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# Simulator Evaluation of a Medium-Cost Variable Stability System for a Business Jet

A. Mirza, M. M. van Paassen, T. J. Mulder and M. Mulder

This paper discusses an approach to convert the longitudinal dynamics of the Cessna Citation into a variable stability platform using response feedback, thereby enabling it to take different positions on the Control Anticipation Parameter (CAP) handling quality criterion. The different positions of an aircraft on the criterion reflect different handling qualities, short period damping ratios and CAP. An experiment is performed to investigate whether the handling qualities found analytically, as a result of a variable stability control law, match those found practically from pilot tests on an aircraft simulator. Results of the experiment show that pilots are able to sensitive to even small changes in aircraft dynamics caused by the variable stability system, however, their judgment of the handling qualities does not always agree with handling qualities predicted analytically from the CAP criterion.

## Nomenclature

$\alpha$	= Angle of attack [rad]	CitAST	= Citation Analysis and Simulation Toolkit
$\omega_e$	= Equivalent natural frequency [rad/s]	D	= Aircraft feed-through matrix
$\omega_{sp}$	= Aircraft short period natural frequency [rad/s]	EE	= Equation Error
$\theta$	= Pitch angle [rad]	GUI	= Graphical User Interface
$\zeta_e$	= Equivalent damping ratio	HMI Lab	= Human Machine Interaction Laboratory
$\zeta_{sp}$	= Aircraft short period damping ratio	HOS	= High Order System
$K_q$	= Pitch rate feedback gain	HQ	= Handling Quality
$K_\alpha$	= Angle of attack feedback gain	IFS	= In-Flight Simulation
$u_a$	= Surface command from controller	LOES	= Low Order Equivalent System
$u_f$	= Surface feedback command	LOS	= Low Order System
$u_p$	= Surface command from pilot	OE	= Output Error
A	= Aircraft dynamic/state matrix	q	= Pitch rate [rad/s]
B	= Aircraft input matrix	RF	= Response Feedback
C	= Aircraft output matrix	VISTA	= Variable In-flight Simulator Test Aircraft
CAP	= Control Anticipation Parameter	VS	= Variable Stability
CH	= Cooper Harper	x	= Aircraft states

## I. Introduction

A Variable Stability (VS) aircraft allows variations of response characteristics and handling qualities of an aircraft, so that a pilot can determine suitability of these characteristics in actual flight [1]. By allowing for changing aircraft characteristics, the VS system has a diverse range of applications which include aircraft development, research of handling qualities, system tests and pilot training [1]. Perhaps the most important use of a VS system is its ability to change an aircraft's stability and flying characteristics to match those of another aircraft [2]. This is demonstrated by [3] in which a T-6A, a single engine turboprop, is made to simulate A-4 and F15 aircraft. Currently, Calspan's F-16 VISTA (Variable In-flight Simulator Test Aircraft), is the most advanced VS In-Flight Simulation (IFS) aircraft. The F-16 VISTA has been extensively used for new aircraft development, handling qualities research and systems development projects [1]. Given that there is a wide range of applications for a VS aircraft, we investigated whether the Cessna Citation II (jointly operated by TU Delft and the Netherlands Aerospace Center (NLR)) can be converted into a variable stability aircraft.

The response of an aircraft to an input signal can be defined by certain response characteristics. They include damping ratio, natural frequency and time constant of certain eigen motions [4]. These characteristics define the

aircraft's handling qualities. Thus, if one can change the aircraft responses, one can also change the handling qualities of the aircraft. One option for changing these characteristics is the application of a stability augmentation system [5]. There are several control approaches possible, one is to use feedback control [6]. A VS system with feedback control uses control laws to change the dynamics of an aircraft to simulate different aircraft response characteristics.

Today, the concept of the VS aircraft has progressed into IFS that are routinely used as an extension of ground-based simulators [1]. In-flight (VS) simulators can be broken down into many categories. Two such categories are dynamic simulators and performance simulators [7]. Dynamic simulators have control systems designed specifically to overpower the natural response of the aircraft in order to control its dynamics. Alternatively, performance simulators can match the performance characteristics of different aircraft. Furthermore, dynamic simulators have two categories [8], a response feedback (RF) system and a model-following system. The response feedback system senses the response of an aircraft and feeds it back to the aircraft to change its control input. By varying the feedback gains, various responses and aircraft characteristics are achieved. The model-following system "uses on-board computers to simulate desired responses to pilot inputs. It then converts these into the surface deflections required to force the actual aircraft response to follow the on-board computer model. All of this happens in real-time." [3]. The present research focuses on dynamic simulators using a response feedback system.

One possible application of a VS aircraft is in pilot training. Test pilots need to learn to handle and evaluate a large range of aircraft characteristics, and they need to be able to classify handling qualities. Aircraft handling qualities can also be predicted by the application of handling quality criteria. One such criterion is the Control Anticipation Parameter (CAP) [9] which focuses on the short period pitch response of the aircraft.

Theoretically, a VS system (using a response feedback control law) should be able to place a single aircraft on different positions on the CAP handling quality criterion. This can be extended to find an envelope of all positions an aircraft can cover on CAP criterion. The main goal of this research can be formulated as follows: *Can the Cessna Citation II, for its longitudinal dynamics, and with limited-authority control actuators, be converted to a variable stability platform using a response feedback system?*

To assess its practicality, the VS system will be implemented on the fixed-base flight simulator at Delft University of Technology. This objective can be broken down as follows. First, what is the range of handling qualities that can be achieved using response feedback? Second, do the handling qualities found analytically, from computer-based simulations, match those found practically, from pilot evaluations on an aircraft simulator?

The paper first discusses the theory critical to this research. Then some initial computer simulations are performed to check the effects of Mach number, altitude and feedback gains on aircraft handling qualities. Results from these simulations were analyzed to help narrow down experimental conditions. The third section elaborates on the experiment designed to answer the research questions. The fourth part states the results of the experiment and discusses some of the key findings, followed by conclusions and recommendations.

## II. Background

### A. Response Feedback

Fundamentally, a RF system uses an aircraft's response and feeds it back to the aircraft in order to modify its control inputs. Figure 1 shows a typical configuration of this system. Though this applies to the linear model, in case this model is sufficiently close to the non-linear real aircraft dynamics, similar changes in aircraft behavior can be expected.

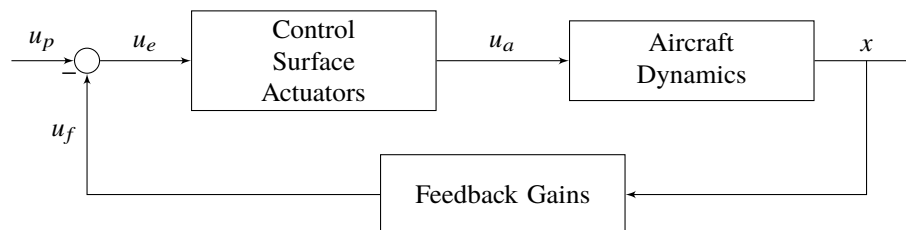


Fig. 1 Response feedback system.

The mathematics defining this method show its simplicity [10]. A linear approximation of the motion of any aircraft

can be expressed in a state space format by Eq. 1.

$$\dot{x} = Ax + Bu_e \quad (1)$$

The  $A$  matrix in Eq. 1 represents the aircraft dynamics, its coefficients determine the aircraft model's stability derivatives. Changing these coefficients changes the aircraft model.

A feedback loop, and the effective input to the aircraft  $u_e$  is composed of a feedback component and the pilot's (possibly scaled) input, Eq. 2

$$u_e = u_p - u_f = u_p - K^T x \quad (2)$$

Substituting Eq. 2 into Eq. 1 gives Eq. 3

$$\dot{x} = Ax + B(u_p - K^T x) = (A - BK^T)x + Bu_p \quad (3)$$

From Eq. 3 it can be seen that by changing the feedback gain matrix  $K$ , the matrix  $A$ , governing aircraft dynamics, changes to  $A - BK^T$ . Varying the feedback gains change the value of this matrix thereby enabling various aircraft responses and aircraft dynamic characteristics to be achieved. These characteristics are then evaluated using handling quality criteria.

## B. Control Anticipation Parameter

The MIL-STD-1797A, Flying Qualities of Piloted Aircraft [11] defines several criteria on which an aircraft's HQ can be judged. One such criterion is the Control Anticipation Parameter (CAP) [9]. CAP is a HQ criterion which focuses on the short period pitch response of aircraft. CAP is defined for an un-augmented aircraft as the ratio of initial pitch acceleration to the steady state normal acceleration [9] and is expressed by Eq. 4.

$$CAP = \frac{\ddot{\theta}(0)}{n_{z,ss}} \quad (4)$$

where

$$n_{z,ss} = \frac{V}{g} q_{ss} \quad (5)$$

The magnitude of CAP gives pilots an indication of change in steady-state normal acceleration from aircraft's initial pitching acceleration. This is because there is a lag between a pilot giving the input and the aircraft attaining final steady-state normal acceleration. For example, aircraft with a large CAP have large initial pitching accelerations compared to final steady-state normal accelerations. The pilot senses this large initial pitching acceleration and reduces control inputs to avoid the anticipated large normal acceleration. As a result, pilots typically *undershoot* the desired flight path and classify the aircraft as being fast, abrupt, and sensitive [12]. And vice versa for aircraft with low CAP, pilots would typically classify the aircraft as being sluggish.

For an aircraft with a classical longitudinal second order response (Eq. 6), CAP can be calculated using aircraft short period characteristics. This is shown in detail by [13] and expressed as Eq. 7.

$$\frac{q}{\delta_e} = \frac{K_\theta(s + \frac{1}{T_{\theta_2}})}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2} \quad (6)$$

$$CAP \approx \frac{\omega_{nsp}^2}{n/\alpha} \approx \frac{\omega_{nsp}^2}{\frac{V}{g} \frac{1}{T_{\theta_2}}} \quad (7)$$

As a HQ criterion CAP is expressed in conjunction with the aircraft's short period damping ratio. The CAP HQ criterion is sub-categorized by aircraft classes (I, II, III, IV) and flight phases (A, B, C); and is segmented into three levels of acceptability (Level 1, Level 2, Level 3) with Level 1 indicating flying qualities adequate for mission flight, Level 2 expressing flying qualities adequate to accomplishing the mission with increased pilot workload and Level 3 pointing to flying qualities which cause excessive workload on the pilot and cause inadequate mission effectiveness. These sub-categories are elaborated in MIL-STD-1797A [11].

### C. Low Order Equivalent System

Bihle's development of CAP was done for un-augmented aircraft for which control system dynamics effects were assumed to be negligible [13]. This means that only the basic second order short period dynamics were considered, otherwise known as a Low Order System (LOS). With addition of even simple dynamics, such as an elevator servo, to the aircraft short period dynamics the initial response of the aircraft changes. Such a system is referred to as a High Order System (HOS). For LOS the aircraft's initial pitch acceleration is also the maximum pitch acceleration. This is not the case for a HOS where the aircraft's maximum pitch acceleration occurs some time after  $t = 0$ , and the CAP HQ criterion breaks down. This is because CAP uses initial pitch acceleration to calculate aircraft's position on the criterion. This effect is shown in Figure 2.

Use of a Low Order Equivalent System (LOES) provides a means to re-use CAP criterion. DiFranco [14] in his experiment showed that "the aircraft's short period response to step stick force inputs can be reasonably well represented by a time delay and an equivalent second-order term". This is expressed by Eq. 8 and shown by Figure 3.

$$\frac{q}{\delta_e} = \frac{K_\theta(s + \frac{1}{T_{\theta_2}})e^{-\tau s}}{s^2 + 2\zeta_e\omega_e s + \omega_e^2} \quad (8)$$

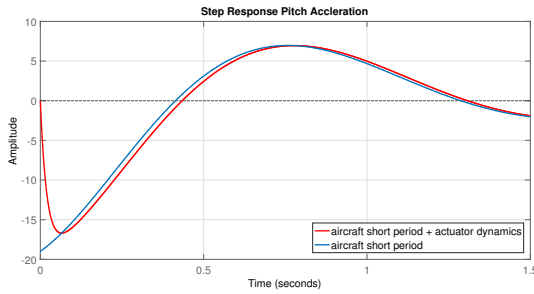


Fig. 2 Pitch acceleration LOS and HOS.

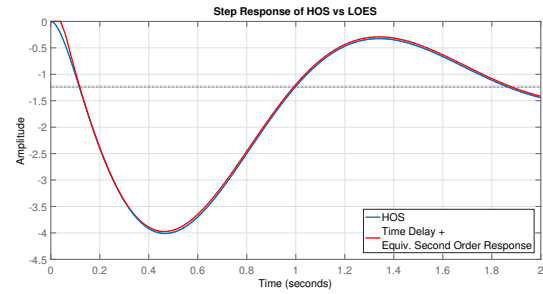


Fig. 3 Pitch acceleration HOS and LOES.

This idea of equivalent models was developed into LOES in [15]. The equivalent system is created by matching complex frequency response of a HOS with a classical LOS and a time delay term to derive equivalent short period frequency and damping ratio. Usually this frequency matching is done at frequencies from 0.1 to 10  $rad/s$ , which are also associated with aircraft manual control [16].

For this research the LOES approach suggested by Morelli [17] was used. The approach uses two equations; the Equation Error (EE) and Output Error (OE) in frequency domain. The most effective results are obtained by using the EE results as starting values for OE problem. This two-step approach helps retain favorable statistical properties of the OE parameter estimates [18] and avoids convergence problems that might result from starting values of the parameters being far from the minimum. Both the EE and OE are optimization problems which vary LOES parameters to find the best parameters which help reduce a certain cost function. The approach re-parametrizes the Eq. 8 to Eq. 9, where the parameter relationships are stated in Eq. 10.

$$\frac{q}{\delta_e} = \frac{(b_1 s + b_0)e^{-\tau s}}{s^2 + a_1 s + a_0} \quad (9)$$

$$b_1 = K_\theta \quad b_0 = \frac{K_\theta}{T_{\theta_2}} \quad (10)$$

$$a_1 = 2\zeta_e\omega_e \quad a_0 = \omega_e^2$$

For OE, the parameters are adjusted so that the sum of squared OE, over  $m$  frequencies used in Fourier transformation, is minimized. This expression is given by Eq. 11.

$$J_{OE} = \frac{1}{2} \sum_{i=1}^m |\hat{q}_{E_i} - \hat{q}_i|^2 \quad (11)$$

Substituting  $s = j\omega$  in Eq. 9 transforms the transfer function into a frequency-response:

$$\tilde{q} = \frac{(b_1 j\omega + b_0)e^{-j\omega\tau}}{j\omega^2 + a_1 j\omega + a_0} \delta_e \quad (12)$$

The quantity  $\hat{q}_i$  is computed from Eq. 12 using estimated parameter values  $b_1, b_0, a_1, a_0$  and  $\tau$  along with measured  $\delta_e$ .

For EE (Eq. 9 with  $s = j\omega$ ) is written as Eq. 13.

$$-\omega^2 \tilde{q} = b_1 j\omega \delta_e e^{-j\omega\tau} + b_0 \delta_e e^{-j\omega\tau} - a_1 j\omega \tilde{q} - a_0 \tilde{q} \quad (13)$$

Parameters are adjusted so that the sum of squared EE, shown by Eq. 14, over the  $m$  frequencies used in the Fourier transformation, is minimized.

$$J_{EE} = \frac{1}{2} \sum_{i=1}^m |\omega_i^2 \tilde{q}_{E_i} - \omega_i^2 \hat{q}_i|^2 \quad (14)$$

The quantity  $\omega_i^2 \hat{q}_i$  is computed from Eq. 13 using estimated parameter values  $b_1, b_0, a_1, a_0$  and  $\tau$  along with measured  $\delta_e$ . Eq. 14 shows that the equation error cost function included frequency weighting on differences  $\tilde{q}_{E_i} - \hat{q}_i$ .

Additionally, Morelli also stresses the importance of using an input signal with a mix of high and low frequencies in order to minimize parameter correlations.

### III. Initial Considerations

To answer the research question, a preliminary analysis was done using the aircraft dynamics. The analysis focused on the effects of different feedback gains, variation in altitude and variation in Mach number on the position of aircraft on the CAP HQ criterion. These considerations helped confine the research by evaluating factors that might or might not have an effect on VS of the aircraft.

#### A. Aircraft Model

The choice of aircraft for this research was the Cessna Citation II, Model 550. The aircraft is a light business jet which has been converted into a research aircraft by Delft University of Technology and has been used by the university for several years in wide range of research areas. The aircraft dynamics were obtained using Citation Analysis and Simulation Toolkit (CitAST) [19]. For the purpose of this research only the longitudinal short period dynamics were considered. Elevator actuators are the only added dynamics. These are modeled by a first order transfer function:

$$H_{elevator} = \frac{13}{s + 13} \quad (15)$$

Since the aircraft will be flown manually during the validation phase of research, low Mach numbers have to be used. For practical reasons, altitudes up till 7,000 meters were used for preliminary analysis.

#### B. Variable Stability Controller

The VS system can simply be constructed using RF. The block diagram given by Figure 4 shows the VS controller. It is the pictorial representation of Eq 3, repeated here for convenience as Eq 16. Here the two feedback signals are pitch rate ( $q$ ) and angle of attack ( $\alpha$ ). A combination of these two feedback signals are used in Eq 16 to get new aircraft longitudinal short period dynamics. These dynamics are then used to obtain the position of aircraft on CAP HQ criterion.

$$\dot{x} = Ax + B(u_p - K^T x) = (A - BK^T)x + Bu_p \quad (16)$$

where  $u_p$  is the pilot input.

#### C. Effect of Feedback Gain

Following the theory in Section III.B effect of changing  $K_q$  and  $K_\alpha$  was observed. The data points on Figure 5 indicate the achievable position of aircraft due to different combinations of these two state feedbacks.

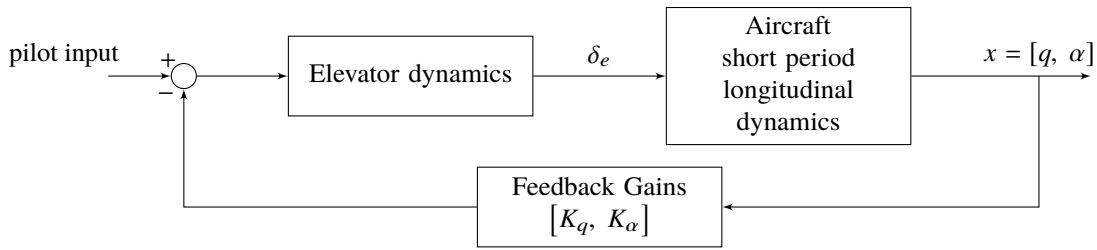


Fig. 4 VS controller.

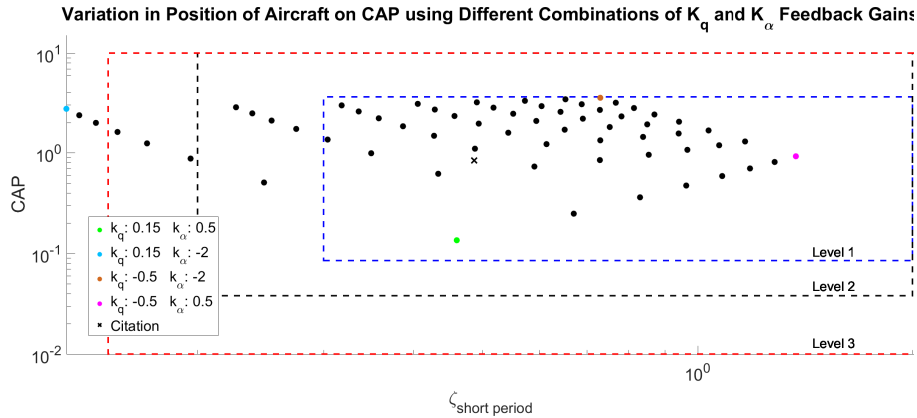


Fig. 5 Achievable aircraft positions on CAP HQ criterion using combination of  $q$  and  $\alpha$  state feedback.

#### D. Effect of Mach number

To check the effects of variations in the aircraft CAP HQ criterion due to Mach number and altitude, four test points were selected. These test points represent different positions of the aircraft on the CAP HQ criterion. The points were arbitrarily chosen, and were generated using a combination of  $q$  and  $\alpha$  state feedback gains. The effect of varying Mach numbers while keeping all other factors constant was observed. Five Mach numbers 0.25, 0.3, 0.35, 0.4 and 0.45 were chosen. The simulation was run at a constant altitude of 5,000 meters. Results of the simulation are presented in Figure 6. The figure shows that although there is variation in CAP and damping due to changing Mach numbers, this variation is not too large and does not cause a significant change in position of aircraft on CAP criterion.

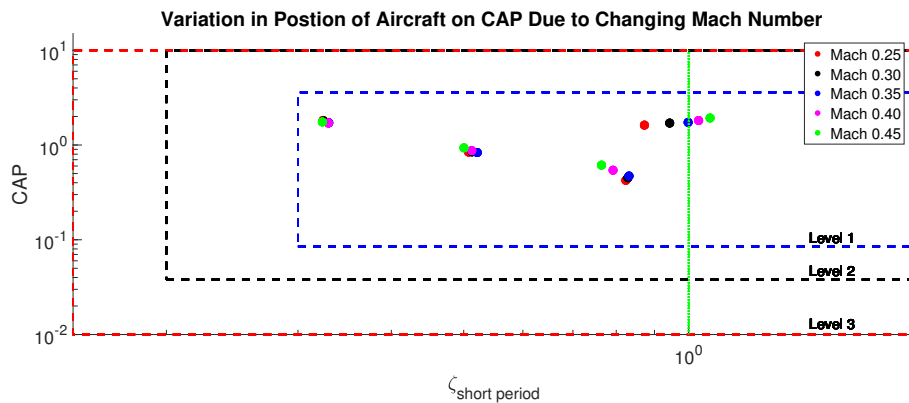


Fig. 6 Change in position of aircraft on CAP due to variation in Mach number.

## E. Effect of Altitude

Similar to the effect of changing Mach numbers, effect of varying altitude on aircraft's position on CAP was observed. Four altitudes 2000, 4000, 6000, and 8000 meters were chosen. The simulation was run at a constant Mach of 0.3. The results of simulation are presented in Figure 7. Similar to the case of Mach number, variations in altitude show a limited change in CAP and damping. Again, deviations are minor.

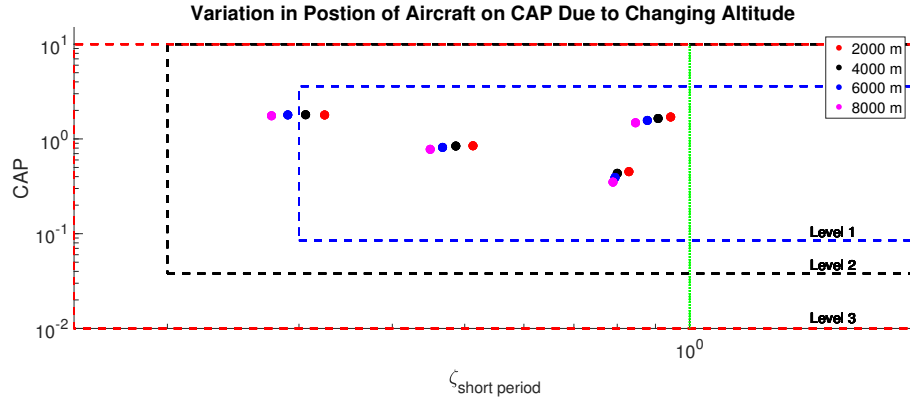


Fig. 7 Change in position of aircraft on CAP due to variation in altitude.

## IV. Experiment

### A. Apparatus

The experiment was performed at Delft University of Technology's Human Machine Interaction Laboratory (HMI Lab). The HMI Lab can be used as a fixed base simulator for an aircraft. Figure 8 shows the layout of the aircraft configuration. The lab is split up into an observation room, where the researcher is controlling the experiment, and an experiment room, where aircraft simulation is taking place. The experiment room consists of a fully adjustable aircraft seat, a control-loaded hydraulic side stick, a set of electrically control-loaded rudder pedals, two throttle levels, flap levels and a speed brake lever. There are two 18 inch LCD panels for instrument displays with a  $1280 \times 1024$  pixel resolution. Outside visuals are displayed using three DLP projectors with HD resolution. The projectors use a three-sided projection screen, and cover a field of view of over  $180^\circ$ , providing a truly immersive experience.

The aircraft model was a non-linear model of the Citation I dynamics[19], combined with a non-linear model of the aircraft elevator actuators [20]. This best represents the state of the experimental fly-by-wire system currently in the university's Citation II laboratory aircraft. That system uses the standard autopilot actuators of the aircraft, in combination with a modified experimental autopilot unit, that could be controlled with signal from the experimental measurement and control system installed in the aircraft. The actuator model was derived on the basis of first principles from measurements of the aircraft's actuation system and specification data for the hardware. The responses of the linear and non-linear models will be compared later. If the response of the linear model is sufficiently close to the non-linear model, the linearity assumption used in the CAP analysis can be considered valid.

### B. Experiment Design

For this research, changes caused by the VS system were primarily focused on the aircraft short period mode, more specifically, the aircraft initial pitch response (CAP) and pitch damping. The experiment and accompanying questionnaire should be designed such that the initial pitch response and damping are easily registered by the pilot and subsequently reflected in their answers on the questionnaire. For this reason the experiment was designed to achieve the following goals:

- 1) To identify whether pilots experience changes caused by VS system.
- 2) Determine to what extent can pilots identify the changes in aircraft HQ, CAP and damping?
  - Can pilots identify small changes in HQ caused by slight variations in VS configurations?





**Fig. 8 HMI Lab aircraft configuration Layout.**

- Can pilots specifically identify changes in damping and CAP when there is a large change in aircraft dynamics?
- 3) Pilots should be able to register enough information about aircraft motion to fill out the questionnaire accurately.

### **Experiment - Climb Cruise Descent**

The experiment consists of several runs under different VS configurations. For each run pilots perform two main tasks while maintaining a climb/descent rate of  $\pm 500$  to 1000 feet per minute:

- 1) Climb up an altitude of +1000 feet at a climb rate between 500 to 1000 ft/min.
- 2) Climb down an altitude of -1000 feet at a descent rate between -500 to -1000 ft/min.

These two maneuvers, though simple, achieve the goal set out for the experiment. The rationale behind this is simple:

- The most prominent effects of change in CAP will be experienced during pitch up/down.
- By making pilots climb/descent we are causing them to pitch up/down. This will allow to get a comprehensive idea about CAP.
- By giving them a climb/descent rate to maintain, they are given a task that will help them figure out aircraft damping and generally the aircraft HQ.
- Performing the same tasks for different VS configurations will allow us to compare the changes experienced by the pilots under each configuration.

### **Questionnaire**

The questionnaire was divided into three sections. All sections contained rating scales to help identify different areas of interest of the research. The first section focused on aircraft pitch motion. The second section focused on aircraft pitch damping under current configuration compared to the inherent Cessna Citation damping. The last section contained the Cooper-Harper Rating Scale.

Different parts of the questionnaire were aimed at different parts of the experiment goal. The sections on aircraft pitch motion and pitch damping were aimed to get an approximation of whether pilots can identify different CAP and damping ratio values for different VS configurations. The Cooper-Harper Rating Scale would not only help identify different HQs as per pilot opinion, but also help distinguish between configurations that will be close together.

### **Initial Conditions**

All runs for the experiment start at the same initial conditions. It was established in the preliminary analysis that changes

in altitude and Mach number do not have a significant effect on the position of aircraft on CAP criterion. Hence, there is no constraint on either. However, in the interest of maintaining consistency, all simulations started at 4000 meters and Mach 0.3.

Test pilots who participated in the experiment were from the Netherlands and were used to flying around Schiphol International Airport. To give pilots a sense of familiarity, outside visuals were around Schiphol International Airport.

Since the goal of the experiment is to identify aircraft characteristics and handling qualities, external disturbances like turbulence are not included.

Lastly, the simulation will always start at straight and level flight, in a stable situation and using inherent Cessna Citation dynamics. This will give time to pilots to get re-acquainted with the aircraft inherent dynamics he/she would need to compare proceeding configurations with. These initial conditions are given in Table 1.

**Table 1 Experiment initial conditions**

Flight Condition	Straight and Level
Altitude	4000 meters ( $\approx$ 13000 feet)
Mach	0.3
Turbulence	Nil
Outside Visual Coordinates	52.31 , 4.77

### C. Test Point Selection

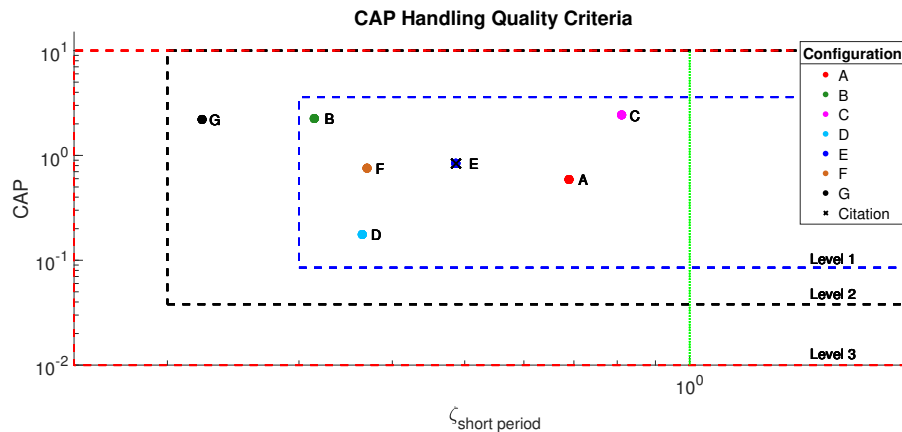
To validate results only a few test conditions were selected for the experiment. Selected test points are shown in Figure 9. The dashed green line indicates a damping ratio of 1. Generally, for an aircraft the damping ratio does not exceed 1. The CAP, damping ratios and  $K_q$ ,  $K_\alpha$  feedback gains used to obtain these points are given in Table 2.

**Table 2 VS test configurations.**

VS configuration	$K_q$	$K_\alpha$	$\zeta$	CAP
A	-0.05	0.3	0.69	0.586
B	0	-1.35	0.32	1.833
C	-0.45	-1.0	0.81	1.820
D	0.16	0.45	0.37	0.175
E (Baseline)	0	0	0.487	0.84
F	0.07	0.0	0.37	0.752
G	0.08	-1.4	0.22	1.65

Test points were divided into two categories in order to achieve the goals set out for the experiment. VS configurations A, E and F make up the first category, and will be identified as **Close Test Points**. These configurations were relatively close to each other. Their purpose being to check whether pilots can identify differences in the HQ of configurations

that have small variations among them. The second category contained VS configurations B, C, D and G. Their purpose was to check if pilots can identify how CAP and damping changed for different configurations. They will be referred to as **Far Test Points**. The test points contained a good mix of high and low CAP and damping. Though there are several more points that are very desirable to test, a compromise has to be made in order to avoid too many test conditions.



**Fig. 9 VS test configurations. The dashed green line indicates damping ratio of 1.**

#### D. Participants

A total of three participants took part in this experiment. The participants were licensed commercial jet pilots with extensive experience on Cessna Citation. The pilots had many years of flying experience and were well versed in different rating scales used in the aviation industry, especially the Cooper Harper Rating Scale.

#### E. Experiment Procedure

The experiment was broken down into four parts; briefing, baseline familiarization, testing VS and questionnaire. The last three parts were repeated till all runs were completed. In total the experiment consisted of 17 runs distributed over the 7 test configurations mentioned in Table 2. It should be noted that the primary flight display had units in imperial system, therefore all communication with pilots was done in imperial units. From start to finish the experiment lasted two hours, where each run took under ten minutes to complete.

##### 1. Briefing

All pilots received a short briefing before the start of the experiment. In it they were informed about the purpose of the experiment. They were told how the experiment will go about and given instructions about the tasks that needed to be performed (climb up and climb down) and the variables that needed to be kept within limits (climb/descent rates). The briefing further included a small overview of the CAP criterion, information on the aircraft model and available control inputs. During this briefing the rights of participant were also given in writing followed by a standard safety briefing.

##### 2. Familiarization

At the start of the experiment a familiarization run was performed. This was to let pilots get familiar with Cessna Citation inherent dynamics and responses, and establish a baseline with which they will compare proceeding VS configurations. This run started on initial conditions, mentioned in Table 1, followed by the two tasks that would be performed during each run. Of course, with 17 runs ahead this familiarization was performed during the start of each run. The first familiarization run took a good ten minutes. However, by the third cycle this part of the run took under 1 minute.

##### 3. Testing VS

Once pilots got familiarized with the baseline Citation dynamics, a new VS configuration was selected. Pilots were given some time to get the aircraft under control and maintain a stable position under the new configuration. Afterwards,

the pilot was asked to perform required tasks. They were given freedom to take as much time they felt necessary to achieve the tasks, while trying their best to maintain desired climb/descent rates. To evenly distribute workload, easy and difficult configurations were spread out accordingly. The order in which the configurations were simulated is given in Table 3.

**Table 3 Order in which the VS configurations were simulated.**

<b>Run</b>	1	2	3	4	5	6	7	8	9
<b>Configuration</b>	A	B	C	D	A	B	D	E	F
<b>Run</b>	10	11	12	13	14	15	16	17	-
<b>Configuration</b>	G	E	B	F	A	G	C	D	-

#### 4. Questionnaire

Once pilots completed the required tasks for a VS configuration the simulation was paused. Pilots were then given the questionnaire pertaining to current VS configuration. This was considered a single run. Upon finishing the questionnaire, the process was repeated until all 17 runs were completed.

#### F. Hypothesis

The hypotheses for the outcome of the experiment are:

- 1) Pilots will be able to identify the change in HQ for each VS configuration.
- 2) Close Test Points:
  - 1) Pilots will not be able to accurately distinguish any change in CAP and damping due to their close proximity to each other,
  - 2) Differences in HQ for these configurations will be seen in Cooper-Harper Rating Scale.
- 3) Far Test Points:
  - 1) Pilots will be able to distinguish between different CAP and damping for each set of configurations.
  - 2) Pilot will not be able to guess the exact value of CAP and damping, but will be able to indicate the general direction of change from baseline.
  - 3) These configurations are on the boundary of Level 1 and Level 2 and pilots would either mark them very high on Level 1 or very low on Level 2.

### V. Results and Discussion

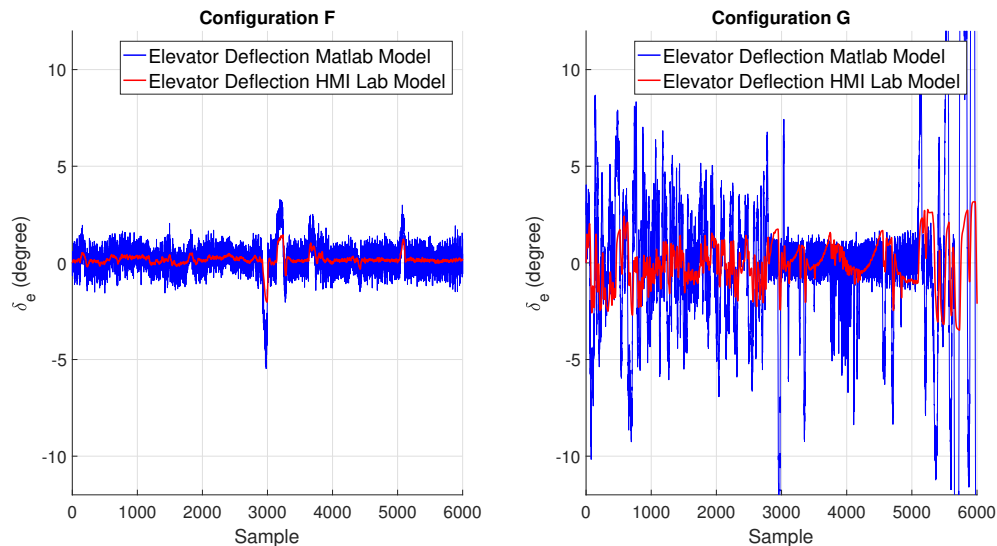
The results are discussed into four parts; The linearity assumption, Close Test Points, Far Test Points and combined handling qualities of all VS configurations. The Close Test Points and Far Test points are followed by performance matrices to evaluate aircraft performance and main pilot comments. We conclude with a discussion of the results.

#### A. Linearity Assumption

The linearized model of the Cessna Citation was used to construct the VS system. All computer-based calculations from finding aircraft damping and CAP to its position on CAP HQ criterion were done using this model. However, the experiment performed on the HMI Lab uses a non-linear model of the aircraft elevator actuators [20]. It was essential to compare the response of the linear and non-linear model for all seven configurations.

With this aim, an input signal was supplied to the linearized Cessna model (in Matlab) as well as to the aircraft model in HMI Lab, and the elevator deflection produced by these models is compared. The input signal used for each configuration was the input measured from pilot 3, while pilot 3 was randomly chosen. Figure 10 shows the elevator deflection caused by linear Matlab model and the HMI Lab model for VS configuration F from Close Test Points and VS configuration G from Far Test Points. From the figure it can be clearly seen that for configuration F, the variation in elevator deflection of Matlab and HMI Lab model is significantly smaller than the variations in configuration G.

The large difference in elevator deflections in configuration G would result in the linear assumption losing validity for this configuration. Having taken a closer look at results from all VS configurations A to G it was seen that a few configurations from Far Test Points (B and G) had a tendency to deviate from the linear model.



**Fig. 10 Elevator deflection for configuration F and G caused by Citation Matlab and HMI Lab model. The data were obtained from the experiment by Pilot 3.**

### B. Close Test Points

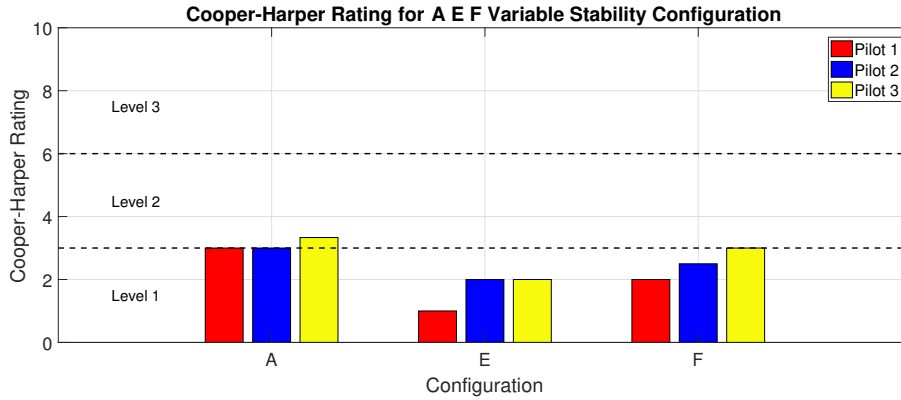
It was hypothesized that due to the close proximity of test points A, E and F, pilots would not be able to distinguish damping and CAP effectively. However, if pilots did feel any variation in HQ this would appear on the CH Rating Scale. This turned out to be true. Looking at the CH Rating Scale in Figure 11 it can be clearly seen that for the three configurations:

- Pilots did in fact register a change in HQ of the aircraft.
- All pilots show a similar trend in the HQ experienced for the configurations.
- Pilots found HQ pertinent to configuration E the best among the three. This configuration represents the inherent HQ of the Cessna Citation.
- Pilots 1 and 2 gave Level 1 to all three configurations. Pilot 3 varied slightly in the rating given.

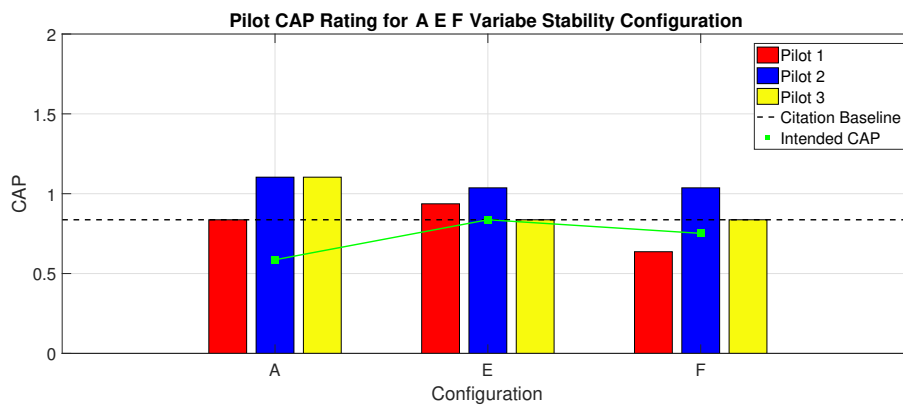
Figures 12 and 13 reflect positively on the hypothesis with regard to distinguishing CAP and damping. All pilots noticed small variations in CAP and damping, but were unable to correctly identify the direction of change of either.

### Performance Matrix for Close Test Points

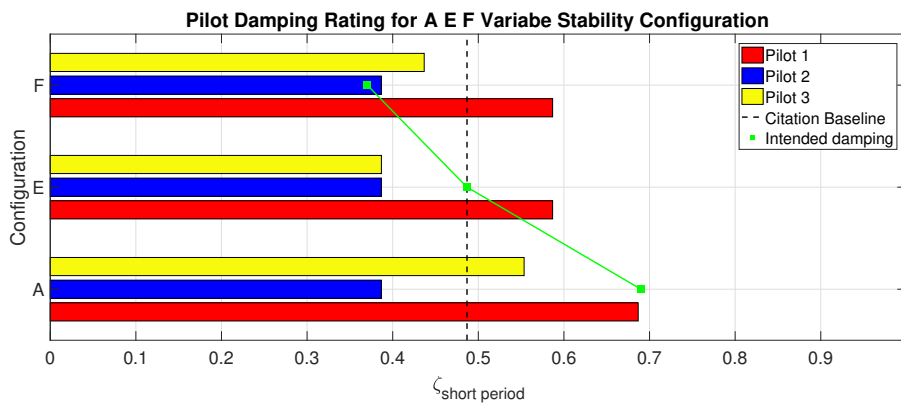
The target defined for pilots was to maintain a climb/descent rate  $\pm 500$  to  $1000$  ft/min. Essentially, the larger the deviation from this target, the more difficult it was to control the aircraft. Keeping this in mind, a performance matrix was constructed to see for how long pilots were able to stay within this target range for each configuration. Table 4 shows, as percentage, the time pilots were able to maintain target range for A, E and F configurations.



**Fig. 11** Cooper Harper Rating for A, E and F configurations.



**Fig. 12** Pilot CAP rating for A, E and F configurations.



**Fig. 13** Pilot damping ratings for CAP to A, E and F configurations.

From Table 4 it is clear that for all configurations pilots were able to maintain the target easily and for a large portion of the experiment. The results varied slightly for each configuration and for each pilot, but were mostly similar to each other. For Pilot 2 configuration E had the highest percentage, where as for Pilots 1 and 3 it was configuration F. Though for all pilots the remaining configurations were still comparable with the best configuration.

**Table 4 Performance matrix for Close Test Points showing percentage of time pilots were within target.**

Pilot	Configuration		
	A	E	F
Pilot 1	86%	82%	93%
Pilot 2	92%	98%	94%
Pilot 3	87%	83%	91%

### Main Pilot Comments

For configuration A, all pilots agreed that this configuration was easily controllable, especially using a low gain strategy. Pilot 1 commented that it was *slightly* more difficult to obtain and maintain the target. This comment by the pilot is in congruence with the aforementioned hypothesis as it confirms Pilot 1 experienced a difference in HQ. Pilot 2, on the other hand, said that the aircraft was *slightly* less damped than run 13 (configuration F). This was not true, as configuration A actually had a slightly higher damping than F.

For configuration E comments of all pilots reflected that the aircraft behavior felt *almost* like the original (which it was) and that the configuration had excellent controllability. Pilot 1 said that the aircraft felt *slightly* more damped than the original, while Pilot 2 said that damping was *slightly* less. Similar to configuration A it was apparent that the pilots could not accurately pinpoint the change in response characteristics. Similar to the previous two configurations, for configuration F all pilots agreed that the aircraft showed good controllability and registered a slight variation in handling from the baseline.

These pilot comments for A, E and F configurations match the expectation from the hypotheses made for Close Test Points. That is, pilots will be able to identify difference in HQs. However, they will not be able to accurately judge how CAP and damping changed during the configurations.

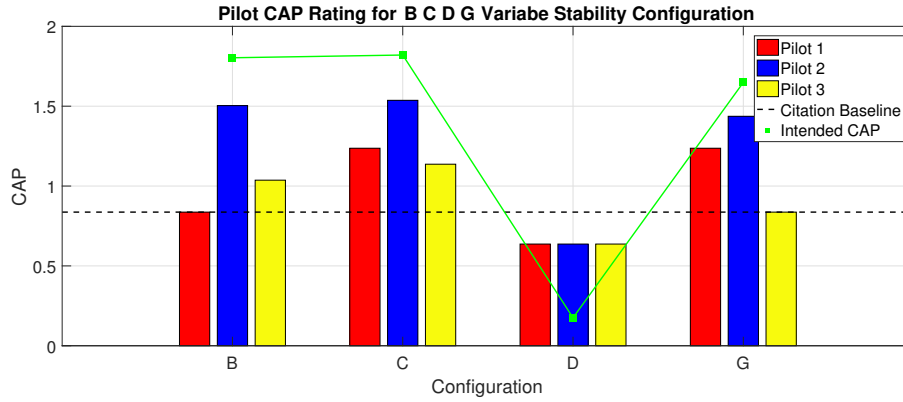
### C. Far Test Points

Test points B, C, D and G were primarily selected to see whether pilots can determine how CAP and damping change for different configurations. As mentioned earlier, it is important to know that pilots might not be able to identify the exact values of CAP and damping. Therefore the general direction (high or low CAP, high or low damping) was observed.

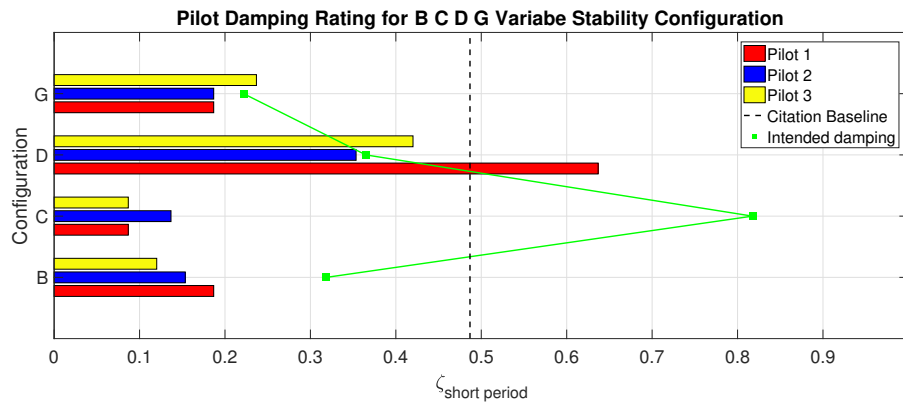
Figure 14 shows how pilots perceived change in CAP for the B, C, D and G configurations. Pilots 2 and 3 were able to follow exact trend of change in CAP due to different configurations. Pilot 1 was not able to correctly identify the direction of CAP in configuration B. However, for the rest of the configurations Pilot 1 also followed the general trend of change in CAP.

Figure 15 shows how the pilots perceived change in damping for B, C, D and G configurations. Unlike CAP, damping was a little more difficult for pilots to correctly identify. Pilots 2 and 3 were able to identify direction of different damping for G, D, and B configurations. Pilot 1 was able to identify this trend only for configuration C and G. All pilots failed to correctly identify the direction of damping for configuration C.

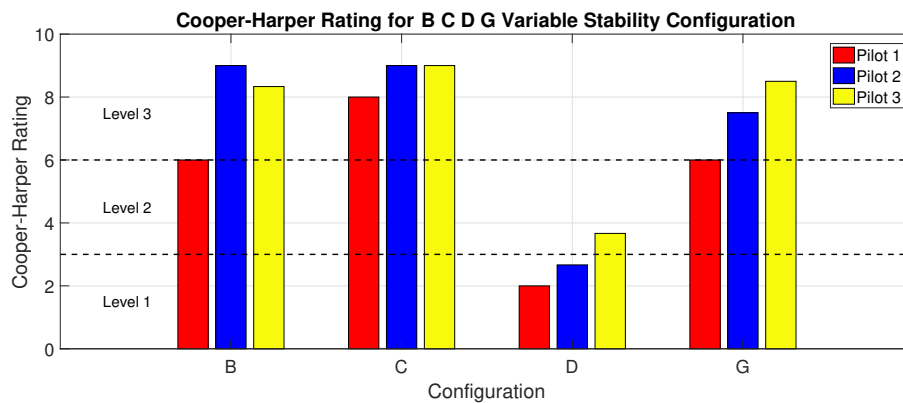
Figure 16 show the CH ratings for each configuration. It was hypothesized that since configurations B, C and D were close to Level 1 boundary, pilots might identify them as Level 2. The results were far more surprising. Except for configuration D, all pilots ranked that handling of all configurations very poorly. Pilots 2 and 3 gave a Level 3 rating to B, C and G configurations, while Pilot 1 rated configuration C as Level 3 while configurations B and G were at the boundary between Level 2 and 3.



**Fig. 14** Pilot CAP rating for B, C, D and G configurations.



**Fig. 15** Pilot damping rating for B, C, D and G configurations.



**Fig. 16** Cooper Harper Rating for B, C, D and G configurations.

**Performance Matrix for Far Test Points**

Similar to the Close Test Points, a performance matrix was constructed to see for how long pilots were able to stay within  $\pm 500$  to  $1000$  ft/min vertical speed target range for each configuration. Table 5 shows, as percentage, the time pilots were within target range for B, C, D and G configurations. Observing Table 5 it is evident that configuration D was the easiest to control for all pilots while the other configurations were equally difficult to control.



**Table 5 Performance matrix for Far Test Points showing percentage of time pilots were within target.**

Pilot	Configuration			
	B	C	D	G
Pilot 1	39%	33%	97%	54%
Pilot 2	55%	58%	88%	63%
Pilot 3	50%	70%	71%	40%

**Main Pilot Comments**

For configuration B, all pilots stressed that the aircraft was difficult to control and required high effort. All pilots also mentioned that the aircraft had a high initial pitching response which reflects that they were able to identify a high CAP. All pilots also agreed that damping was far too less. Pilot 2 commented that this configuration was more controllable than run 10 (configuration G). Configuration G was a Level 2 configuration and reflected positively that the pilot could distinguish accurately between the two configurations in terms of HQ.

Configuration C was nearly impossible for all pilots to control. Configuration D was the only configuration of the Far Test Points which exhibited a positive response from pilots in terms of HQ. All pilots mentioned that target was easily achievable and the configuration exhibited easy control. Pilot 2 pointed out that performance was a bit worse than run 6 (configuration B). Pilot 3 complained about the damping being low. For configuration G, the pilots were of the opinion that it was difficult to maintain the desired vertical speed, and the task was barely achievable.

**D. Combined Handling Qualities**

Figure 17 show the combined mean pilot CH rating for configuration A through G. Table 6 shows the accompanying performance matrix for all configurations. Observing the two in conjunction it is clear that configuration A, D, E and F were easy to control and had desirable handling qualities. The pilots were able to stay within target limits for a large portion of the experiment (over 85%). The performance values for these configurations are also very close to each other (within 8%). As for CH ratings, all pilots gave Level 1 to these configurations which agree with their ratings found on CAP using computer based simulations.

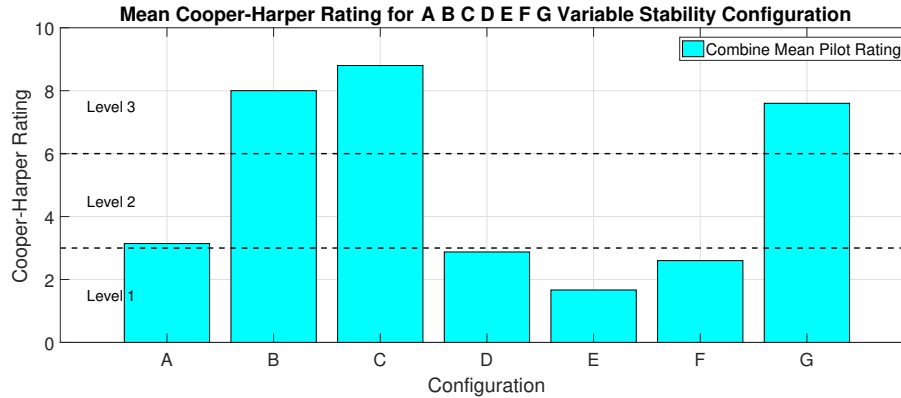
As for configurations B, C and G the performance matrix indicates the configurations were very difficult to control. Almost 50% of the time pilots were unable to maintain the target. With a rating of Level 3, the expected results were very different from the ones simulated.

**Table 6 Performance matrix for all VS configurations showing percentage of time pilots were within target.**

	Configuration						
	A	B	C	D	E	F	G
Mean All Pilots	88%	48%	54%	85%	88%	93%	52%

**E. Discussion**

Examining the results, we can clearly see that test pilots were able to experience changes in handling qualities caused by the VS system. A few outcomes agreed with the hypothesis, such that pilots would not be able to correctly identify changes in CAP and damping for Close Test Points. Other results contradicted our hypotheses, for example the large



**Fig. 17** Combine mean pilot Cooper Harper rating for A, B, C, D, E, F and G configurations.

difference in expected handling qualities identified by pilots for Far Test Points. This discussion is primarily focused on these results.

Focusing on Far Test Points it was seen that configurations B and G did not follow the linear model. Though the general direction of CAP and damping identified by the pilots was correction it cannot be taken for granted and requires verification against flight test data.

Focusing further on Far Test Points configuration D was the only configuration in Far Test Points that was marked Level 1 by all test pilots and was in accordance to expected results. It was interesting to see how configuration D differed from B, C and G that caused such a huge difference in HQs. Configurations B, C and G all had very high CAP values while configuration D had a low CAP value. This might have been the reason for this difference. However, due to the lack of test configurations with low CAP values, it cannot be confirmed whether CAP was the only reason that caused this large discrepancy in results.

## VI. Conclusions

The purpose of this research was to investigate whether the Cessna Citation II, for its longitudinal dynamics, can be converted into a variable stability platform using response feedback. This objective was further expanded to see what range of handling qualities are achievable and whether the handling qualities determined by computer based simulation match the actual pilot's opinion on an aircraft simulator. The Control Anticipation Parameter (CAP) was the criterion used to judge aircraft handling quality.

The main conclusions are that:

- 1) Test pilots were able to experience and identify changes in handling qualities caused by variable stability system for both Close Test Points and Far Test Points.
- 2) For configurations in Close Test Points, pilots were not able to correctly identify how CAP and damping changed.
- 3) For configurations in Far Test Points, pilots were able to identify the general direction of change in CAP and damping. However, pilots were not able to accurately pinpoint the values of CAP and damping.
- 4) Handling qualities, identified by pilots, for Close Test Points matched the handling qualities obtained through the CAP analysis.
- 5) However, for Far Test Points, handling qualities identified by pilots were very different than handling qualities from the analysis.
  - 1) For configurations B, C and G pilots rated handling quality as Level 3. Computer-based simulations showed B and C as Level 1 and G as Level 2.
  - 2) Only configuration D was correctly identified by test pilots as Level 1.

Concluding, it seems indeed possible to convert the Cessna Citation II into a variable stability platform using response feedback, and there is a fair range of handling qualities that can be achieved using this method. The variation in how pilots perceive damping and CAP is similar to criteria-based predictions. However, the handling qualities identified on CAP criterion using computer simulations do not always match pilot opinion, which might be due to non-linear effects. For variations close to inherent Cessna Citation configurations and for low CAP values the handling qualities

match. For configurations with large CAP there is a huge deviation in perceived handling qualities.

Future work will focus on the verification of the actuator model, using newly available flight test data, and the possibility of creating the VS system with different control laws.

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