Research on the Neal&Smith Criterion Application on Aircraft Flight Control System Handling Qualities Assessment

Wei Guo

1Shanghai Aircraft Design and Research Institute, NO.5188 Jinke Road, 201210, Pudong, Shanghai, China

Email: guowei6@comac.cc

Abstract. This paper utilized Neal&Smith criterion to quantify handling qualities of some aircraft augmented with Control and Stability Augmentation System (CSAS) over the flight envelop. Some aircraft mathematical model which augmented by longitudinal pitch Rate Command-Attitude Hold (RCAH) controller are employed. The aircraft handling qualities are described in terms of transfer functions of the pilot mathematical model, which includes a pilot’s neuromuscular delay, phase and gain compensation terms. If desirable closed loop dynamic performance can be obtained by the pilot mathematical model described by transfer function characteristics, then the satisfactory closed loop dynamic performance will also be achievable for the human pilot with decent workload. Consequently, the assessment results can be used to identify CSAS controller’s satisfactory effect domain, and furthermore, in aid of CSAS gain scheduling strategy design.

1. Introduction

Aircraft handling qualities tend to be quantitatively expressed rather than in terms of pilot’s opinion during the aircraft Control and Stability Augmentation System (CSAS) design and test process. Neal&Smith criterion is one of the existing aircraft handling qualities assessment criterion, which is developed in aid of the design of an airplane flight control system’s dynamic characteristics. Usually, several criterion, such as Gibson&Bandwidth criteria, C’ and Control Anticipation Parameter (CAP), can also be applied simultaneously for ensuring satisfactory dynamic response characteristics[1] [2]. Neal&Smith criteria estimates aircraft handling qualities on the basis of pilot mathematical model compensation[3]. Some certain pilot flight mission which related with different flight phases, need more stringent requirements to complete the tasks successfully. The specification requirements are stated in respect of airplane classification, flight phase categories and handling qualities levels. Usually, those missions requiring similar handling qualities are grouped into three flight phase categories (e.g. flight phase Category A, B, and C)[4] [5]. This paper applied Neal&Smith criterion to quantify handling qualities of some aircraft augmented with a CSAS controller over the flight envelop (F) in category B. The assessment results can be used to identify CSAS controller’s satisfactory effect domain (1F1), and furthermore, in aid of CSAS gain scheduling strategy design.

2. Neal&Smith Criterion

Neal&Smith criterion shows a critical measure of pilot’s handling perception for the pitch tracking task, which is assumed that pilot model trims the gain and phase characteristics to minimize aircraft closed loop resonance and the low frequency droop[3]. If desirable closed loop dynamic performance
can be obtained by the pilot mathematical model described by transfer function characteristics, then the satisfactory closed loop dynamic performance will also be achievable for the human pilot with decent workload [4].

2.1. Transfer function

In order to apply Neal&Smith criterion to assess the handling qualities of some aircraft augmented with CSAS, an aircraft and pilot closed-loop system models equation (1) is conducted in figure 1. The aircraft handling qualities are described in terms of transfer functions of gain and phase compensations in this situation. The pilot model transfer function is described as equation (2), which includes a pilot’s neuromuscular-delay, phase and gain compensation terms[6][7].

\[ T(s) = F_p(s) \cdot \frac{\theta(s)}{\delta_{elevator}(s)} \]  

(1)

\[ F_p(s) = K_p \cdot P_d \cdot \frac{(1+sT_p)}{(1+sT_{p2})} \]  

(2)

Where,

- \( T(s) \) equation (1), is pilot and aircraft transfer function, where \( \frac{\theta(s)}{\delta_{elevator}(s)} \) describes the aircraft pitch attitude \( \theta(s) \) response to the elevator.
- \( F_p(s) \) equation (2), is the pilot mathematical model.
- \( K_p \) is pilot gain compensation term.
- \( P_d \) is a time delay. Here the pilot’s neuromuscular-delay is described as
  \[ P = \frac{s^2 - 20s + 133}{s^2 + 20s + 133} \]
  in 2\(^{nd}\)-order transfer function form.
- \( \frac{(1+sT_p)}{(1+sT_{p2})} \) is phase compensation.

![Figure 1. Aircraft and pilot closed-loop system model structure](image)

2.2. The criterion

For flight phase Category B, minimum bandwidth \( \omega_{bw} = 1.5 \text{rad} \cdot s^{-1} \) is determined. The criterion limiting values for the handling parameters are defined as shown in table 1.

**Table 1.** Criterion boundaries

| Characteristic Parameter                  | Value                  |
|------------------------------------------|------------------------|
| Minimum \( \omega_{\text{bandwidth}} \) at phase -90deg | \( 1.5 \text{rad} \cdot s^{-1} \) |
| Maximum low frequency droop \( F_{\text{droop}} \) | -3dB                   |
| Closed-loop resonance                    | The best minimum peak value that can be achieved |
3. Pilot model compensated aircraft

In the basis of the transfer function equation (1) and (2) in section 2.1, the basic aircraft open loop $T_{openloop}(s)$ transfer function (3) and the closed-loop $T_{closedloop}(s)$ transfer function (4) can be obtained.

For $T_{closedloop}(s)$, the $\frac{\theta(s)}{\delta_{elevators}(s)}$ term is derived from some aircraft mathematical model augmented with a longitudinal pitch Rate Command Attitude Hold (RCAH) controller. This RCAH controller ($C_i$) is designed based on one fixed equilibrium point of flight and aircraft condition (airspeed, altitude, C.G, Flight Condition, etc.) in the form of damping ratio decreases the pilot compensation in order to achieve 1.5rad·s$^{-1}$ closed-loop bandwidth. Meanwhile, the improvement of damping ratio decreases the closed loop resonance peak efficiently. Both of these endow the closed-loop aircraft with the Level 1 handling qualities in Neal&Smith Criterion.

4. Neal&Smith Criterion Check

As the full-compensation pilot model conducted above, the aircraft handling qualities can be assessed against the criterion chart. From gain and phase characteristics assessed in Nichols chart, the parameters can be obtained as follows:

- Resonance peak (closed loop)=10.4 dB
- Pilot phase compensation at 1.5rad·s$^{-1}$=23 deg

Figure 2 shows Neal&Smith assessment comparison, which indicates open-loop aircraft with Level 3 handling qualities for the flight Phase Category B. For the closed-loop aircraft short period mode, an increased natural frequency effectively reduced the pilot compensation in order to achieve 1.5rad·s$^{-1}$ closed-loop bandwidth. Meanwhile, the improvement of damping ratio decreases the closed loop resonance peak efficiently. Both of these endow the closed-loop aircraft with the Level 1 handling qualities in Neal&Smith Criterion.

5. Assessment of Aircraft with RCAH controller ($C_i$) over Flight Envelop ( )

The handling qualities assessment of the aircraft augmented by $C_i$, which is implemented on a series of aircraft models over F, is conducted systematically. The main purpose is to identify $C_i$’s satisfactory effect domain $F_i$, which can be in aid of the further gain scheduling strategy design. The handling qualities assessment results of the series of open-loop (basic) aircraft, as well as the closed-loop (augmented) aircraft models with $C_i$ over F are plotted in figure 3.

Figure 3 shows the change in Neal&Smith parameters along with variation in altitude and airspeed, which can be analyzed in two cases.

- Case 1: Varying altitude at constant airspeed
  It can be observed that aircraft augmented with $C_i$ is more sluggish at the higher altitude, and the stronger Pilot Induced Oscillation (PIO) tendency introduced. Accordingly, pilot compensation and resonance peak amplitude increased as altitude rising, which lead to a handling qualities degraded trend.

- Case 2: Varying airspeed at constant altitude
  Increasing airspeed at constant altitude is less sluggish, due to the resonance peak drops with bigger damping ratio in pitch oscillations. Accordingly, pilot compensation and resonance peak amplitude decreased as airspeed increasing, which lead to a satisfactory handling qualities trend.

Consequently, $F_i$ can be identified approximately as shown in figure 4, by relocating these equilibrium points of the the aircraft augmented by $C_i$ in figure 3 back to F chart.
Figure 2. Neal&Smith criterion assessment comparison

Figure 3. Neal&Smith parameters of controller with change in altitude and airspeed.
6. Conclusions
This paper applied Neal&Smith criterion to quantify handling qualities of some aircraft augmented with $C_g$ over $F$ in category B. With varying flight condition parameters (altitude and airspeed), the basic aircraft handling qualities are much different from the augmented one. Instead of representing natural response of the basic one, the augmented aircraft handling qualities assessed by Neal&Smith criterion more depend on the equilibrium point which the flight controller is designed upon. For the future research direction, the second equilibrium point in the uncovered area of $F$ could be chosen to design the second local controller. Furthermore, the gain scheduling strategy can be designed motivated by this research for the purpose of full coverage.

![Figure 4. $F_1$ identification](image)

This paper is on the assumption of constant stability and control characteristics throughout $F$. The contents and analysis of handling qualities and performance can be extended to the different flight conditions and flight mission based on the mathematical model, such as crosswind landing, single engine failure and takeoff phase configurations.

7. References
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