^{t_d} e^{A(t_d-\tau)} d\tau\right] Bu(t) \tag{2.10}$$

$$\Phi = e^{At_d} \tag{2.11}$$

$$\Psi = \int_0^{t_d} e^{A(t_d-\tau)} d\tau \tag{2.12}$$

Equation (2.10) can be resulted as

$$x_c = \Phi x + \Psi Bu \tag{2.13}$$

Where x_c is a predicted state, and Φ and Ψ are the state transition matrix and the convolution integral matrix, respectively. Now, the predicted output can be calculated by

$$y_c = C\,x_c = (C\,\Phi)x + (C\,\Psi\,B)u \tag{2.14}$$

Where y_c is a predicted output, and C is an output-influence matrix of the system measurement equation, $y = Cx$. Form Eq. (2.10), the structure of the state space predictor can be illustrated as Fig. 2.10.

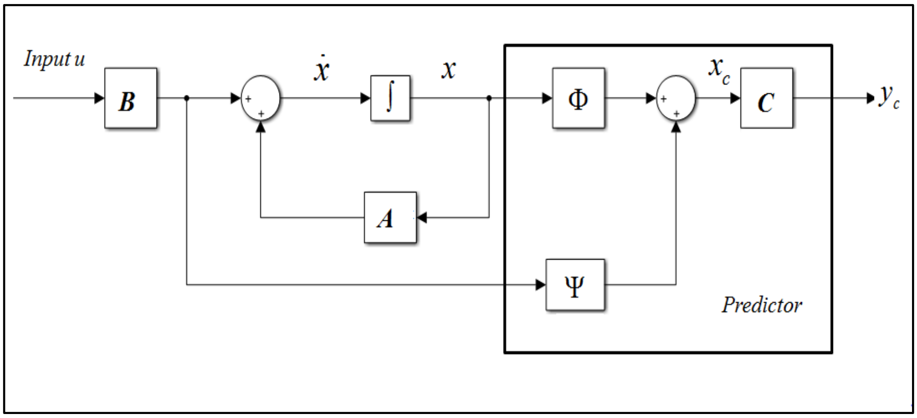

Figure 2.10 State Space Predictor in an Open-Loop System [21]

Theoretically, SSP can compensate longer delay than the McFarland's Velocity Predictor because it uses more system information, i.e., the full state vector, though it requires complicated calculations. The transfer functions of the pilot model, the aircraft dynamics, and the delay are transformed to the state space equations. The matrices **A**, Φ, and Ψ contain all information about the time delay, and therefore, they are of 10th order for the longitudinal dynamics. The compensated system can be represented as

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= C\Phi x + C\Psi Bu \end{aligned} \tag{2.15}$$

Note that the matrix $D = C\Psi B$, a scalar now (a one-by-one matrix) for single-input single-output system, is not zero. The unit output feedback closed-loop system with a state compensation is shown in Fig. 2.5. The state equation and output equation of the closed-loop compensated system can be written as

$$\begin{aligned} x &= (A - BGC\Phi)x + BGr,\ u = r - Cx_c \\ y &= C\Phi Gx + C\Psi BGr,\ y_c = Cx_c \end{aligned} \tag{2.16}$$

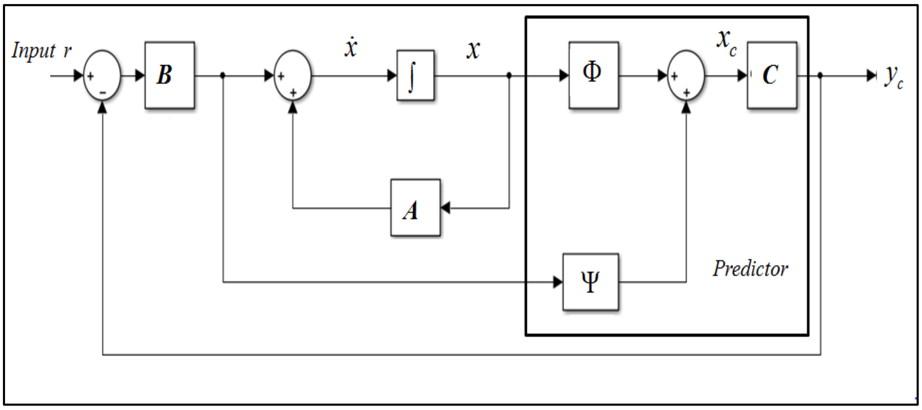

Figure 2.11 Output Feedback, State Space Predictor [21]

Where $G = (I + C\Psi B)^{-1}$ is, a feed forward (predictor or estimator) gain of the closed-loop compensated system, and r is a pilot input or a reference input. The state feedback can also be used in a state transition matri $\dot{x}$ x-based compensation. In fact, the Sobiski/Cardullo predictive filter uses The state feedback, as shown in Fig. 2.6. If The state feedback is used, the feed forward gain matrix becomes $G = (I + K\Psi B)^{-1}$. The feedback matrix K is designed using any control scheme including a pole placement technique so that the closed-loop poles of the compensated system consist of the closed-loop poles of the undelayed system.

In this study, the following steps are used. In the first step, K_{fdbk} is obtained using ordinary pole placement so that the homogeneous equation $\dot{x} = (A - BK_{fdbk})x$ has the desired poles. The second step is to calculate the feedback gain K as follows. Comparing $\dot{x} = (A - BK_{fdbk})x$ with the first equation of Eq. (2.16) gives $K_{fdbk} = GK\Phi$. And, the equations $G = (I + K\Psi B)^{-1}$ and $K_{fdbk} = GK\Phi$ provide the feedback gain as

$$K = K_{fdbk}(\Phi - \Psi BK_{fdbk})^{-1} \tag{2.17}$$

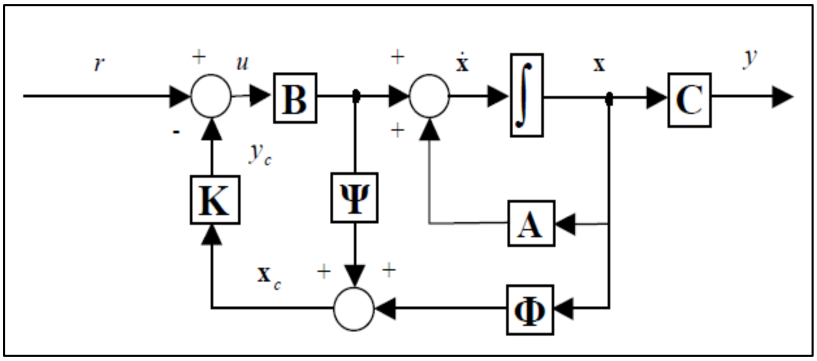

Figure 2.12 State Feedback, State Space Predictor [21]

Now, the state equation and state feedback equation of the closed-loop compensated system can be written as

$$\begin{aligned} \dot{x} &= (A - BGK\Phi)x + BGr, \; u = r - Kx_c \\ y &= Cx, \quad y_c = Kx_c = K(\Phi x + \Psi B u) \end{aligned} \tag{2.18}$$

In this study, the state feedback closed-loop method is adopted, because it has better performance than the Output Feedback method due to the degree of freedom.

Chapter 3

PIO Tendency

3.1 PIOs

Since the Wright brothers' aircraft, Pilot-Induced Oscillations (PIOs) have been appeared and regarded as HQ problem. PIOs are a particular part of HQ that needs special attention.

On April 25, 1992 the YF-22 took off from Edwards Base for a Flutter Excitation System test mission. On returning to Edwards, the pilot performed an uneventful low approach, selected military power and raised the landing gear. Following a second 'low approach', the pilot initiated a go-around, selected afterburners and raised the landing gear. Upon raising the gear, the aircraft began a series of pitch oscillations at an altitude of approximately 40 feet above the ground. After 4 to 5 oscillations, the aircraft impacted the runway [35]. Since the YF-22 PIO and crash, the Air Force Flight Test Center used PIO as an acronym for 'Pilot-In-the-loop Oscillation' or 'Pilot-Involved Oscillation', because PIO occurred at advanced flight control system, irrespective of the pilot intention [36].

MIL-STD-1797A [12] defines PIO to be "sustained or uncontrollable pitch oscillations resulting from efforts of the pilot to control the aircraft." And McRuer [37] defines it as "rare, unexpected, and unintended excursions in aircraft attitude and flight path caused by anomalous interactions between the aircraft and pilot." In other words, PIO is not a result of pilot mistake but a special phenomenon that is originally involved, and this must be prevented.

Since fly-by-wire technology is becoming increasingly complicated in order to meet the control requirement of MIL-SPEC and the commercial safety requirements, further research is needed to predict the PIO susceptibility of the aircraft. The MIL-SPEC was considered as minimum requirements so that only satisfying boundary conditions, but cannot be expected to lead to PIO. For the flight conditions of the YF-22 crash, every pitch axis metric violated MIL-SPEC boundaries, even the small amplitude linear characteristics [35]. Consequently, the Ralph Smith (or Smith-Geddes) criterion was adopted in the MIL-STD-1797A as PIO specification in 1995 even though this criterion has not met general acceptance. Further methods of applying Ralph Smith criterion will be explained in Section 3.3.

Interaction between the aircraft and pilot does not provide exception to the UAS. Especially, time lag induced by various sources including transport delay makes ground pilot difficult to control, which may lead to PIO. In this reason, the study on the PIO prediction for the UAS is meaningful, and the effective compensation preventing the PIO is more significant.

3.2 PIO & Handling Quality

PIO occurs when something arouses the aircraft response to be 180° out of phase with the command of the pilot. Unsuitable flight control system design such as excessive filtering or lags could make this problem. The PIO can be also occurred by mechanical origin; bobweights coupled with static friction, or owing to compensation added to the flight control system. And it is often owing to nonlinear events such as saturation of control rate of position limits [10]. Other known sources are short-period dynamics (large $\omega_{SP}, T_{\theta_2}$), feel system phasing, and sensitive control force and motion gradients [12].

PIOs have occurred for nearly every new aircraft during the development phase. The severity of the oscillation is sufficiently low when the PIO is detected, and the flight control system is modified. Figure 3.1 show the YF-22 accident that led to a gear-up landing and crash.

In a report for the U.S. Air Force, Mitchell and Hoh [38] outlined 10 steps for reducing the risk of PIO. Two of them are related with the importance of applying PIO criteria during the development, which are summarized as follows.

1. Apply valid prediction criteria early in the design process
2. Continue to apply criteria as the accuracy of the model improves.

In these reasons, a prominent PIO criterion will be explained in next Section.

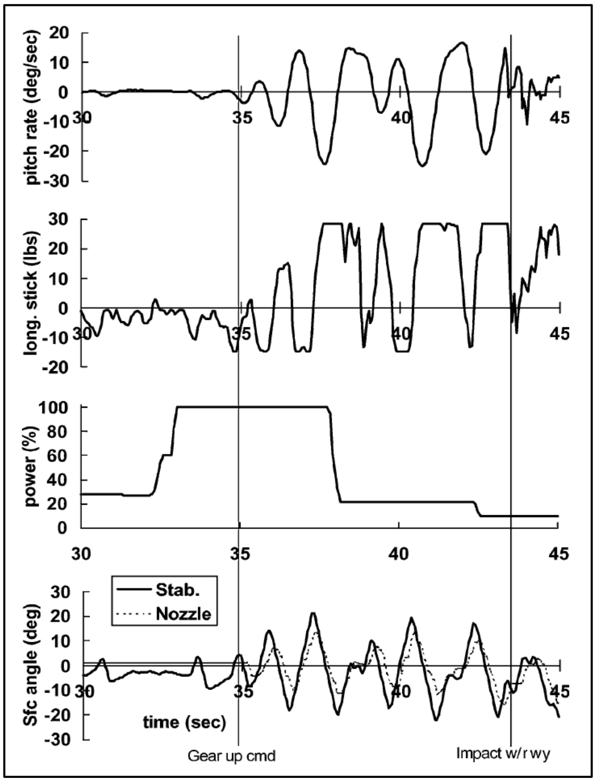

Figure 3.1 Time History of the YF-22 PIO [35]

3.3 Ralph Smith Criterion

Ralph Smith and Norman Geddes combines time response methods of determining HQ with frequency response methods, Ralph Smith (Smith-Geddes) criterion in 1978 [39]. Time response methods use the response to an input to relate HQ with aircraft parameters such as rise time, or settling time. Frequency response methods, on the other hand, predict the HQ by relating parameters to a pilot model. The Ralph Smith (or Smith-Geddes) criterion is an open-loop criterion, as shown in Fig. 1.2, however it was derived using an optimal pilot model as well as flight test data from Neal and Smith [31].

The Ralph Smith criterion has been used by Air Force Flight Test Center with remarkable success for several years. This criterion was used in the Space Shuttle, the F-15 with CAS-off, the Advanced Fighter Technology Integration, the AFTI/F-111, the AFTI/F-16, the C-17, and the YF-22. In an analysis of three PIOs in the Space Shuttle, the Ralph Smith criterion correctly predicted the PIO tendency and closely predicted the frequency of the PIO [12].

The Ralph Smith criterion consists of three parameters [39], time to first peak, t_q, average slope, $\overline{S}$, and phase lag, $\angle\theta / F_s(j\omega_c)$. In order to determine the HQ level, one must go through all three parameters. The overall value is determined by the worst rating of the three parameters. For instance, if the three ratings are 1, 2, and 3, then the overall HQ level would be Level 3.

1) Time to First Peak, t_q

The time to first peak parameter, t_q, is defined as the time to first peak of the pitch rate response, *q(t)*, to a step input of stick force. If the response is over-damped, t_q is defined as the time to 90 percent of the steady state value.

Table 3.1 Ralph Smith Criteria

Parameter	Level 1	Level 2	Level 3
t_q (s)	$0.2 \le t_q \le 0.9$	None	None
$\bar{S}$ (dB/oct)	< -2	None	None
$\angle \frac{\theta}{F_s}(j\omega_c)$	$\ge -123^\circ$	$-123^\circ \ge x \ge -165^\circ$	$\le -165^\circ$

The lower bound is an approximate representation of the limit on human time delay. If t_q is less than 0.2 seconds, the pilot tends to chase the response and then typical pilot comment would be that the aircraft response is too abrupt. With a time to first peak less than 0.2 seconds, precision maneuvering will be difficult without excessive pilot compensation. The upper bound is set from the Neal-Smith flight test data. According to pilot comments, if a system with t_q is more than 0.9 seconds, then aircraft tends to be too sluggish. These results from excessive lag in the phase angle of $\angle\theta / F_s(j\omega_c)$ [9, 39]. In practice, t_q parameter requirement is often omitted when performing the calculations by hand. This comes from the experience that when $\bar{S}$ parameter requirement for Level 1 HQ is satisfied, then the t_q parameter requirement is also met [36].

2) Slope Parameter, $\bar{S}$

The slope parameter, $\bar{S}$, is defined as the average slope of the magnitude plot of the transfer function, $\angle\theta / F_s(j\omega_c)$, on the frequency range of $1 \le \omega \le 6$ rad/sec. This slope is representative of the sensitivity of the response to pilot technique. The parameter takes into account the variability of pilots by requiring the slope to be small, thus making the aircraft resistant to different pilot techniques of skill level. The magnitude of the slope can be determined using a least squares best fit straight line on the frequency range [9, 39].

3) Phase Lag Parameter, $\angle \frac{\theta}{F_s}(j\omega_c)$

The Phase lag quantifies the level of pilot compensation needed to perform maneuvers. The criteria levels were determined from flight test data and pilot comments. Physically, phase lag is the amount of time between the input of a command and when the response of the aircraft is noticed by the pilot. In order to calculate $\angle\theta / F_s(j\omega_c)$, the criterion frequency, ω_c, needs to be determined. This criterion frequency is nearly the crossover frequency of the pilot-aircraft system for pitch angle tracking. It was determined by using the crossover frequency of the forcing functions, impulse, step, and parabolic input from McRuer's experiments [40]. By plotting these crossover frequencies against the forcing function's slopes in dB/octave, the criterion frequency can be defined. Figure 3.2 shows that the criterion frequency is given by the following equation of the best fit straight line through the crossover frequencies.

$$\omega_c = 0.24\bar{S} + 6.0 \ (radians / s) \tag{3.1}$$

Once the criterion frequency is calculated, $\angle\theta / F_s(j\omega_c)$ can be found. This is done by locating the phase angle at ω_c on the Bode phase plot [9, 39].

Susceptibility to pitch PIO is predicted if $\angle\theta / F_s(j\omega_c) \leq -180^\circ$, but is not predicted if $\angle\theta / F_s(j\omega_c) > -180^\circ$ as shown in Fig. 3.3. When susceptibility to pitch attitude PIO is predicted, and the PIO dynamics are linear, then the criterion frequency, ω_c, will be the PIO frequency [36].

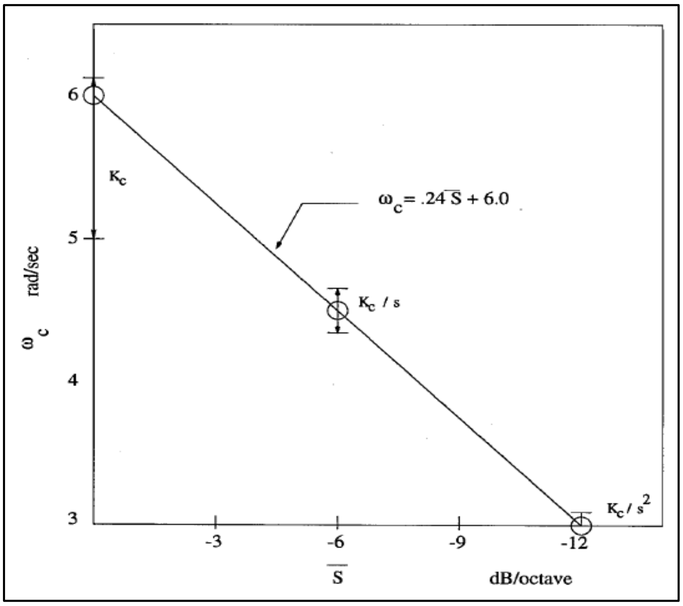

Figure 3.2 Specification of the Criterion Frequency [9]

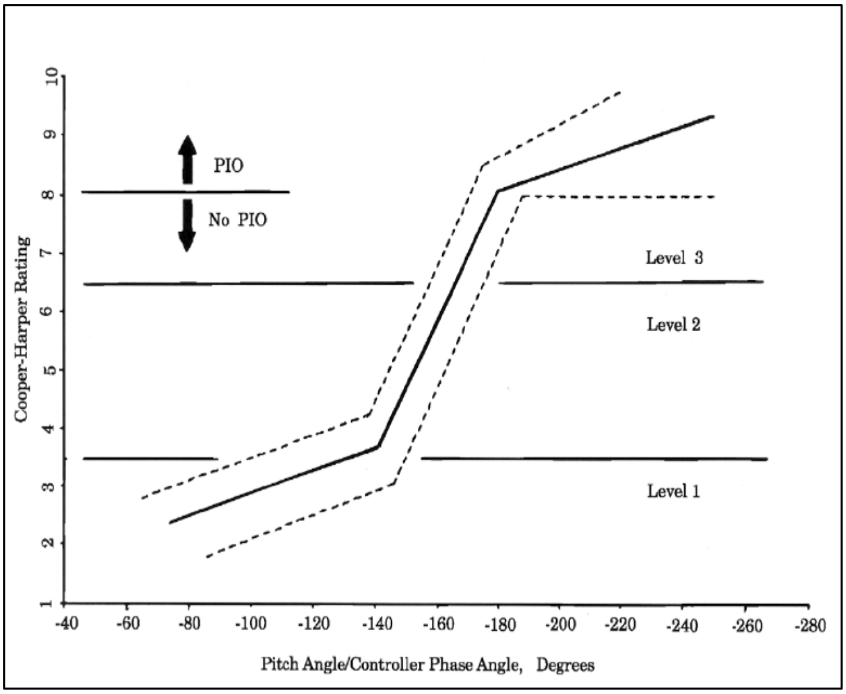

Figure 3.3 Ralph Smith Criterion $\angle\theta / F_s(j\omega_c)$ vs. HQ Rating [36]

Chapter 4

Numerical Simulation

4.1 Simulation Configuration

To verify the performance of the proposed compensation, numerical simulation is performed and three HQ criteria are applied. First, Neal-Smith criterion is applied, and then Bandwidth criterion is used for HQ performance. Finally, Ralph Smith criterion is applied for both HQ and PIO evaluation.

The most prominent compensation techniques are applied, which are Lead Compensator (LC) and State Space Predictor (SSP), because current research showed the superiority of SSP over McFarland velocity predictor in the delayed human-machine system [21, 41]. Therefore, in this study, these two methods are applied, for a High maneuverability UAS model, Art-Tech ASK 21 [42]. System identification was performed to obtain the aircraft model.

Table 4.1 ASK 21 UAS Model for Simulation

Length	1.29 m
Wingspan	2.67 m
Flying Weight	4.0 Kg
Flight Condition	Cruise (Category B)
Cruise Speed	18 m/s
Mission Altitude	200 m
Max Bank Angle	40 deg

4.2 Neal-Smith Criterion Results

The Neal-Smith Criterion is applied to the ASK 21 UAS model. The effect of delay of the ASK 21 in cruise condition (Cat B) is shown Fig. 4.1. The bandwidth specified in the Neal-Smith criterion of the MIL-STD-1797A for the cruise condition is 1.5 rad/s as mentioned in Table 2.1.

4.2.1 Lead Compensator

The decrease in performance, measured by closed-loop resonance peak increase, is clearly presented. Additional pilot workload caused by an increasing amount of the pilot lead compensation may also be observed.

Figure 4.2 shows that Lead Compensator (LC) provides slight improvement until 0.2s delay. It also improves HQ Level for the 0.4s delay case. However, in 0.3s delay case, LC does not provide improvement, but degrade HQ Level. Analysis on this degradation is performed in Section 4.3.1.

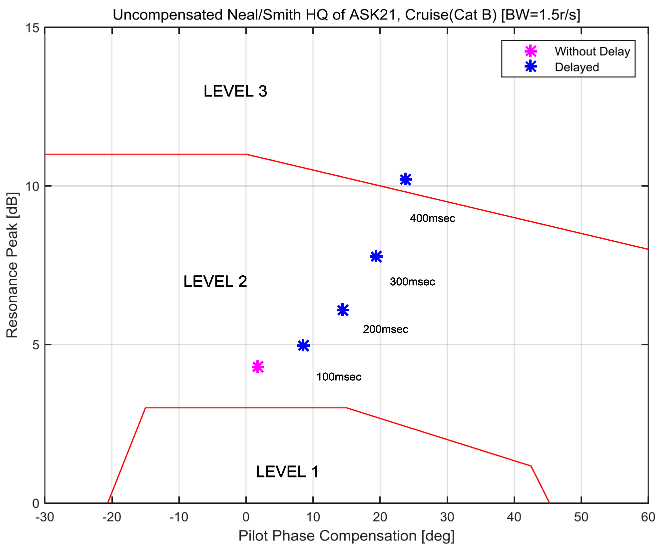

Figure 4.1 Delay Effect, Neal-Smith Criterion

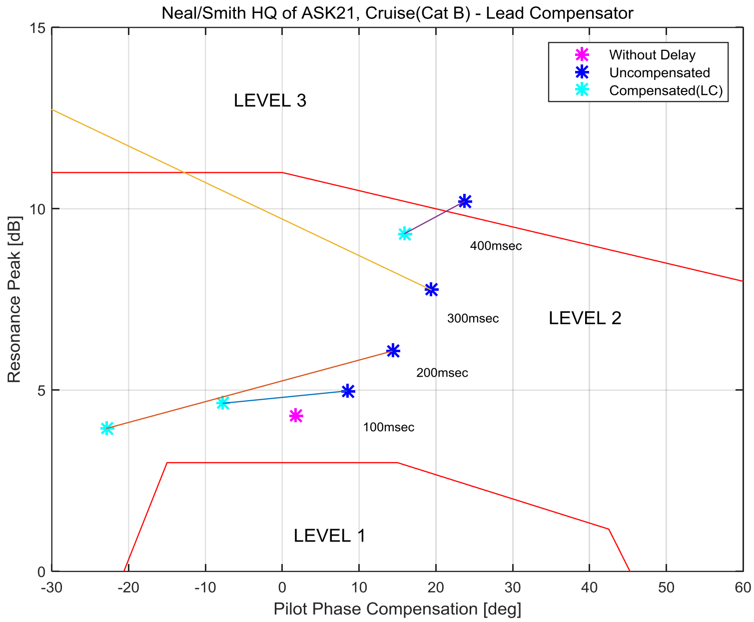

Figure 4.2 Neal-Smith, Overall Results, Lead Compensator

As mentioned in the previous chapter, lead compensator cannot compensate the entire delay. Lead compensator is useful when it is used to compensate the delays of less than approximately 0.1s [21], which should be considered as the upper limit of the filter.

The computation workload of lead compensator is higher than that of the state space predictor. The lead compensator takes 0.362s, while state space predictor takes 0.468s. Generally the state space predictor takes more time because of complex calculation. However, computation workload is not a main requirement for a good compensator, and it does not show any significant difference.

In short, although LC has low computation workload, it does not provide sufficient phase lead and it makes gain distortion in 0.3s delay case.

4.2.2 State Space Predictor

As mentioned in 2.2.1 Section, Neal-Smith HQ graph consists of three mathematical terms: Bandwidth, Droop, and Closed-loop resonance. Figure 4.3 shows how State Space Predictor (SSP) each term makes final HQ graph in 0.2s delays condition compensated by SSP.

State space predictor decreases HQ Level, which means that SSP is a good compensator, even though time delays increase. Figure 4.4 shows that the compensator returned HQ rating to the almost ‘Without Delay’ case for smaller time delay case, and it significantly improved the system for large delay case. Especially, there is HQ Level improvement in 0.4s delay case with noticeable change.

Since SSP uses more system information including the control input information, compensation effect in superior. Because of the calculation of the state transition matrix and the convolution integral matrix, SSP also requires a large computation time. However, it meets the first two criteria, and the computation burden is relatively low as explained in Section 4.2.1. Therefore, it can be stated that SSP is desirable to compensate the time delay problem and to make HQ better even in the condition of large delays.

Furthermore, Neal-Smith criterion could estimate the PIO tendency by the resonance peak parameter as shown in Fig. 2.5. From about 9-10 dB, the aircraft could show strong PIO tendencies and 0.3-0.4s delayed results are met. However, the compensated results by SSP do not show strong PIO tendencies, because all the parameters are below 6 dB. Hence, the state space predictor is also a suitable compensator for the PIO.

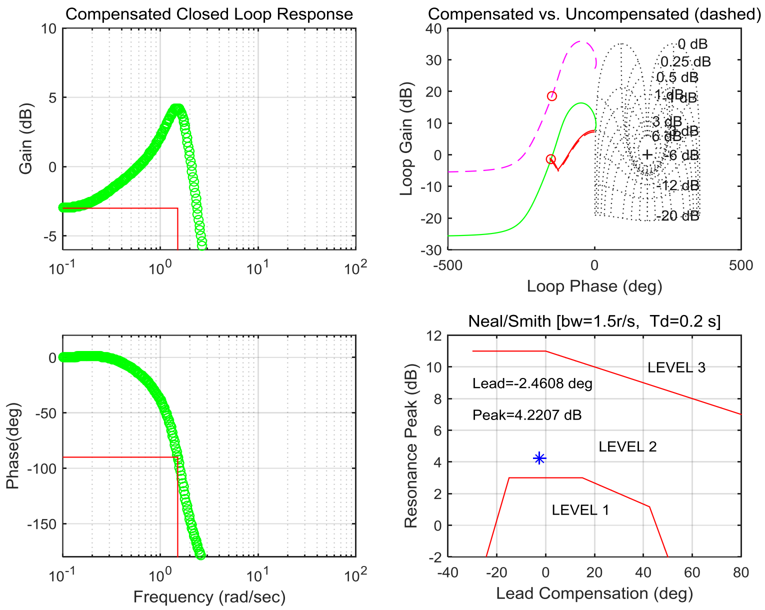

Figure 4.3 Neal-Smith Process, 0.2s Delay, State Space Predictor

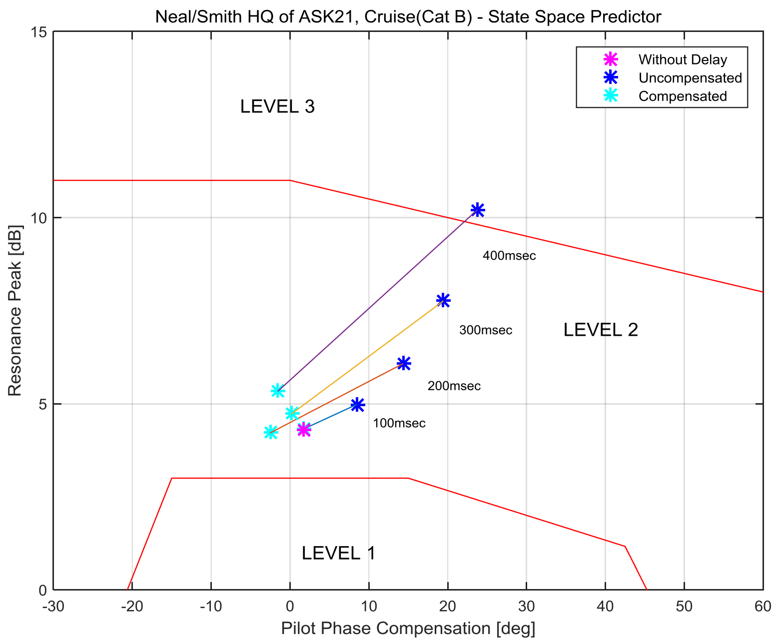

Figure 4.4 Neal-Smith, Overall Result, State Space Predictor

4.3 Bandwidth Criterion Results

The Bandwidth Criterion as discussed in the previous chapter is applied to the ASK21 UAS Category B (Cruise condition) model. Unlike the Neal-Smith criterion, simple pilot model suggested by Sobiski [23] is used in Bandwidth Criterion.

4.3.1 Lead Compensator

The effect of time delay that worsens HQ Level as delay increases is shown in Fig. 4.5. Each Bandwidth parameter is almost same around 2 rad/s, but phase delay, τ_p, increases as time delay increases. Figure 4.6 show the gain distortion in 0.3s delay, therefore it provides negative effect on HQ. Pole frequency is 0.027 while zero frequency is 0.0000014, which means high gain distortion. LC provides slight improvement like Neal-Smith results; however, the amount of compensation is not enough to improve HQ as shown in Fig. 4.7. Like Neal-Smith results, LC is undesirable to compensate the time delay problem especially for large delays.

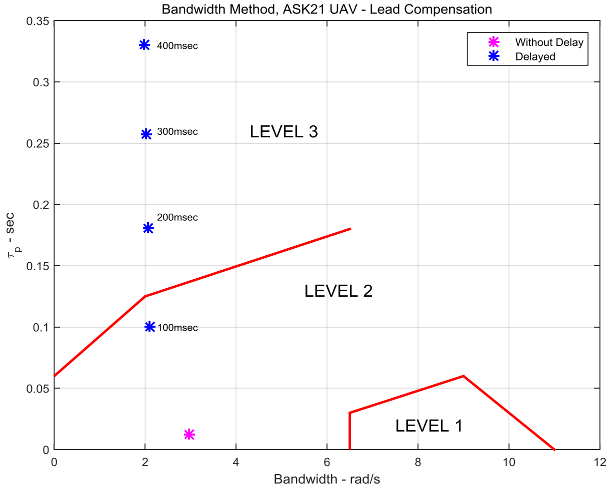

Figure 4.5 Delay Effect, Bandwidth Criterion

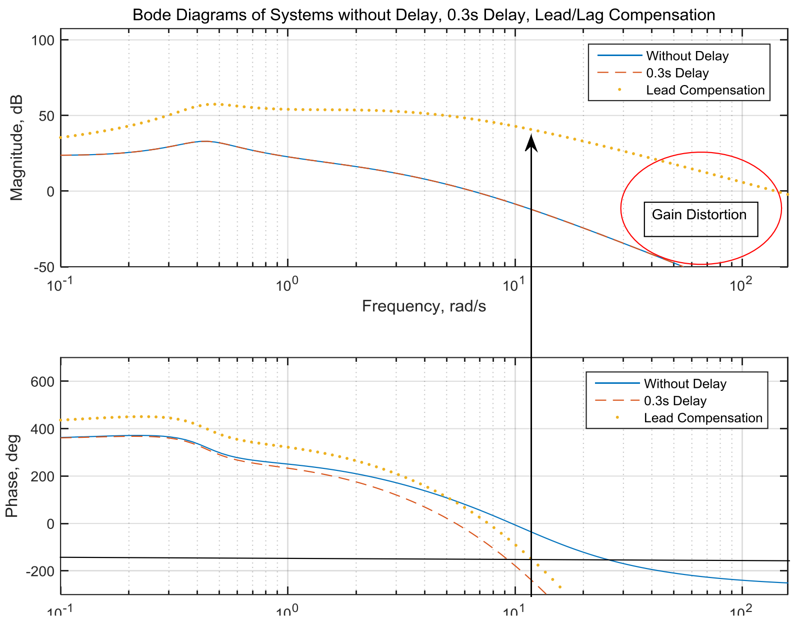

Figure 4.6 Bandwidth, 0.3s Delay, Gain Distortion, Lead Compensator

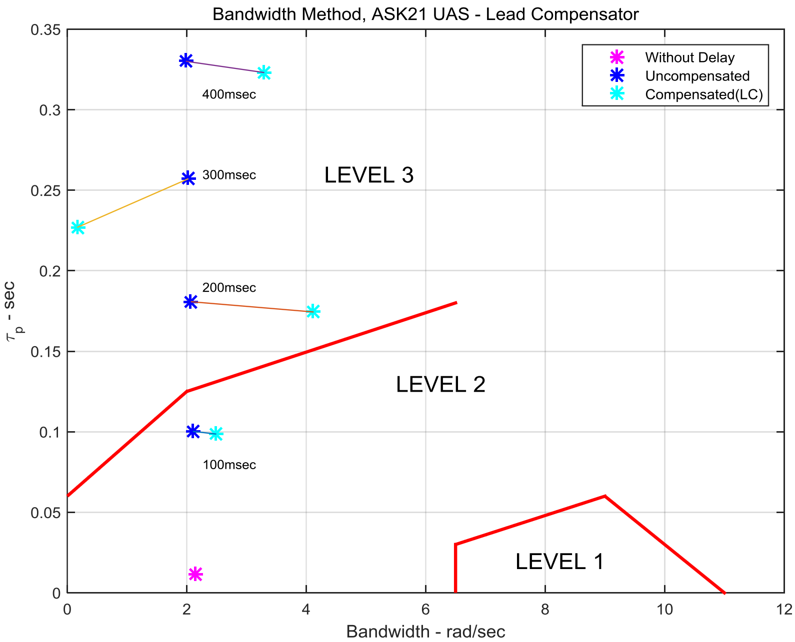

Figure 4.7 Bandwidth, Overall Result, Lead Compensator

4.3.2 State Space Predictor

As mentioned in Sec. 2.2.2, Bandwidth HQ graph consists of two mathematical terms: bandwidth frequency, ω_{BW} , and phase delay, τ_p . As shown in Fig. 4.8, SSP decreases the HQ Level, which means it is a good compensator even though time delays increased. Figure 4.9 shows that SSP decreases the HQ Level from Level 3 to Level 2, especially in 200msec (0.2s) case.

Bandwidth Criterion also shows the superiority of the SSP compensation. Especially, Bandwidth is improved, HQ Level from Level 3 to Level 2, which means 'Acceptable'. Therefore, analysis on what makes difference between LC and SSP by the frequency domain and time domain analysis should be performed.

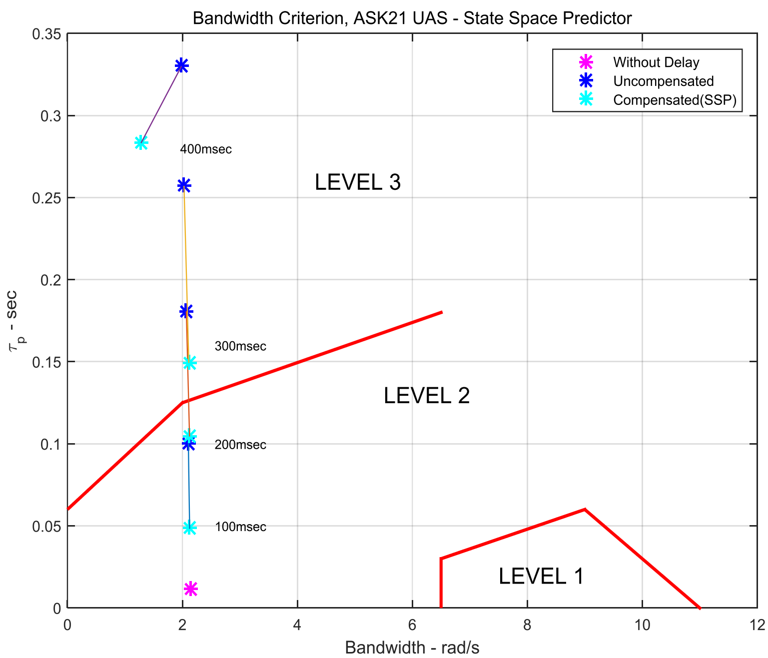

Figure 4.8 Bandwidth, Overall Result, State Space Predictor

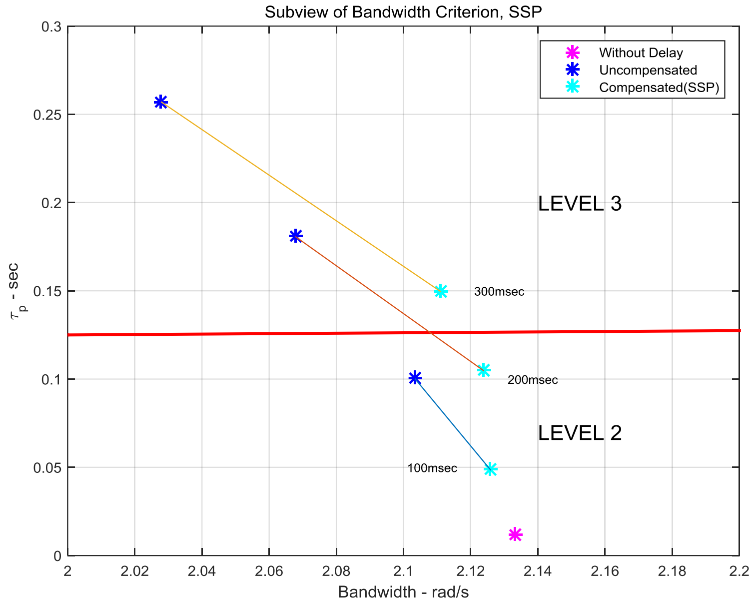

Figure 4.9 Bandwidth, Subview of Overall Result, State Space Predictor

4.3.3 Frequency & Time Domain Analysis

For the Bandwidth Criterion of 0.2s time delays case, LC does not improve HQ Level. On the other hand, SSP improves HQ Level. Let us perform the frequency and time domain analysis.

For the frequency domain analysis, the Bode plot is used. The gain margin and the phase margin are positive in SSP while negative in LC. It means the compensated systems are not always stable as shown in Table 4.2, Fig. 4.10 and Fig. 4.11. The Bode plot, frequency domain analysis, proves the significant difference between LC and SSP. In 0.2s time delay condition, LC provides some phase lead, but it is not effective because crossover frequency is increased. However, phase curve of SSP follows ‘Without Delay’ curve until crossover frequency. It means that SSP compensate the delayed system to the 'Without Delay' level, whereas LC does not. Figures 4.12 and 4.13 show these differences.

For the time domain analysis, the step response is used. Figures 4.14 and 4.15 show that LC curve does not follow the 'Without Delay' curve, while SSP curve follows. It also means that SSP is better compensator than LC, though initial compensation condition of the LC is fast.

Table 4.2 Gain & Phase Margin of Compensated System

	Lead Compensator	State Space Predictor
Gain Margin	-2.24 dB	4.58 dB
Phase Margin	-45.1 deg	23.7 deg

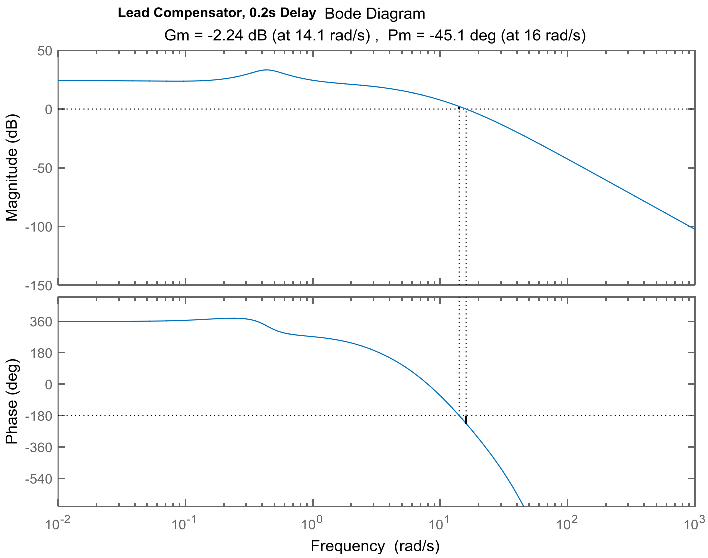

Figure 4.10 Gain & Phase Margin, Lead Compensator

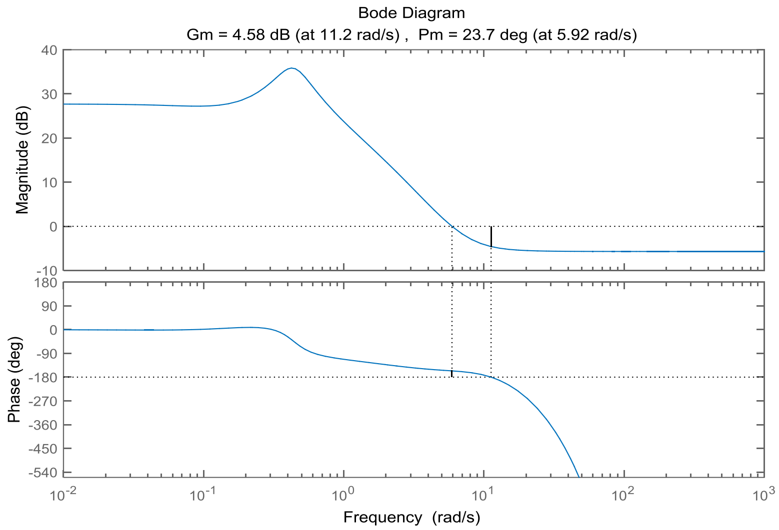

Figure 4.11 Gain & Phase Margin, State Space Predictor

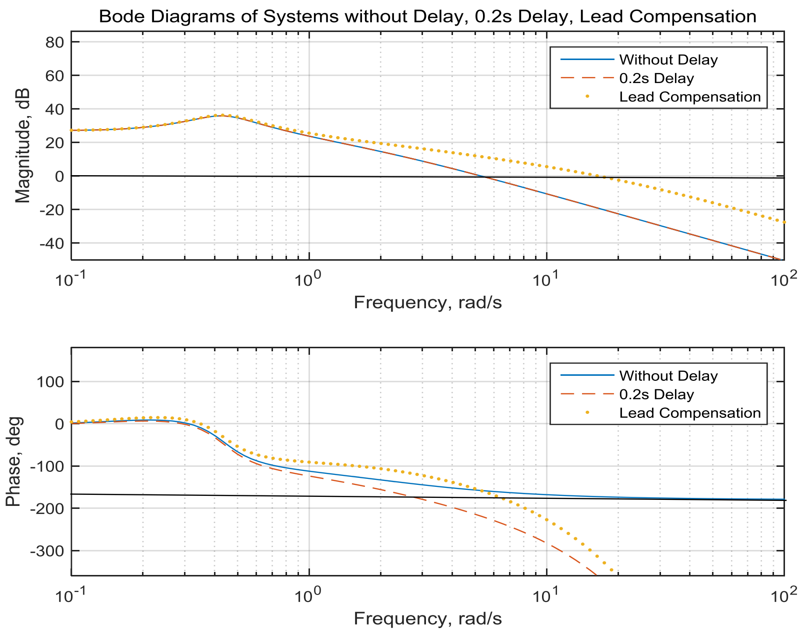

Figure 4.12 Bode Plot, 0.2s Delay, Lead Compensator

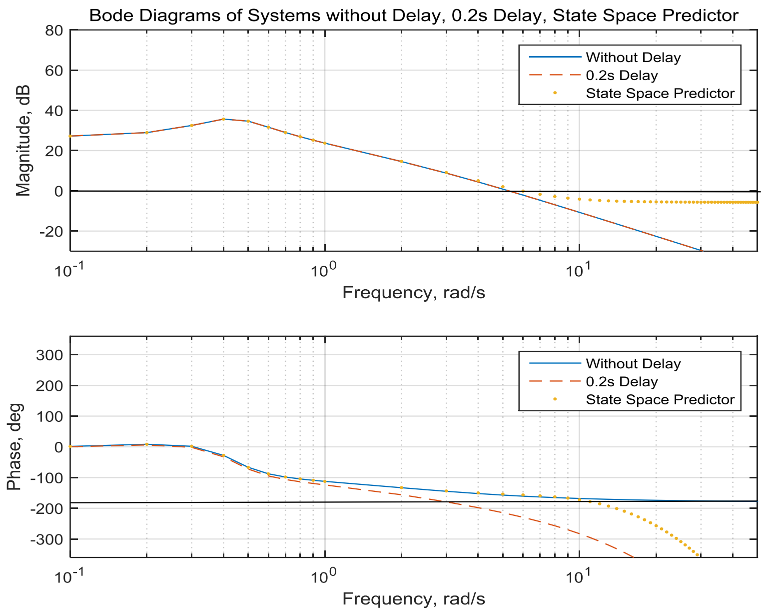

Figure 4.13 Bode Plot, 0.2s Delay, State Space Predictor

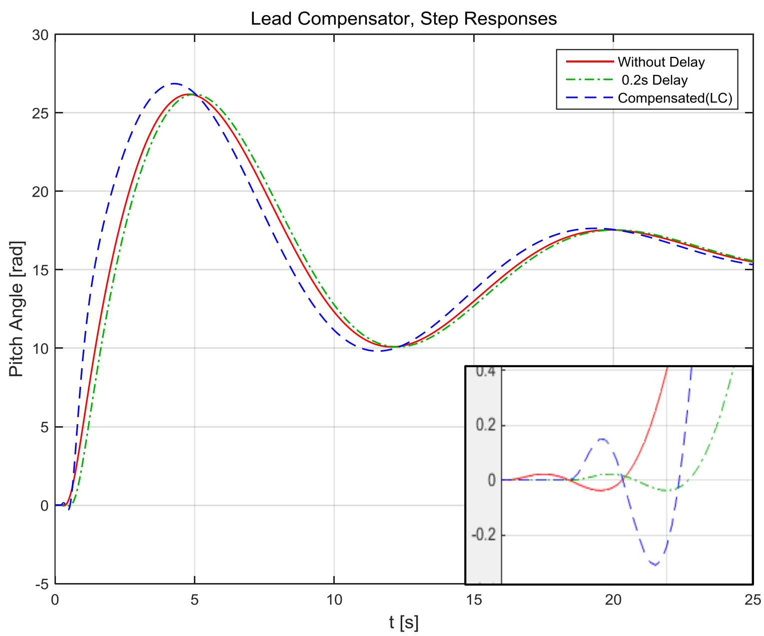

Figure 4.14 Step Responses, Lead Compensator

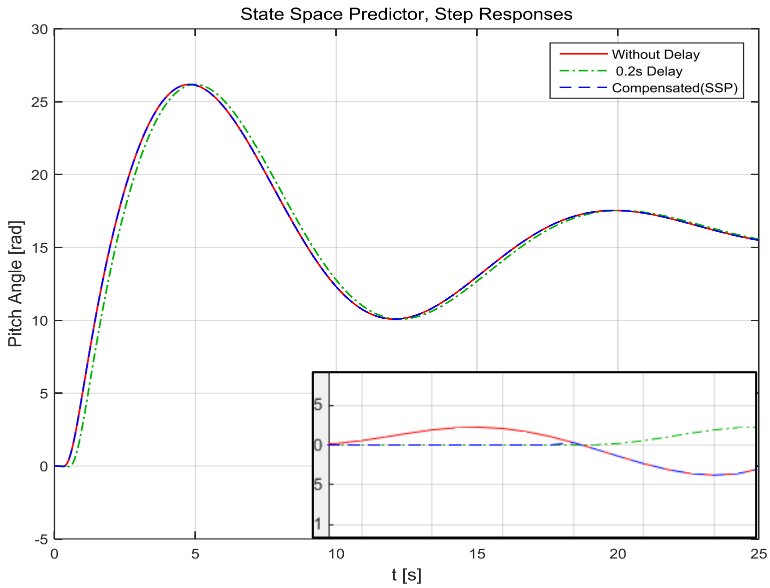

Figure 4.15 Step Responses, State Space Predictor

4.4 Ralph Smith Criterion Results

The Ralph Smith (or Smith-Geddes) Criterion as discussed in the previous chapter is applied to the ASK21 UAS Category B model. The criterion predicts HQ and PIO tendency with time delay, and then the results are analyzed for the compensation effect.

4.4.1 Lead Compensator

Figure 4.16 shows that the effect of the time delay worsens HQ Level as delay increases. Each Ralph Smith parameter is moving toward PIO section, and it increases CHR to worse HQ as time delay increases. Delayed HQ Level is all 3, whereas Bandwidth Criterion presents Level 3 for the system with over 0.2s delay.

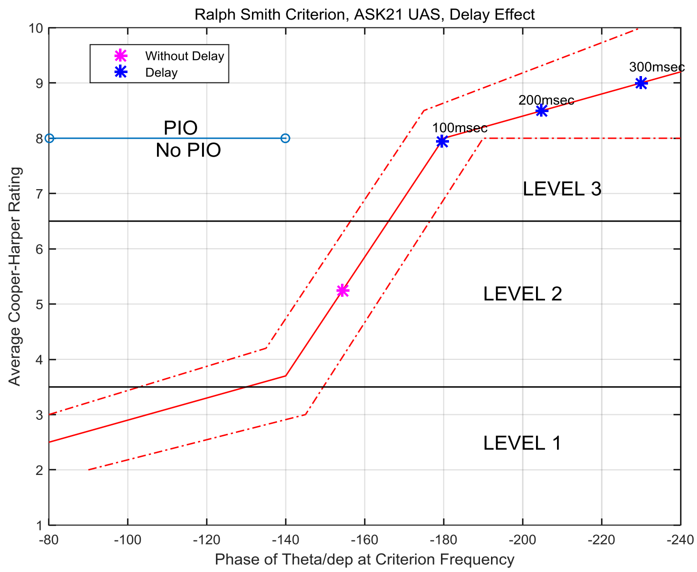

Figure 4.16 Delay Effect, Ralph Smith Criterion

Susceptibility to pitch attitude PIO is predicted, if $\angle\theta / F_s(j\omega_c) \le -180^\circ$ and it is susceptible to PIO from 0.2s delay (0.1s delay result is -179 degree), as shown in Fig. 4.16. It is confirmed that the time delay worsens HQ, and it also causes PIO. It is possible to deal with these problems using the compensator. Figures 4.17 - 4.19 show Ralph Smith HQ results for the system with lead compensation, especially for the case of 0.2s delay. Ralph Smith criterion, t_q analysis is omitted as explained in Section 3.3. The average slope, $\bar{S}$ of the magnitude plot of the transfer function, $\theta / F_s(j\omega_c)$ is presented in Fig. 4.17. The $\bar{S}$ satisfies second Ralph Smith Level 1 criterion, $\bar{S} < -2$, and it is used for calculation of the crossover frequency, ω_c, by Eq. (2.3). Using the Bode plot, the phase lag parameter, $\angle\theta / F_s(j\omega_c)$ is acquired by ω_c as shown in Fig. 4.18, and then CHR is calculated using the $\angle\theta / F_s(j\omega_c)$ by Ralph Smith graph as shown in Fig. 4.19.

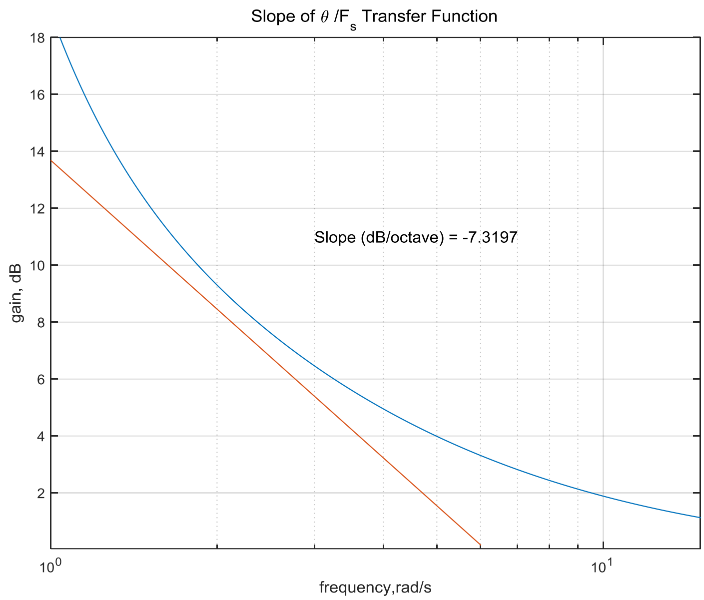

Figure 4.17 Ralph Smith, Slope Parameter, $\bar{S}$, Lead Compensator

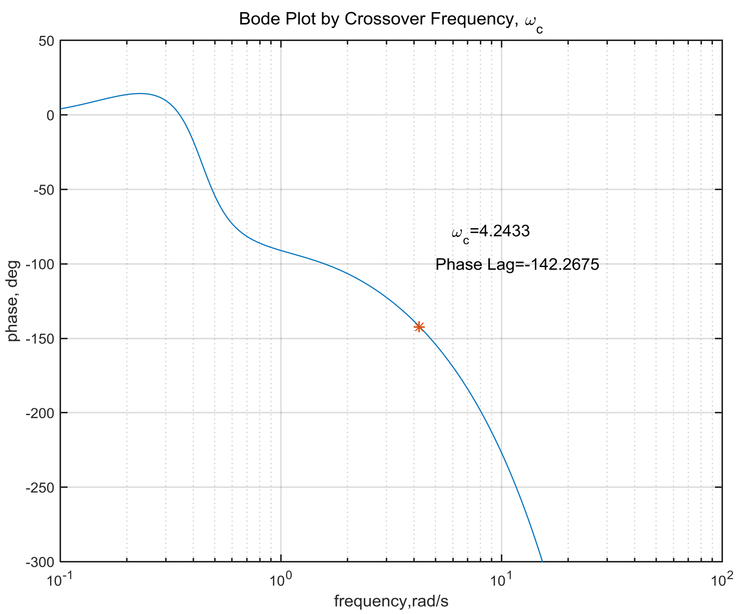

Figure 4.18 Ralph Smith, ω_c & $\angle \frac{\theta}{F_s}(j\omega_c)$, Lead Compensator

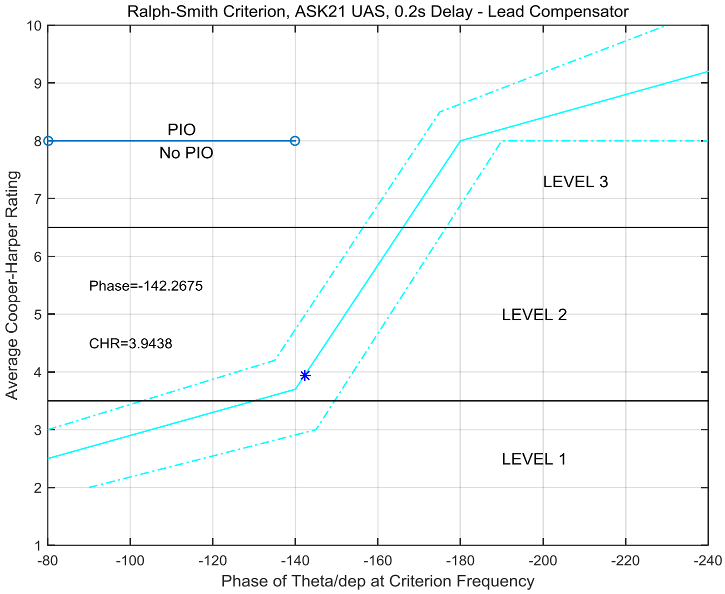

Figure 4.19 Ralph Smith, 0.2s Delay, Lead Compensator

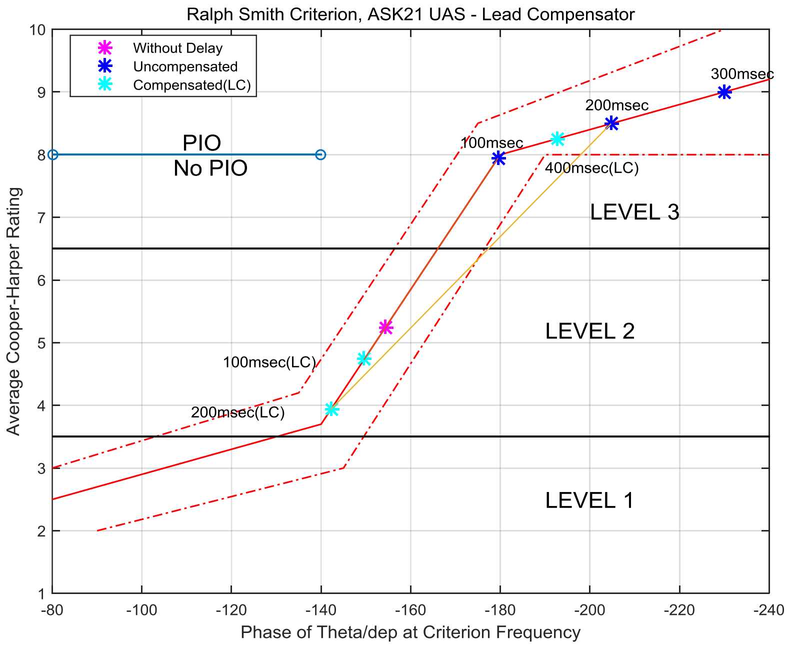

Figure 4.20 Ralph Smith, Overall Result, Lead Compensator

When PIO is predicted and the PIO dynamics are linear, the criterion frequency ω_c is the predicted PIO frequency. Therefore, 4.24 rad/s is the predicted PIO frequency for the 0.2s delay case.

Overall results using LC for 0.1s and 0.2s delay case (0.4s delay and 0.3s compensation results are out of graph) are presented in Fig. 4.20. LC improves both HQ Level and PIO tendency until 0.2s. However, as the other HQ criteria results, it could not improve all condition, especially for 0.3s compensation case. Also, it could not reduce PIO tendency in 0.4s delay condition. It can be stated that LC does not improve the HQ Level and the PIO tendency especially for the large delay conditions.

4.4.2 State Space Predictor

As mentioned in Section 3.3, Ralph Smith method consists of three criteria to evaluate HQ and predict PIO. Figures 4.21 - 4.23 show the Ralph Smith HQ results using SSP, especially for 0.4s delay case. Ralph Smith criterion, t_q analysis is omitted for the same reason as mentioned in Section 4.4.1. The average slope, $\bar{S}$ of the magnitude plot of the transfer function, $\theta / F_s(j\omega_c)$ is presented in Fig. 4.21. Ralph Smith Level 1 criterion, $\bar{S} < -2$, is satisfied, and the phase lag parameter, $\angle \theta / F_s(j\omega_c)$, is acquired by ω_c as shown in Fig. 4.22. Ralph Smith HQ graph is also presented by the $\angle \theta / F_s(j\omega_c)$ as shown in Fig. 4.23.

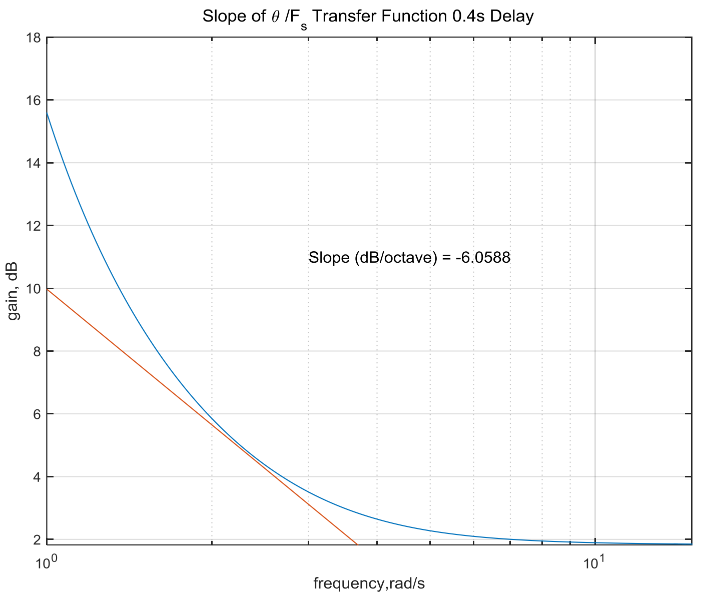

Figure 4.21 Ralph Smith, Slope Parameter, $\bar{S}$, State Space Predictor

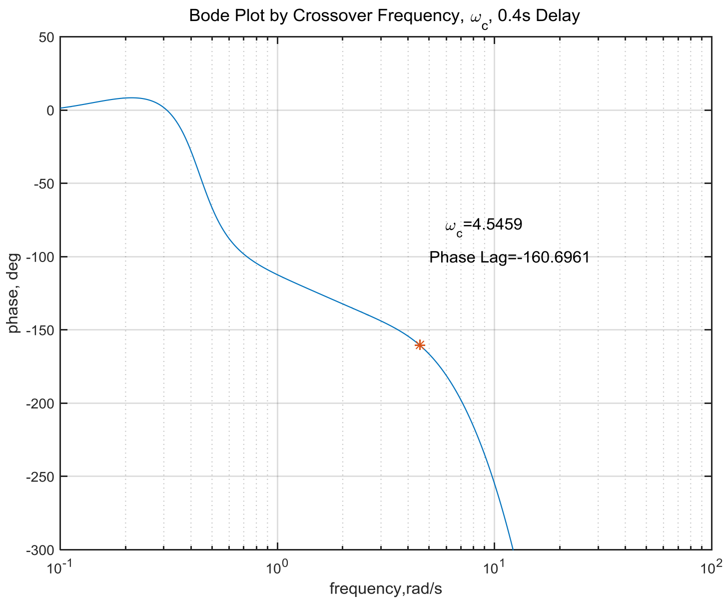

Figure 4.22 Ralph Smith, ω_c & $\angle\dfrac{\theta}{F_s}(j\omega_c)$, State space predictor

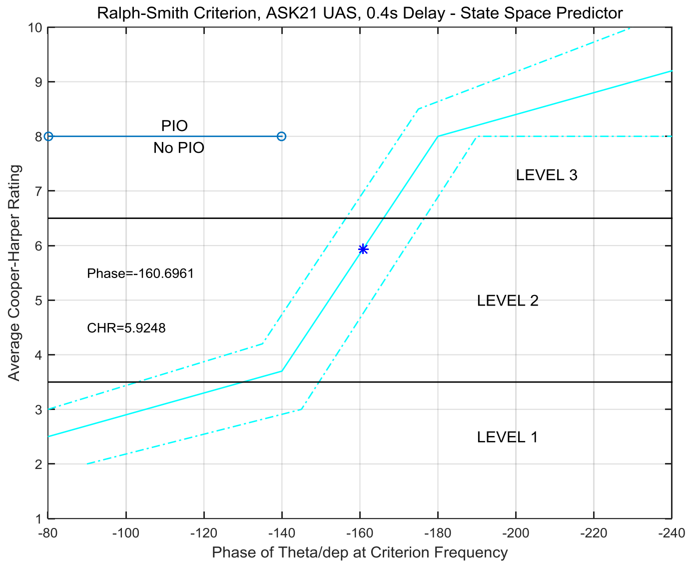

Figure 4.23 Ralph Smith, 0.4s Delay, State Space Predictor

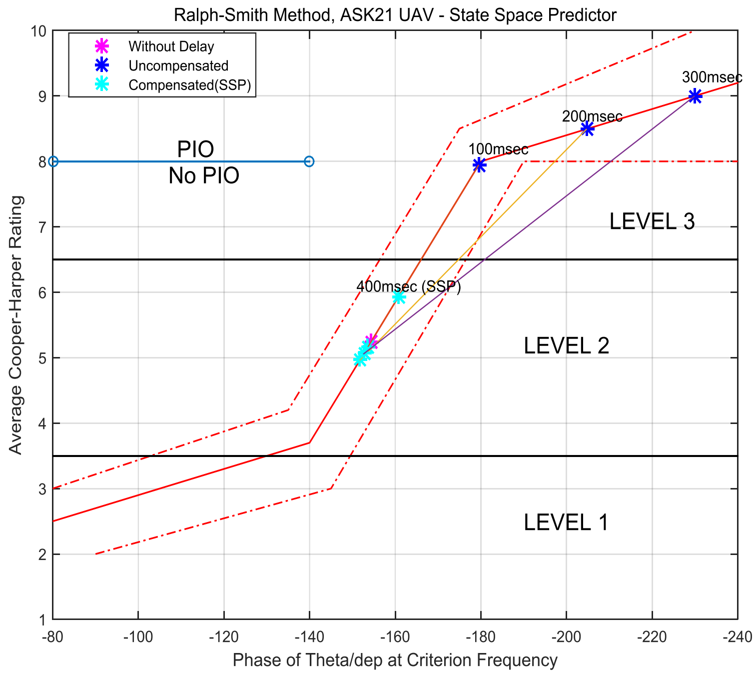

Figure 4.24 Ralph Smith, Overall Result, State Space Predictor

The compensated result is significantly improved by SSP. Even though without compensation, HQ Levels are improved from Level 3 to Level 2 and PIO tendency disappeared as shown in Fig. 4.23.

As shown in Fig. 4.23, when the phase lag increases, CHR also increases, that is, HQ degrades. Note that the phase lag is closely related with PIO tendency. If $\angle\theta / F_s(j\omega_c) \le -180^\circ$, it is susceptible to PIO. However, the phase lag increased by time delay is decreased to almost 'Without Delay' level until 0.3s delays, and it is noticeably improved in 0.4s delays case. Therefore SSP shows its good compensation result not only for HQ but also PIO in Ralph Smith criterion.

4.5 Numerical Simulation Results Analysis

In this Section, the numerical simulation results are analyzed to evaluate The state space predictor by three HQ results.

In Section 4.2, the Neal-Smith criterion is applied to verify The state space predictor performance for HQ and PIO tendency. The Lead compensator has relatively small computational workload, which is 0.106s faster than State space predictor. However, it could not provide sufficient phase lead while The state space predictor significantly improves to the almost 'without delay' level even for large delays. And The state space predictor also improves the PIO tendency by reducing the resonant peak parameters (below 6 dB). In Section 4.3, the Bandwidth criterion is used for HQ evaluation. The state space predictor is generally effective, and it shows better performance especially for the 0.2s delay case that is improved from HQ Level 3 to Level 2. The analysis of 0.3s LC compensation result which provides gain distortion in higher frequency is performed. In Section 4.4, the Ralph Smith criterion shows the good compensation performance of the SSP for both HQ and PIO tendency.

For the comparison, both the frequency domain and the time domain analysis are performed. Using Bode plot, significant difference is founded that the lead compensator curve does not follows ‘Without Delay’ curve, while the state space predictor follows similarly. Lead compensator provides unstable results by the gain and phase margin. The state space predictor shows that it is more effective for the time delay compensation. For the time domain analysis, step response method is applied. It shows almost similar results as in the frequency domain results. The lead compensator curve does not follow the ‘Without delay’ curve, while the state space predictor follows the curve immediately. It means that the SSP would compensate the delayed system to almost original level.

The state space predictor could satisfy all the basic criteria of the good predictor. It provides sufficient phase lead to compensate the phase lag caused by the time delay and has minimum gain distortion. Furthermore, it has smaller computational workload than the Lead compensator.

Chapter 5

Conclusion & Future Work

5.1 Conclusion

A state space predictor algorithm was proposed for UAS time delay compensation. To evaluate the compensation performance, the prominent Lead compensator was compared and three Handling Quality and Pilot-Induced Oscillation evaluation criteria were applied.

The Bandwidth criterion show that the performance of the state space predictor are better than that of lead compensator; it improved not only Handling Quality but also Pilot-Induced Oscillation.

For these simulation results, it can be stated that the state space predictor is a more effective and desirable compensator than the lead compensator for time delayed UAS with high maneuverability.

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5.2 Future Work

This study has not been applied to flight tests, but it is important for the state space predictor to be applied to non-linear conditions. The final goal is to compare the predictive simulation result with a pilot rating of the flight test. Recently, Pilot-Induced Oscillation prevention studies were performed by UAS owing to its safety and economic advantages. Hence, it is desirable to test this algorithm for the Handling Quality and the Pilot-Induced Oscillation tendency using suitable UAS.

Furthermore, other Handling Quality and Pilot-Induced Oscillation criteria such as the Gibson criterion could be applied to verify the performance of the state space predictor. Other modern control schemes could be needed to design a controller to compensate for the time delay problem.

For UCAV application, numerous studies will be necessary especially during Category A, which contains rapid maneuver and precision tracking as well as Category C, which is the terminal phase, during which it may be highly susceptible to PIO.

References

[1] Taylor, J. W. R., *Jane's Pocket Book of Remotely Piloted Vehicles*, Collier Books, New York, NY, 1977.

[2] Military, *Unmanned Systems Integrated Roadmap FY2011-2036*, Department of Defense, USA, 2011, p.46.

[3] Scott, W. B., “X-36 Testing Gives Boeing Jump on UCAV Works," *Aviation Week and Space Technology*, Vol. 148, 2 Mar. 1998, pp. 58-60.

[4] Cook, M. V., *Flight Dynamics Principles*, Arnold, London, U.K., 1997, Chap. 1.

[5] Langdon, S. D., et al., *Fixed Wing Stability and Control Theory and Flight Test Techniques*, USNTPS-FTM-No. 103, U.S. Naval Test Pilot School, Patuxent River, MD, 1975

[6] Etkin, B., and Reid, L. D., *Dynamics of Flight, Stability and Control*, Third Edition, John Wiley & Sons Inc., New York, NY, 1996, Chap. 1.

[7] Cooper, G. E., and Harper, R. P., “The Use of Pilot Rating in the Evaluation of Aircraft Handling Quality,” NASA TN D-5153, National Aeronautics and Space Administration, Apr. 1969.

[8] Carlucci, L. A., “Comparison of the Ralph Smith and The Time Domain Flying Quality Criteria,” MS Thesis, AFIT/GAE/ENY/95D-05, Graduate School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, Dayton, OH, 1995.

[9] Mitchell, D. G., Doman, D. B., Key, D. L., Klyde, D. H., Leggett, D. B., Moorhouse, D. J., Mason, D. H., Raney, D. L. and Schmidt, D. K., "Evolution, Revolution, and Challenge of Handling Quality," *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 1, 2004, pp. 12-28.

[10] Prosser, C. F., and Wiler, C. D., “RPV Flying Quality Design Criteria,” No. C76-1391/034C, Missile Systems Division, Rockwell International Corporation, Columbus, OH, 1976.

[11] Standard, Military, “Flying Quality of Piloted Airplanes, MIL-F-8785C,” Department of Defense, USA, Nov. 1980.

[12] Standard, Military, “Flying Quality of Piloted Aircraft, MIL-STD-1797A,” Department of Defense, USA, Jan. 1990; Notice of Reinstatement, Aug. 2004.

[13] McFarlane, C., Richardson, T., Jones, C., "Unmanned Aerial Vehicle Flying Quality," *AIAA Guidance, Navigation and Control Conference and Exhibit*, Honolulu, HI, Aug. 2008.

[14] Breneman, K., and Lower, M., "Flying Quality of a Remotely Piloted Vehicle," *28th National Heat Transfer Conference*, San Diego, CA, Aug. 1992.

[15] Stachowiak, S. J., and Bosworth, J. T., “Flight Test Results for the F-16XL with a Digital Flight Control System,” NASA/TP-2004-212046, NASA Dryden Flight Research Center, CA, 2004.

[16] Han, Y., “Performance Evaluation of UAV Control System Using Design Requirement for High Performance Aircraft,” MS Thesis, Dept. of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea, 2006.

[17] Hodgkinson, J., and Johnston, K. A., "Initial Results of an Inflight Simulation of Augmented Dynamics in Fighter Approach and Landing,” *AIAA Guidance and Control Conference*, Boulder, CO, Aug. 1979.

[18] Cardullo, F. M., and George, G., "Transport Delay Compensation: An Inexpensive Alternative to Increasing Image Generator Update Rate," *AIAA Flight Simulation and Technologies Conference*, Monterey, CA, Aug. 1993.

[19] McFarland, R. E., "Transport Delay Compensation for Computer-Generated Imagery Systems," NASA Technical Memorandum 100084, NASA Ames Research Center, CA, Jan. 1988.

[20] Crane, D. F., "Compensation for Time Delay in Flight Simulator Visual Display System," *AIAA Flight Simulation and Technologies Conference*, Niagara Falls, NY, Jun. 1983.

[21] Guo, L., Cardullo, F. M., and Kelly, L. C., "Advanced Control Algorithms for Compensating the Phase Distortion Due to Transport Delay in Human-Machine Systems," NASA/CR-2007-215095, NASA Langley Research Center, VA, 2007.

[22] Franklin, G. F., Powell, J.D., Emami-Naeini, A., *Feedback Control of Dynamic Systems*, Sixth Edition, Pearson, Upper Saddle River, NJ, 2010, Chap.6.

[23] Sobiski, D. J., and Cardullo, F. M., "Predictive Compensation of Visual System Time Delays," *AIAA Flight Simulation and Technologies Conference*, Monterey, CA, Aug. 1987.

[24] Thurling, A. J., "Improving UAV Handling Quality Using Time Delay Compensation," MS Thesis, AFIT/GAE/ENY/00M-01, Graduate School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH, 2000.

[25] Smith, R. E., and Sarrafian, S. K., "Effect of Time Delay on Flying Quality: An Update," *Journal of Guidance, Control, and Dynamics*, Vol. 9, No. 5, 1986, pp. 578-584.

[26] Hodgkinson, J., "History of Low-Order Equivalent Systems for Aircraft Flying Quality," *Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 4, Jul-Aug. 2005, pp. 577-583.

[27] Morelli, E. A., "Identification of Low Order Equivalent System Models From Flight Test Data," NASA/TM-2000-210117, NASA Langley Research Center, VA, Aug.

2000.

[28] Berry, D. T., Powers, B. G., Szalai, K. J. and Wilson, R. J., "In-Flight Evaluation of Control System Pure Time Delays," *Journal of Aircraft*, Vol. 19, No. 4, 1980, pp.318-323.

[29] Bailey, R. E., Knotts, L., Horowitz, S., Malone, H., "Effect of Time Delay on Manual Flight Control and Flying Quality During In-Flight and Ground-Based Simulation," *AIAA Modeling and Simulation Technologies Conference*, Monterey, CA, Aug. 1987.

[30] Neal, T. P., and Smith, R. E., "An Inflight Investigation to Develop Control System Design Criteria for Fighter Airplanes," AFFDL-TR 70-74, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Dayton, OH, Dec. 1970.

[31] Neal, T. P., and Smith, R. E., "A Flying Quality Criterion for the Design of Fighter Flight-Control Systems," *Journal of Aircraft*, Vol. 8, No. 10, 1971, pp.803-809.

[32] Hodgkinson, J., Wood, J. R., and Hoh, R. H. "An Alternate Method of Specifying Bandwidth for Flying Quality," *AIAA Guidance and Control Conference*, San Diego, CA, Aug. 1982.

[33] Ricard, G. L., and Harris, W. T., "Lead/Lag Dynamics to Compensate for Display Delays," *Journal of Aircraft*, Vol. 17, No. 3, 1980, pp. 212-217.

[34] Sobiski, D. J., and Cardullo, F. M., "Predictive Compensation of Visual System Time Delays," *AIAA Flight Simulation and Technologies Conference*, Monterey, CA, Aug. 1987.

[35] Harris, J. J., and Black, G. T., "F-22 Control Law Development and Flying Quality," *AIAA 21st Atmospheric Flight Mechanics Conference*, San Diego, CA, July 1996.

[36] USAF TPS Textbook, *Handling Quality Design Guidance*, Chapter 16, Part 4 Flying Quality Testing, U.S. Air Force Test Pilot School, Edwards, CA, 1986.

[37] McRuer, D. T., *Aviation Safety and Pilot Control : Understanding and Preventing Unfavorable Pilot-Vehicle Interactions,* Committee on the Effects of Aircraft Pilot Coupling on Flight Safety, National Academy Press, Washington, DC, 1997, Chap. 2.

[38] Mitchell, D. G., and Hoh, R. H., "Development of Methods and Devices to Predict and Prevent Pilot -Induced Oscillations," AFRL-VA-WP-TR-2000-3046, The U.S. Air Force Research Lab., Jan. 2000, cited by : Mitchell, D. G., et al., "Evolution, Revolution, and Challenge of Handling Quality," *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 1, 2004, pp. 12-28.

[39] Smith, R. H., and Geddes, N. D. "Handling Quality Requirements for Advanced Aircraft Design: Longitudinal Mode," AFFDL-TR-78-154, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Dayton, OH, Aug. 1979.

[40] McRuer, D., Graham, D., Krendel, E. S., Reisener Jr., W., "Human Pilot Dynamics in Compensatory Systems: Theory, Models and Experiments with Controlled Element and Forcing Function Variations," AFFDL-TR-65-15, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Dayton, OH, Jul. 1965.

[41] Guo, L., Cardullo, F. M., and Kelly, L. C., "Advanced Transport Delay Compensation Algorithms: Results of Delay Measurement and Piloted Performance Tests," NASA/CR-2007-215096, NASA Langley Research Center, VA, 2007.

[42] Park, C., and Kim, Y., “The Leader-Follower Formation Flight of Fixed-Wing UAV by Real-time Onboard Communication,” *KSAS Fall Conference*, Jeju, Jeju Province, Korea, Nov. 2013.

국문 초록

현대의 전자식 비행제어 시스템은 복잡한 구조에 의한 시간지연을 내포하고 있다. 특히 무인기는 지상 조종사와의 데이터링크를 통한 전송 시간지연이 비행제어시스템 내부의 시간지연에 추가되어 나타난다. 이러한 시간지연은 비행성 저하와 PIO를 발생시킬 수 있으며, 이는 정밀조종을 요구하는 사격, 공중기동, 공중급유, 정밀접근 등에서 임무효율 저하를 가져오고 심할 경우 비행사고로 연결될 수 있다. 무인기의 자동화 수준이 높아짐에도 여전히 안전과 임무변경을 위한 조종사의 역할은 요구되고 있으며, 시험비행에는 반드시 요구되고 있다. 따라서 무인기에도 기존의 유인기에 적용되었던 비행성 규정(MIL-STD-1797A)의 적용이 필요하며, 개발을 위해서는 요구되는 기준을 만족해야 한다.

본 논문에서는 시간지연에 의해 발생 가능한 PIO(Pilot-Induced Oscillation)를 포함하여 저하된 무인기 조종사의 비행성에 대해 다루었다. 비행성과 PIO 경향성을 개선하기 위하여 상태공간 보상기법을 적용하였고, 시간지연으로 저하된 비행성이 개선되는 효과를 확인하였다.

본 논문에서는 Art-Tech ASK21 무인기의 비행성 개선을 위하여 최신 보상기법 중 상태공간 보상기법을 적용하였고, 비행성 규정에서 제안하는 Neal-Smith와 Bandwidth 기준을 만족하는지 판단하였다. 또한 PIO 경향성을 판단할 수 있는 Ralph Smith 기준을 적용하여 보상기법의 효과를 확인하였다.

분석 결과 상태공간 보상기법은 앞섬/뒤짐 보상기법에 비해 시간이 지남에도 월등한 비행성 개선효과를 나타내었고, PIO 경향성도 감소되어 고기동성 무인기의 시간지연 개선에도 효과적인 보상기법임을 확인하였다.

주요어: 비행성, 시간지연, 보상기 (보상기법), 무인기 (UAV 또는 UAS), PIO (조종사 유도 진동)

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