Faculty of Aerospace Engineering

Effects of Helicopter Degree of Freedom and Motion Cues On Allowable Error Envelopes

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Effects of Helicopter Degree of Freedom and Motion Cues On Allowable Error Envelopes

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Effects of Helicopter Degree of Freedom and Motion Cues On Allowable Error Envelopes"** by **Li Mengyang** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Acronyms

AEE	Allowable Error Envelopes
ANR	Alteration Noticeability Rating
C&S	Control & Simulation
CFD	Computational Fluid Dynamics
DOF	Degree of Freedom
DUT	Delft University of Technology
EOM	Equation of Motion
FFD	Full Flight Simulator
HOS	Higher order system
HQ	Handling Qualities
HQR	Handling Qualities Rating
ICAO	International Civil Aviation Organization
LOES	Low Oder equivalent system
MCQFS	Manual of Criteria for the Qualification of Flight Simulators
MFR	Motion Fidelity Rating
MTE	Mission Task Element
MUAD	Maximum Unnoticeable Added Dynamics
SCAS	Stability & Control Augmentation System
SFR	Simulation Fidelity Rating
STD	Simulator Training Device

List of Symbols

Greek Symbols

δ_A	Lateral Cyclic input
δ_B	Longitudinal Cyclic input
δ_C	Collective input
δ_P	Pedal input
ϕ	Roll angle [rad]
ψ	Yaw angle [rad]
θ	Pitch angle [rad]
ω_b	1st order motion filter break frequency[rad/sec]
ω_n	2nd order motion filter break frequency[rad/sec]
$\omega_n p$	pole natural frequency[rad/sec]
$\omega_n z$	zero natural frequency[rad/sec]
ζ	Damping ratio

Roman Symbols

$L_{()}$	Rolling moment normalized stability derivative[1/sec]
$M_{()}$	Pitching moment normalized stability derivative[1/sec]
$N_{()}$	Yawing moment normalized stability derivative[1/sec]
p	roll rate in body frame [rad/s]
q	pitch rate in body frame [rad/s]
r	yaw rate in body frame [rad/s]
u	velocity in x direction in body frame [ft/sec]

v	velocity in y direction in body frame [ft/sec]
w	velocity in z direction in body frame [ft/sec]
$X_{()}$	X force mass normalized stability derivative[1/sec]
$Y_{()}$	Y force mass normalized stability derivative[1/sec]
$Z_{()}$	Z force mass normalized stability derivative[1/sec]

Contents

Part I

Technical Paper

Effects of Helicopter Degree-of-Freedom and Motion Cues on Allowable Error Envelopes

Li Mengyang*

Abstract—The fidelity of helicopter simulator models can be assessed in both time domain and frequency domain. The frequency domain method of Allowable Error Envelopes (AEE) attempts to identify the acceptable mismatches in magnitude and phase between two models that human pilots will not perceive any differences. This paper investigates the sensitivity of this AEE method to the presence of simulator motion and to the degree-of-freedom (DOF) in which the dynamics are altered. It presents the result of an experiment performed in a 6-DOF motion base simulator. The participant had to fly the helicopter model to perform a hovering precision task, then the model was adding a second order lead/lag and lag/lead filter, participant had to fly it again with and without motion. The rating given by participant, which evaluating the noticeability of the added dynamics, was collected and analysed. The result of experiment shows that there is no common pattern on effect of motion except for high frequency, pilot becomes more sensitive to added dynamics with motion. It also shows that the form of added dynamics influences the result. Further study on AEE is needed to investigate the effect of helicopter DOF on AEE.

Index Terms—Maximum Unnoticed Added Dynamics, Allowable Error Envelopes, Helicopter Model Validation, Simulator Motion Cues.

1 Introduction

Simulator Training Devices (STD) for fixed wing aircraft are playing an important role in pilot training. The challenge of training with STDs is that it is never capable of fully providing a coherent representation of reality [1]. Hence the study of simulation fidelity becomes relevant to determine the sufficient fidelity level for different training purposes. On the other hand, the risk of an accident with a helicopter is much higher than with a fixed wing aircraft [2], and statistics show that accidents are often caused by human error [3]. Thus more effort should be done to improve pilot training for helicopters. For hazardous conditions which give the highest accident rates, for example, flight in extreme operational environments or system failure, training with STDs has become the most suitable choice. However, the helicopter simulators are not as developed as a fixed wing simulators.

One important reason why development on helicopter simulator is lacking behind is that the STD qualification standards for helicopter need to be improved. As mentioned in [1], the current qualification is based on certain tolerances on limited aircraft responses, and matching responses may not guarantee similar handling qualities. On the other hand, indicated by Timson [4], the qualification based on aircraft responses should be supplemented with handling qualities and pilots' perception on aircraft dynamics.

The current qualification is solely based on the time domain tolerance in performance. However, according to [4], the qualification should also connect to handling qualities. Some handling qualities aspects are difficult to be analyzed in time domain [5], hence a validating method based on frequency response analysis is suitable. One approach is to develop a criteria of acceptable mismatches between helicopter simulator model and a reference model, like a real helicopter. The mismatches in frequency domain hence defines the boundaries that show the threshold of pilot's perception on modelling error. These boundaries is called Allowable Error Envelopes (AEE). The magnitude and phase of the dynamics as function of the frequency can hence be analyzed to assess handling qualities, which are difficult to handle in the time domain.

1.1 MUAD to AEE

AEE are based on theory of Maximum Unnoticeable Added dynamics (MUAD), while the origin of MUAD is the equivalent system approach, or more commonly known as Lower-Order Equivalent System (LOES) [6]. LOES uses a lower order system to approximate the high order augmented system so that the classical handling quality can be assessed easily. The idea of MUAD is originally used as the criteria of LOES. It defines the boundaries that any added dynamics which is added to the aircraft within the boundaries, will not be noticed by a pilot.

The MUAD envelopes, as shown in Figure 1, are defined by the Bode plot of the critical added dynamics. The shape of MUAD envelopes is like an hourglass. It is clear that the envelopes are narrower at frequencies from 0 to 10 rad/s which are associated with manual control [7]. Pilots are more sensitive to added dynamics in this region. At either end of the envelopes, the shape gets wider. This means that beyond these frequencies, pilots barely excite vehicle dynamics at those frequencies, hence they are less sensitive to the added dynamics.

The concept of MUAD is simple and straightforward and the envelopes have been used for different purposes.

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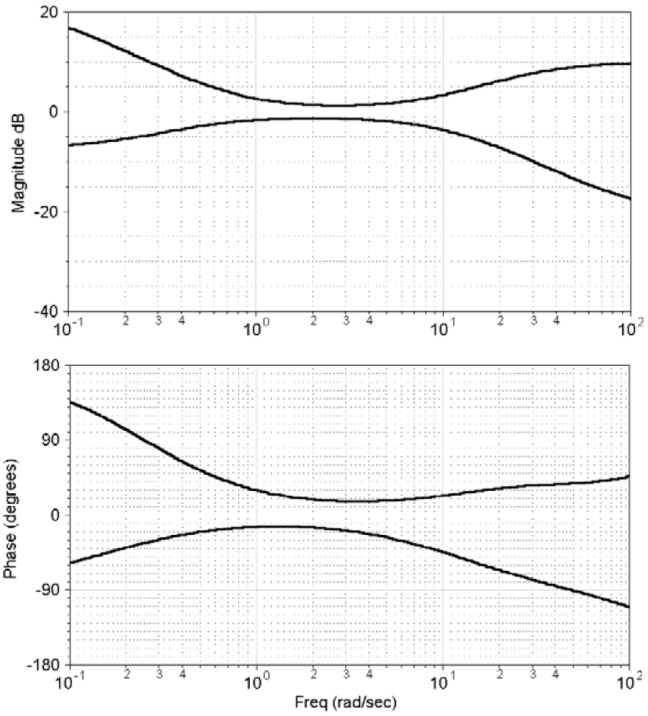


Fig. 1. Envelopes of MUAD [8]

Not only for the LOES approach, but also the application to simulation model validation. In 2006, Mitchel et al. [8] tried to apply MUAD on helicopter simulator model validation. Mitchell's experiment was to study the pilot sensitivity to variations in the helicopter dynamics.

One of the most important characteristics of MUAD is that, the noticeability of added dynamics are defined by the degrading of handling qualities. However, instead of assessing Cooper and Harper handling quality rating [9], Mitchell directly asked pilots if the change of dynamics were noticed or not. It resulted that MUAD is not verified to be a suitable tool for helicopter model validation because it depends on the task as well as simulation set up. However, with the added dynamics that considered to be unnoticed by the pilot, it was possible to find out another acceptable envelopes that define the maximum allowable error. A new name AEE was given, to be distinguished from MUAD envelopes. More importantly, the new term AEE has a more specific purpose: to define the allowable error in simulation model validation. [8]

The effect of multiple pilots and simulators on AEE was analyzed in Penn's study in 2013 [10]. His research was to replicate Mitchell's experiment and to investigate the sensitivity of the boundaries. Six helicopter simulations were performed in the fixed-base Helicopter Pilot Station at National Aerospace Laboratory of The Netherlands and the 6 DOF motion base simulator SIMONA at Delft University of Technology by using three subjects. The results showed that the AEE was dependent on the subject's experience level. More experienced pilots were more sensitive to added dynamics. On the other hand, evidence was found that simulator attributes also had effects on the shape of AEE. Since two different simulators were used, simulation cues like visual and motion were different. One needs to investigate which simulation cue contributes more to the effect on AEE.

1.2 Objectives of this study

This study is to further investigate the effect of simulation cues on AEE, with a focus on only one cue: Motion. Penn improved Mitchell's study by using multiple pilots and two different simulators. This study will use only one simulator but with isolated motion system. In this way, other simulation cues can be controlled.

In previous study on AEE, the added dynamics are applied on helicopter roll axis. To investigate the effect of helicopter degree of freedom on AEE, the added dynamics is applied on pitch axis in this study. The research question of this study is hence formulated:

What is the effect of motion and D.O.F of added dynamics on AEE for helicopter simulation model validation?

One of the objectives of this study is to verify the method of MUAD and try to build AEE. The rest of the paper presents the detail of this study. Section 2 gives a preliminary consideration and conclude with the hypothesis. A detailed motion filter design is given in Section 3. Section 4 describes the experiment proposed in this study. Section 5 shows the experiment results and Section 6 gives an analysis and discussion based on the results. And finally, a conclusion will be drawn.

2 Preliminary Consideration

To answer the research question, a preliminary consideration on the helicopter D.O.F and simulator motion cues is given in this section. To investigate the effect of helicopter D.O.F in which the dynamics are altered, the helicopter model should be discussed.

The helicopter model used in this study is identical to Mitchell's experiment. To replicate the experiment and compare the result, it is reasonable to use the same model. Besides the dependent variable, the simulation set up should be as similar as possible.

A first order state space system is shown in Equations 1 to 5. The 8 states represent velocity in three axis, angular velocity and angular rate.

There are four control inputs. δ_B is longitudinal cyclic, δ_A is lateral cyclic, δ_C is collective and δ_P is pedal input. Note that these control inputs are dimensionless, they present the ratio of the maximum control inputs.

$$\dot{x} = Ax + Bu \tag{1}$$

$$u = \{u,\ w,\ q,\ \theta,\ v,\ p,\ r,\ \phi\ \}^T \tag{2}$$

$$x = \{\delta_B,\ \delta_C,\ \delta_A,\ \delta_P\}^T \tag{3}$$

$$A = \begin{bmatrix} X_u & 0 & 0 & -g & 0 & 0 & 0 & 0 \\ 0 & Z_w & U_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_q & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & Y_v & 0 & -U_0 & g \\ 0 & 0 & 0 & 0 & 0 & L_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & N_r & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{4}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Z_{\delta_C} & 0 & 0 \\ M_{\delta_B} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & L_{\delta_A} & 0 \\ 0 & 0 & 0 & N_{\delta_P} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

The stability derivatives are showed in Table 1. U_0 is the trim airspeed and g is the gravity. Note that these stability derivatives are mass or moment normalized. These derivatives are from [8] except the yaw damping N_r. It was tuned and tested by Penn in his study [10] because it is not published in the previous study .

TABLE 1
Model Parameters [11]

Derivatives	Value	Unit
U_0	0	ft/sec
g	-9.81	m/sec2
X_u	-0.01	1/sec
Z_w	-1	1/sec
M_q	-3	1/sec
Y_v	-0.02	1/sec
L_p	-5	1/sec
N_r	-0.625	1/sec
Z_{δ_C}	-7	ft/sec2
M_{δ_B}	-0.7	rad/sec2
L_{δ_A}	2	rad/sec2
N_{δ_P}	-3	rad/sec2

The helicopter model is designed to be as simple as possible. According to Mitchell et al. [8] the nonlinear element will affect the pilot more than the added dynamics. The model is designed without any cross-axis coupling. Based on the model, the longitudinal and lateral dynamics are independent. The derivatives that define low frequency oscillation like phugoid motion are neglected.

More importantly, the model is an augmented model. It is designed to represent a hovering rate-augmented helicopter. The model is only valid around hover. This means the trimmed velocity is zero.

2.1 Added Dynamics

The added dynamics are a second order lead/lag or a lag/lead filter. This form is identical to Mitchell's experiment. The advantage of using dipole pairs is that it is very easy to shift the peaks of added dynamics, both vertically in magnitude and phase and horizontally in frequency. In this way, it is easier to design the added dynamics for the frequency range of interest.

The added dynamics can be written as Equation 6. Where K is the gain and ζ is the damping ratio, w_{nz} and w_{np} are the natural frequency for zeros and poles.

$$H_{Added\ Dynamics}(s) = K\frac{s^2 + 2\zeta w_{nz}s + w_{nz}^2}{s^2 + 2\zeta w_{np}s + w_{np}^2} \tag{6}$$

The other advantage for these added dynamics is that by adjusting the poles and zeros, the peaks of added dynamics can shift between positive and negative. In this way the AEE can be determined in frequency domain for magnitude changes smaller and larger than 1.

2.1.1 Effect of K

K is the gain, which added directly to the magnitude in frequency domain. Increase of K will shift the magnitude upwards while phase will remain constant. Initially, a constant gain, 1 is used since it is the most obvious case. However, as shown in Figure 2, an amplitude mismatch at low frequency is introduced, which is considered as noticeable by the pilot. According to [10], the dipole's influence is not entirely local but also on magnitude extends to either low or high frequencies.

Since the limits on low frequency and high frequency are different, the aim is to achieve a steady state gain of unity at either high or low frequencies. However, due to the shape of added dynamics, one cannot have unity gain for both high and low frequencies, a choice has to be made. To achieve steady gain of unity at low frequency, a second type of gain is introduced.

$$K_{type1} = 1 \qquad\qquad K_{type2} = \frac{w_{np}^2}{w_{nz}^2} \tag{7}$$

To investigate the effect of gain, other factors were kept constant. So the same damping ratio as well as natural frequency was used. Figure 2 shows the added dynamics with two different types of gain. It is clear that for type 1, the unity gain is achieved at higher frequency. While at lower frequency, the steady state unity gain can be achieved with type 2.

During the experiment, type 2 gain was used. As in this case, pilots were more likely to notice the added dynamics at lower frequency, so the unity gain was chosen to be achieved at lower frequency.

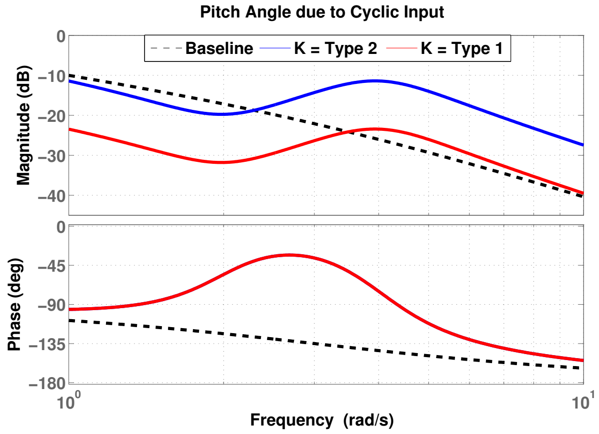


Fig. 2. Effect of Gain on added dynamics

2.1.2 *Effect of natural frequency*

One advantage of using the dipole pair as added dynamics is by changing the natural frequency of poles and zeros, the frequency of added dynamics can be adjusted easily. The peak magnitude of added dynamics falls within the range between natural frequency of pole and zero. Studying the effect of natural frequency will help the design of added dynamics for the experiment. Since by giving different sets of natural frequency, one can apply the added dynamics to the interested range of frequency.

The distance between poles and zeros is also an important characteristic when the added dynamics was designed. As shown in Figure 3, with constant natural frequency on zeros. Shifting the natural frequency of poles will increase the mismatch in the high frequency if a type 2 gain is used.

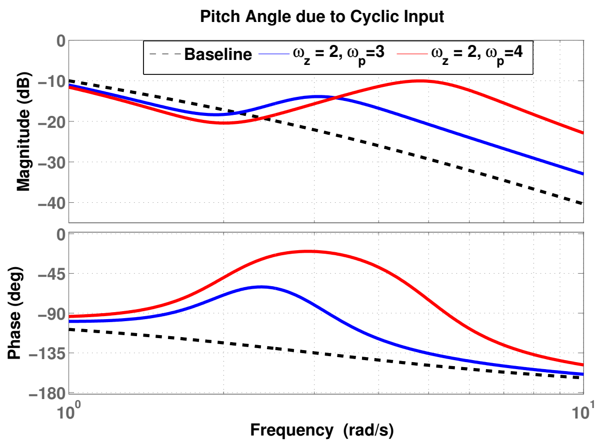


Fig. 3. Effect of distance between pole and zero on added dynamics

In conclusion, the natural frequency of zeros and poles of the added dynamics is designed to fit the interesting frequency range. By adjusting the damping ratio, the height of peaks of added dynamics can shift, hence the intensity of added dynamics is changed.

2.2 Helicopter Degree of Freedom

This study is also trying to find out the effect of dynamics of the helicopter itself to the pilot's ability to perceive the change of dynamics. One major difference between this study and previous research is that, the added dynamics was applied on the pitch axis instead of roll.

To understand the differences between helicopter pitch attitude control and roll attitude control, an analysis based on the helicopter model was performed. The transfer function of angular attitude control for pitch and roll is shown in Equation 8. Derived from the helicopter model, both transfer functions are first order.

$$\frac{\theta}{\delta_B} = \frac{M_{\delta B}}{s(s - M_q)} \qquad \frac{\phi}{\delta_A} = \frac{L_{\delta A}}{s(s - L_p)} \tag{8}$$

Table 2 gives the inputs and outputs for both transfer functions. By neglecting the magnitude gain, $M_{\delta B}$ and $L_{\delta A}$, the two response transfer functions are influenced by their break-off frequencies. Which depends on the so-called damping derivatives.

TABLE 2
Model Parameters [11]

Parameters	Name	Value	Units
θ	Pitch angle	output	rad
ϕ	Roll angle	output	rad
δ_B	Longitudinal cyclic input	input	-
δ_A	Lateral cyclic input	input	-
M_q	Pitch damping derivative	-3	1/sec
L_p	Roll damping derivative	-5	1/sec
$M_{\delta B}$	Pitching moment stability derivative	-0.7	red/sec2
$L_{\delta A}$	Rolling moment stability derivative	2	red/sec2

Figure 4 shows the open loop response of both transfer functions. The magnitude is dropping with slope of -20dB per decade. After the break frequency, the dropping rate increases to -40dB per decade. The break frequency is dependent on the damping of the helicopter dynamics. Based on the model, a pitch dynamics has a break frequency at 3 rad/s while the roll is at 5 rad/s. It means for frequency lower than 3 rad/s or higher than 5 rad/s, pitch and roll will have the same type of response. The interested region is hence the frequency between 3 to 5 rad/s. From the graph, it is also clear that a roll response has a larger phase margin than pitch response.

To investigate the effect of the open loop dynamics on pilot's behavior, a pilot model is added. One of the important rule to use McRuer's cross-over model [7] is that the pilot model should be adjusted to achieve the -20dB/decade slope of the open loop transfer function. By applying verbal adjustment rule, the pilot model can be determined for both pitch and roll response.

At any frequency lower than 3 rad/s, pilot is doing only a gain control. Since the open loop response at this

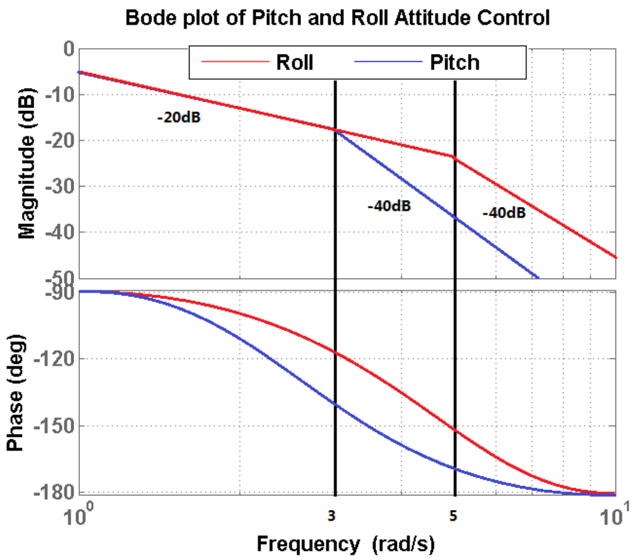


Fig. 4. Response model for Pitch and Roll

frequency has already a slope of -20dB per decade. While for frequencies higher than 5 rad/s, pilot has to generate a first order lead to keep the same slope. However, inside the region between 3 to 5 rad/s, a pilot is doing a gain control for roll dynamics while he has to provide a lead for pitch dynamics. From the point of view of the pilot, inside this region, the pitch is expected to be more challenging to control.

Based on the result of the analysis, in the interesting region, it is assumed that the workload and effort that pilot has to put for the pitch control is higher than the roll control. The added dynamics on pitch hence have a larger effect on pilot. It is assumed pilot will be more sensitive to added dynamics on pitch in the interesting frequencies.

It concludes that between 3 rad/s to 5 rad/s, pilots are expected to be more sensitive to the added dynamics on pitch, which means the shape of the AEE generated with added dynamics on pitch is expected to be narrower than the ones with added dynamics on roll.

2.3 Motion System

Motion cues are an important independent variable in this study. The motion system of the simulator is to replicate the physical movement of the real aircraft, and hence provide pilot a physical sense of motion. Pilot perceives motion with vestibular system. In the range of frequencies associated with manual control, the sensor dynamics of vestibular system is approximated to be a first order integrator. [12]

Figure 5 shows the Bode plot of a pilot model with and without motion. Y_c is the control element, e.g., pitch attitude control, Y_{Pvis} and Y_{Pvest} are the pilot model with only visual and with only motion separately, while Y_{Ptot} is the pilot model with both visual and motion. Y_{OL} is the overall open loop model. To achieve an open loop dynamics with -20dB per decade, Y_{Pvis} needs to generate a visual lead after the break frequency. While when the vestibular system is added, vestibular response can be used as an alternative lead, which can replace the lead generated by pilot. Graphically, it will shift the pilot model with visual response to right. It means the pilot only needs to generate lead for higher frequency.

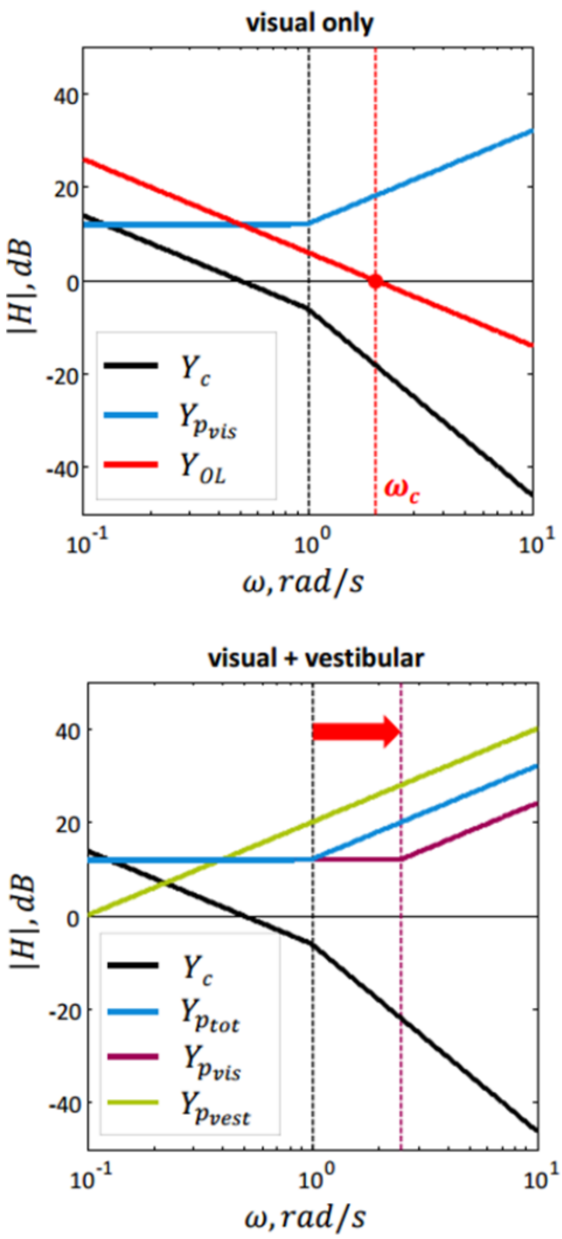


Fig. 5. Pilot Response with Visual /with Visual and Motion. source [12] reproduced from [13]

This change in pilot response is expected to influence the noticeability of added dynamics as well. Since the pilot only needs to perform a first order lead control at higher frequency. That means for a longer range of frequencies, the pilot does a simple gain control and he is expected to be more sensitive to added dynamics with motion. The expected influence on shape of AEE is that the stringent part of the envelope will be longer after the break frequency, 3 rad/s in this case. This means the narrowest part of the AEE envelopes will shift to higher frequencies.

2.4 Hypothesis

The main objective of this study is to investigate the effect of motion and D.O.F on AEE. Based on the preliminary analyses on helicopter dynamics and on motion system, two hypotheses are formulated:

- Hypothesis 1. The shape of AEE for added dynamics on pitch is narrower than those on roll between frequency 3 to 5 rad/s.
- Hypothesis 2. The motion cueing will shift the stringent part of AEE to higher frequency (to right).

The first hypothesis is based on the analysis of the differences between helicopter pitch and roll dynamics. Between 3 rad/s to 5 rad/s, pilots are expected to be more sensitive to the added dynamics on roll. Because pilot control a gain instead of a lead. This means the shape of the AEE generated with added dynamics on pitch is expected to be wider than the ones with added dynamics on roll.

The second hypothesis is based on the preliminary consideration of simulator motion system. It shows that motion cueing can be used as an alternative lead and more advantageous for the human. With higher frequency than the break frequency (3 rad/s), the shape of AEE will be more stringent. This means the narrow part of AEE shifts to higher frequency.

3 Motion Filter Design

One of the challenges on simulator motion system is that the quality of motion provided by the simulator can not be perfectly match the real aircraft. The aircraft flies through the air without any limitation, while the simulator has a limited workspace. A way of transforming real aircraft motion to a reduced version is developed. The algorithms behind this idea is using a motion filter with a washout effect. Since pure scaling, without any filtering, is not very practical due to the extremely low scaling factors needed, which attenuate any useful motions to far below human perception thresholds.

In this section, a design of motion filter is discussed because motion is an important character in this study. To choose a suitable motion filter for the experiment, a preliminary tuning is required. In general, a high pass filter is used, a typical third order high pass filter can be described as:

$$H_{HP}(s) = \frac{K \cdot s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \cdot \frac{s}{s + \omega_b} \tag{9}$$

The first step of motion filter design in this study is based on offline simulation. The simulation represents the altitude, rate and acceleration response of the helicopter before and after filtering during a representative simulation run. The result of offline tuning showed that there is a trade off between translational and rotational motion. When the quality of pitch motion increases, there will be false cues on surge due to gravity. The surge cues is based on the body acceleration and effect of gravity. Based on the simulation, the gravity (due to pitch) dominates the false cues while the body acceleration is trying to work against the false cues, hence reduce it. There are two ways to reduce the false cues: degrading rotational motion or improve translational motion. During the preliminary consideration, three different motion filters were chosen.

3.1 Filter 1: Focus on Pitch

Since the added dynamics are applied on pitch axis, a good motion on pitch is expected. This filter is in favor of pitch, a scaling down is used without any washout. The surge and tilt coordination is off. In this case, the pitch is considered as ”perfect”, while the false cues on surge is very large as well due to false gravity cues. It is one extreme case with maximum false cues on surge.

Table 3 gives the parameters of motion filter in this case. The gain K scales the motion cues directly, which is chosen to be 0.7 for every axis. ζ is the damping, ω_n is the natural break-frequency of the second order filter while ω_b is the pole for first order filter. In this case, a first order filter is used on pitch, while surge channel is off as highlighted in the table.

TABLE 3
Case1: focus on pitch

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw
K	-	0.7	0.5	0.7	0.7	0.3
ζ	-	0.9	0.9	0.9	0.9	0.9
ω_n	-	2	2.5	1.5	0	1.5
ω_b	-	0	0.1	0	1.5	0
$\omega_{n_{lp}}$	-	4	0	0	0	0
switch	0	1	1	1	1	1

Figure 6 shows the simulation results for this filter. The outputs for pitch rate and specific force were compared before and after filter. The performance of the pitch channel was considered as good. It almost represented the motion due to a first order filter. While the false cues on surge were large and because the surge channel was off in this case, the false cues were dominated by gravity. Adding surge or degrading pitch could reduce the false cues. This case was an extreme case for pitch, regardless of false cues on surge.

3.2 Filter 2: Focus on Reducing false cues

The filter shows in Table 4 has a degraded pitch, but false cues are reduced. Second order on rotational axis while first order is used for translational axis. It looks like the motion is in favor of surge and sway. However in this case, the false cues on surge and sway are under threshold. The pitch

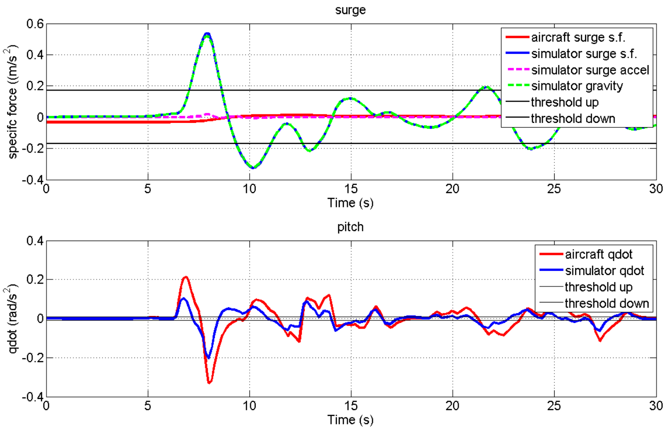


Fig. 6. Surge and Pitch for Case1

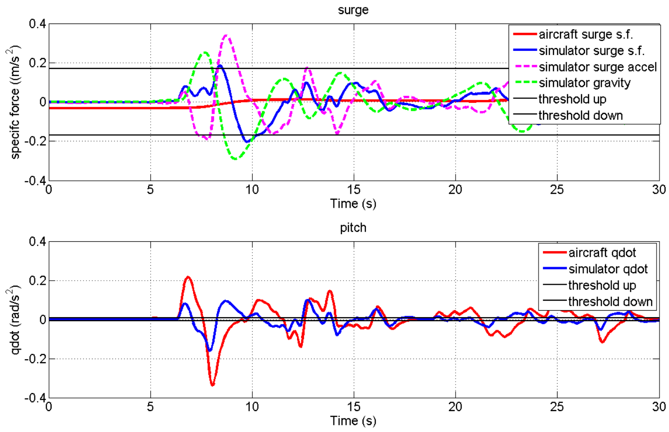


Fig. 7. Surge and Pitch for Case2

TABLE 4
Case2: focus on surge

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw
K	0.7	0.7	0.5	0.7	0.7	0.3
ζ	0.9	0.9	0.9	0.9	0.9	0.9
ω_n	0	0	2.5	1.5	1.5	1.5
ω_b	1.5	1.5	0.1	0	0	0
$\omega_{n_{lp}}$	4	4	0	0	0	0
switch	1	1	1	1	1	1

and roll are very bad instead. This is considered as another extreme case which false cues on surge is minimized.

As shown in Figure 7, the result filtered surge was below the threshold. The threshold is defined in [5] where pilot will not feel the motion below the threshold. It was clear that the surge acceleration (pink line) works against the gravity (green line) so that the false cues were reduced.

3.3 Filter 3: A balanced case

This filter tries to find a balanced point between a degrading pitch and false cues on surge. It is also harmonised for all D.O.Fs, and a first order filter is used for both translational and rotational axes. The false cues are not significant while moderate pitch and roll is achieved. The parameters for this filter are given in Table 5

TABLE 5
Case3: harmonised case

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw
K	0.7	0.7	0.5	0.7	0.7	0.3
ζ	0.9	0.9	0.9	0.9	0.9	0.9
ω_n	0	0	2.5	0	0	0
ω_b	1.5	1.5	0.1	1.5	1.5	1.5
$\omega_{n_{lp}}$	4	4	0	0	0	0
switch	1	1	1	1	1	1

Figure 8 shows the simulation results of the balanced filter. One advantage of this filter is that same filter is used for all the D.O.Fs, the different axis are harmonised in motion. The performance took a balanced point between reducing false cues on surge and degrading motion on pitch.

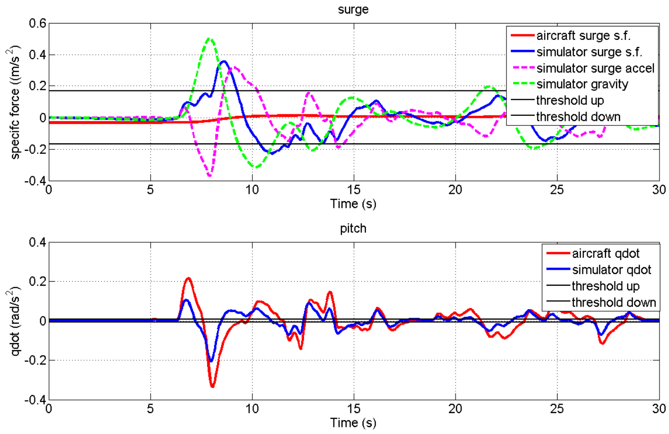


Fig. 8. Surge and Pitch for Case3

In a preliminary test, a test subject was asked to fly with all three motion filters and give feedback. As shown in Table 6, the subject was in favor of the third filter which is the balanced one. Note that even in first case, the subject was not affected by the false cues on surge.

TABLE 6
Pilot's feedback on Motion Filter

Filter	Feedback and Comment
Filter 1	Motion is OK, not so aggressive
Filter 2	Motion is too small, much less than previous one (filter1)
Filter 3	Most favorable one, good pitch and roll

4 EXPERIMENT DESIGN

An experiment was designed to investigate the research question stated in Section 1. The general set up is similar to Mitchell's experiment. [8] The simulation model was implemented on SIMONA Research Simulator at TU Delft, and two different motion conditions were tested: motion on and motion off.

4.1 Flight Task

The flight task that was performed in the experiment was also identical to Mitchell's experiment [8] . Because the task could represent the performance on both longitudinal and lateral dynamics of the helicopter, it was suitable for the research on added dynamics on pitch.

The flight task was the Hover MTE defined by ADS-33E PRF [14]. Initially, pilots were flying at a ground speed of 9 knots, at an altitude less than 20 ft. The target hover point was oriented approximately 45 degrees relative to the heading of the rotor craft with ground reference.The task was to fly the helicopter to that point and hover it with the listed requirements:

- Attain a stabilized hover within 8 seconds of initiation of deceleration.
- Maintain a stabilized hover for at least 20 seconds.
- Maintain the longitudinal and lateral position within ±6 ft of a point on the ground.
- Maintain altitude within ±4ft.

Note that the pilot was only asked to fly the task with required performance. The information on added dynamics or motion condition was not provided. Pilots were not allowed to probe or try to identify the added dynamics. This means the pilot would not perceive any added dynamics if it was not excited during the flight.

The desired maneuver is shown in Figure 9. The out of window view at the final hover position is shown in Figure 10.

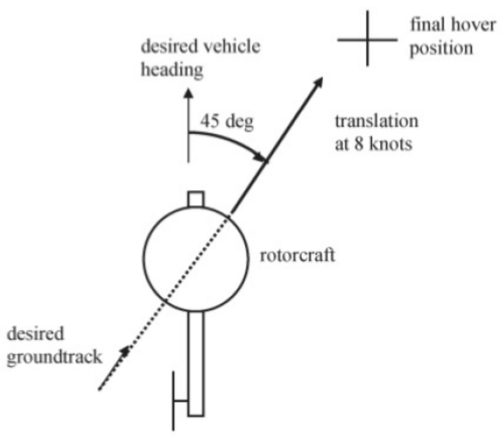
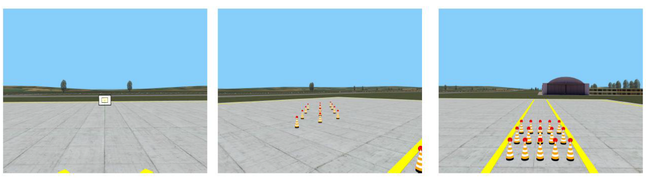


Fig. 9. ADS-33 Hover Mission Task Element



(a) Front view (b) Diagonal view (c) Right view

Fig. 10. Hover Position in Visual

4.2 Apparatus

The experiment was performed on the TU Delft SIMONA Research Simulator. Figures 11 and 12 show the exterior and interior of SIMONA Research Simulator. The SRS has a visual system with 180 degree by 40 degree collimated display. The flight control system is a typical helicopter control system, with a cyclic and collective.

Fig. 11. Exterior of SIMONA Research Simulator

Fig. 12. Interior of SIMONA Research Simulator

TABLE 7
Workspace of SRS

D.O.F	Minimum	Maximum
Surge(X)	-0.981 m	1.259 m
Sway(Y)	-1.031 m	1.031 m
Heave(Z)	-0.636 m	0.678 m
Roll	−25.9°	25.9°
Pitch	−23.7°	24.3°
Yaw	−41.6°	41.6°

The SRS has a 6 D.O.F motion system with a typical hexapod layout. The operational stroke for each actuators is 1.15 m. This gives the SRS a motion space shown in Table 7. The value given in the table are maximum value for each D.O.F independently. During the operation, the motion will be limited by the actuator length as well.

4.3 Procedure

The controlled variables in the experiment were the model configuration, visual cueing and control loading. The control variables were kept constant during the experiment. Finally, the task performance requirements should also be controlled, pilots were asked to fly it with desired performance, or if that was not possible, with adequate performance.

Two main independent variables in this study were: Motion, and Helicopter D.O.F. The designed experiment matrix was described in Table 8. For each condition, there were 8 sets of data dependent on the frequency of added dynamics. In this case, the added dynamics were the last independent variable. While s1 represented the subject, and m1 means with motion, m2 means without motion. The numbers in the table are the run order. Due to the unexpected issue, there was only one subject participated in the experiment.

TABLE 8
Experiment Matrix

wz	wp	s1, m1	s1, m2
2	2.5	15	6
2.5	2	2	10
3	3.75	1	5
3.75	3	8	12
4	5	4	7
5	4	16	13
5.6	7	14	3
7	5.6	11	9

For each set of added dynamics, the pilot would fly randomly with the damping ratios which were designed in a preliminary test. During the preliminary test, a random damping ratio from 0.1 to 0.9 was flew by a pilot. After that, 5 damping ratios were chosen for each set of added dynamics which approximately showed the region of boundaries of noticeability for each frequency. The designed damping ratios were used in the experiment. The order of the runs in the experiment are shown in Table 8. With 8 sets of added dynamics and 2 motion settings, the sixteen conditions were flew randomly. The advantage of this approach was that it saved lots of time during the experiment, and it was more randomized compared to the previous study.

4.4 Subjects and instructors

One subject participated in this experiment. The subject had a wealth of knowledge about helicopter dynamics as well as simulation fidelity. He had experience in helicopter flight simulators, but not actual helicopters. But the subject could fly the task with a constant performance and met all the requirements.

The procedure of the experiment started with a briefing, the pilot got briefed about the task and procedure. After that the pilot got familiar with the simulation setting by flying the simulator freely. Next, the pilot was asked to fly the task with the baseline model, and then fly the task with added dynamics model. During the task, the pilot was instructed to strive for desired performance at all time. After each set, the pilot was asked to go though the noticeability rating scale and evaluated the noticeability of added dynamics. Note that the pilot was not informed about the precise conditions being flown, he had no information about the added dynamics and motion conditions.

This procedure was repeated for each set of added dynamics with and without motion. During the experiment, the pilot could ask to fly the baseline model anytime. After 16 conditions were flown, a debriefing was given.

4.5 Alteration Noticeability Rating

The original MUAD defined the boundaries based on the Handling qualities rating, while to develop AEE, Mitchell directly asked pilot if the change of dynamics was noticed [8]. One of the challenge in this study is to measure the level of noticeability. A rating scale was developed in this study to represent how pilot perceive the added dynamics.

The only dependent measurement in this experiment was the noticeablility rating. Based on the rating, the critical added dynamics were determined. The noticeability rating represented how pilot perceives the change of dynamics in the helicopter model. The origin of the rating scale was the Simulation Fidelity Rating (SFR) Matrix as shown in Figure 13, which represented the two main aspects that the rating scale was considered: Performance and Strategy.

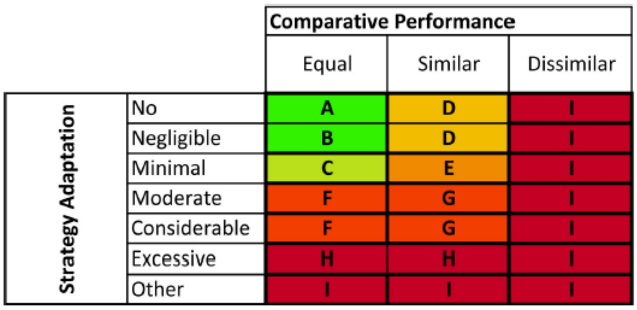


Fig. 13. Simulation Fidelity Rating matrix, source: [15]

Similar to SFR, the Alteration Noticeability Rating (ANR) proposed in this study was defined by the both performance as well as the strategy of pilot. The scores from from A to I were used by ANR. A score A was considered as ”Unnoticed”, scores with C or above was ”Noticed”. While the score B was hence the boundary for critical added dynamics.

Figure 14 shows the question trees of the rating scale. The major difference between ANR to other fidelity rating was that, before assessing performance or strategy, the first question in ANR was to ask directly if the change of dynamics noticed. The perception of pilot was more important in this case. The boundary was defined at score B which means although the pilot did feel the change, it did not affect the performance of task and no adaptation of strategy was needed.

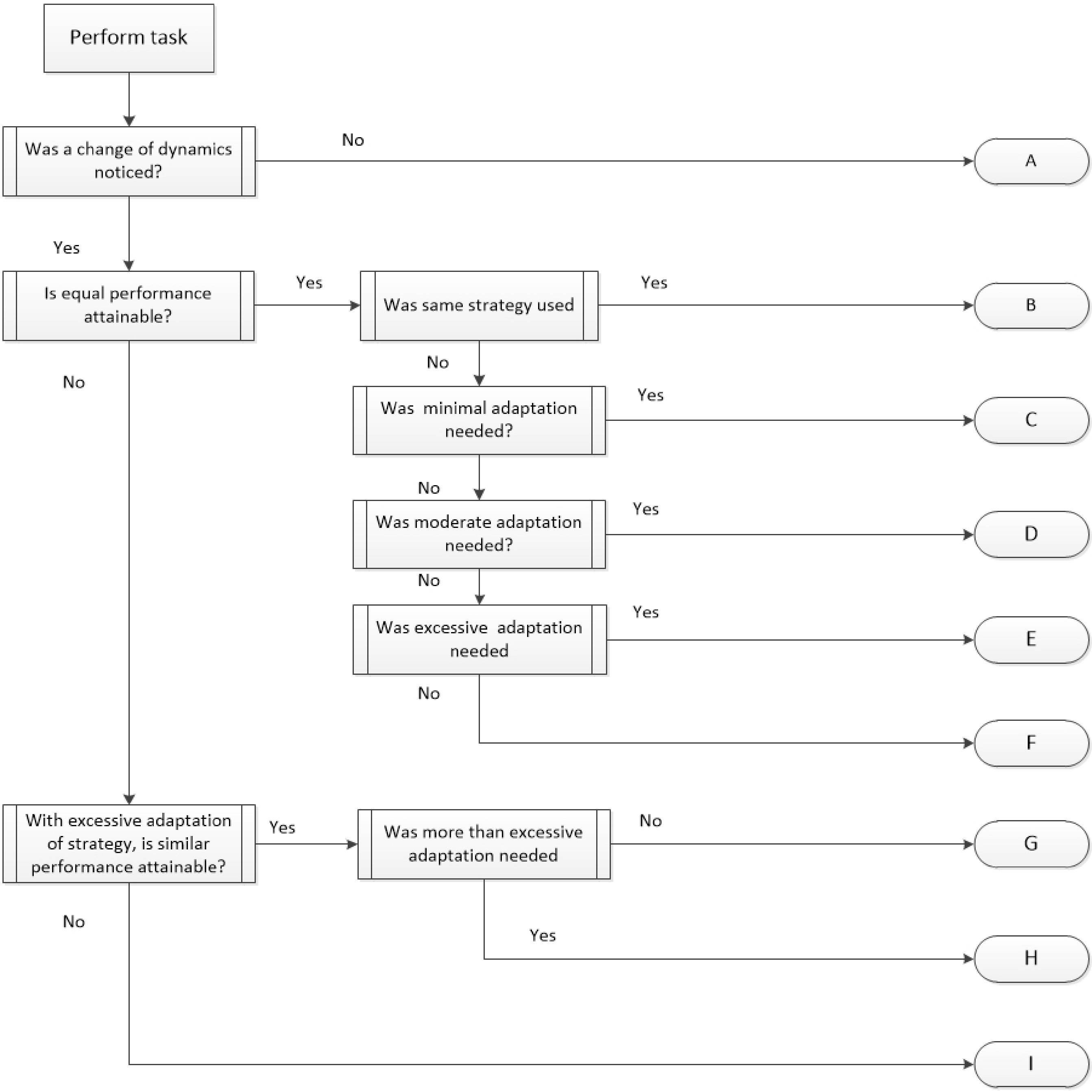


Fig. 14. Noticeability Rating Scales

5 EXPERIMENT RESULT

The only dependent measure in the experiment is the pilot's noticeability rating on added dynamics. Two subjects participated in this study, but data for only one subject was analysed. Due to inconsistent performance, the data from the other subject were not processed in this study.

The AEE is defined by the critical added dynamics. Hence, the boundary for critical case is defined by the rating scale B. For each set, at least 12 runs of test were performed, with 5 different damping ratios.

As a representative example, Table 9 shows the experiment result for one set. With 8 different added dynamics and presence of motion, a total number of 16 sets of these data were captured during the experiment for one subject. As shown in the table, 5 damping ratios were tested in a random order, while 0.1 and 0.01 were two sanity checks. The sanity checks are the extreme conditions that are used to check if the ratings given by pilot are making sense. For example, in this set, the critical case will be the added dynamics with damping 0.05.

By finding out the critical cases for all sets, the

TABLE 9
Example of Experiment Result

w_n	w_p	Motion	Damping	Rating Scale	Comment
3	3.75	On	0.025	C	Feel the change, definitely. Oscillation in pitch
3	3.75	On	0.1	A	No difference
3	3.75	On	0.05	B	Difficult to say, slightly feel something
3	3.75	On	0.01	E	PIO in pitch, less input needed
3	3.75	On	0.01	D	Yes, definitely feel the change
3	3.75	On	0.015	C	Notice something, strategy changed to avoid large pitch input
3	3.75	On	0.015	D	Feel small wobble

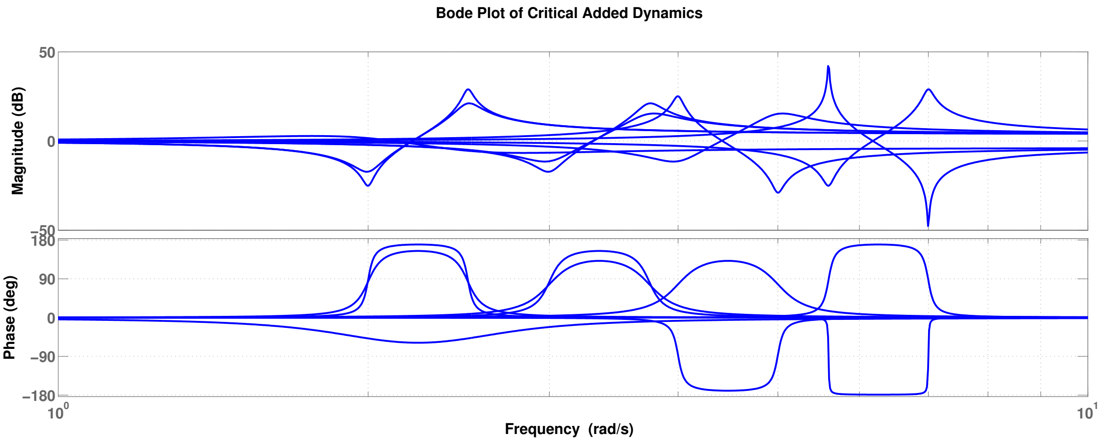


Fig. 15. Critical Added Dynamics without Motion

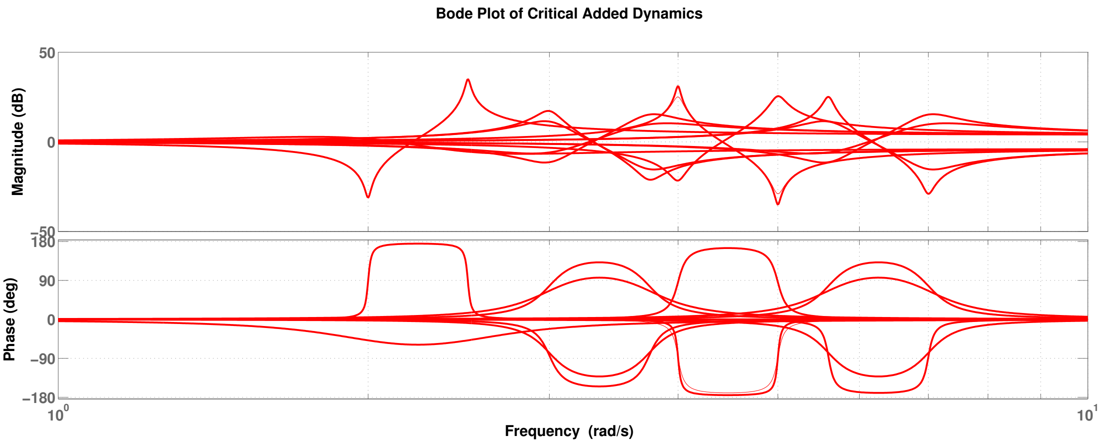


Fig. 16. Critical Added Dynamics with Motion

boundaries can be defined by plotting these critical added dynamics in a Bode plot. Figure 15 shows all the critical cases when motion is off, while Figure 16 shows same thing when motion is on. With these added dynamics, it is possible to develop a boundary in frequency domain.

It is not clear to compare the envelopes on a Bode plot by only looking at these critical added dynamics. Note that the shape of the envelopes can be defined by the peak magnitude and phase of these added dynamics. by simply comparing those peak values, the analysis will be more representable.

To get a more accurate result, not only critical cases are considered. The boundaries will be represented by the region of uncertainty. For most sets, there are multiple critical cases, and the region is defined by the difference between them. If there is no critical case, the region is hence the difference between the most damped noticed dynamics and least damped unnoticed dynamics (between A and C).

In this way, the peak value is given an uncertainty tolerance. It can be represented as an error bar on the graph. Figure 17 shows the peak magnitude of critical added dynamics for both motion condition. The vertical axis is the magnitude in dB, while the horizontal axis is the frequency. The figure clearly compares the peak magnitude between different motion conditions The blue points are the

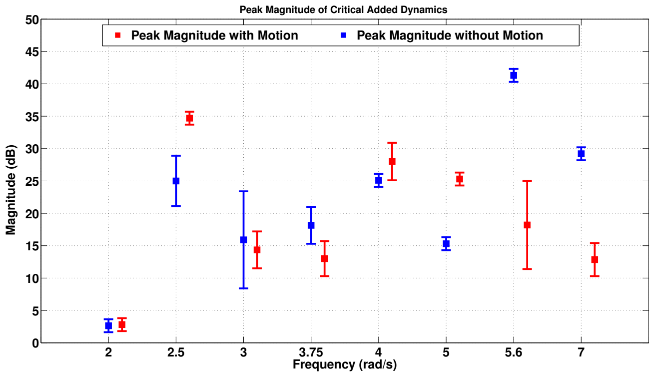


Fig. 17. Positive Peak Magnitude of Critical Added Dynamics

cases without motion, the red ones are with motion.

The negative peak of magnitude is expected to be symmetric to the positive ones. However, by looking at the Bode plot in Figures 15 and 16, there is a difference in magnitude.

Hence the negative peak magnitude for critical added dynamics is also plotted. As shown in Figure 19. Both motion conditions are plotted together. A similar effect was also visible on the phase plot.

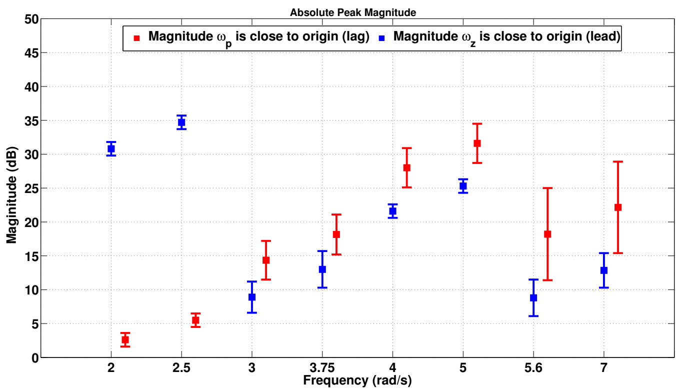


Fig. 18. Absolute Peak Magnitude for lead/lag and lag/lead Added Dynamics

The reason to use both lead/lag and lag/lead added dynamics is to get the both positive and negative boundaries on phase. It is expected that pilot will have similar perception on these added dynamics because they have same absolute peak magnitude and phase, and the peaks are at same frequency.

Figure 18 shows the difference between added dynamics with a smaller ω_z (zero close to origin) and added dynamics with a smaller ω_p (pole close to origin). There is already a clear difference shown on the graph This will be analyzed in the next section.

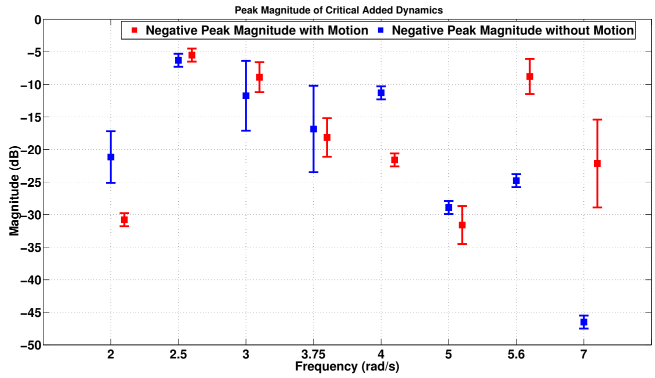


Fig. 19. Negative Peak Magnitude of Critical Added Dynamics

6 DISCUSSION

In this Section, the experiment result is discussed. In total, 200 runs with 8 different added dynamics and two motion conditions were evaluated by one subject. The result is shown in Section 5. Based on the main objective of this study, the discussion will focus on the most important independent variables.

6.1 Effect of Motion

Comparing Figures 15 and 16, it is difficult to find any differences. The only interesting point is at high frequency. The critical case with motion has a larger damping ratio than those without motion. This means the pilot seems to be more sensitive with motion to added dynamics at this frequency.

This phenomenon is confirmed by plotting the peak magnitude. In Figure 17, the differences between motion and non-motion are relatively small, in most frequencies. However, in the last two data point, with frequencies 5.6 and 7 rad/s, the difference between motion and non-motion is more than 20 dB. The same phenomenon happened in the negative part. In Figure 19, the difference between motion and non-motion for last two data sets is also obvious. The red data point (with motion) is much closer to the zero compare to the blue ones (without motion).

During the experiment, this phenomenon was already detected. When the subject flew with a high frequency added dynamics, he barely felt any difference without motion. Only adding a sanity check dynamics with extremely low damping ratio, he could slightly notice something and gave a rating B. While with motion, the subject felt much more difference: "annoying dynamics, high frequency(D)", "oscillation slightly in high frequency(B)". Note that the order of the experiment was random and the subject had no information about the added dynamics.

However, this phenomenon only occurs in the higher frequency range, from 5.6 to 7 rad/s. Actually, through the whole range of frequency (2 to 7 rad/s), no pattern can be found. With only one set of data, there is not enough evidence to determine a general effect of motion cues on pilot's perception on added dynamics.

Recall the hypothesis, "The motion cueing will shift the stringent part of AEE to higher frequencies." Based on the experiment result, there is no confidence to accept this hypothesis. If the phenomenon discussed above is verified, the shape of AEE will only be narrower at higher frequency when motion is added. It does not affect the shape of AEE for low frequency part.

To confirm and verify the effect of motion on high frequency, a test with more subject and different added dynamics (with a range of higher frequency) is needed. To investigate the effect of motion in the low frequency range, a further study is needed.

6.2 Effect of D.O.F of Helicopter Dynamics

The other important independent variable in this study is the Helicopter D.O.F. Simply comparing the critical cases to the data from Penn's study [10], there is not enough confidence to get any conclusion. Although the shape will be largely different from the ones with added dynamics on roll, as shown in Figures 22 and 23. With only one subject, it can not draw a conclusion that pilots are less sensitive to pitch compare to roll.

On the other hand, there are some other factors that may lead to the differences. Firstly, the motion filter used in this study was different. The filter was tuned in favor of pitch. It concludes that there is not sufficient data to accept the hypothesis "The shape of AEE for added dynamics on pitch is wider than those on roll ".

6.3 Effect of Added Dynamics

In this study, 4 pairs of added dynamics were used, each pair of added dynamics is symmetric in Bode plot, the difference is that: for one with smaller ω_z, there is a phase lead, and for one with a smaller ω_p, there is a phase lag.

There are two odd data points in Figure 18. The absolute peak magnitude at frequency 2 rad/s and 2.5 rad/s. The difference between the "pair" of added dynamics is larger than others. This can also be found in the Figure 15 and 16, the phase at low frequency are asymmetric compare to other frequency. To find out the reason, a further study on the added dynamics at this frequency was performed.

Figure 20 shows the critical cases of the added dynamics with $\omega_z = 2$, $\omega_p = 2.5$ and added dynamics with $\omega_z = 2.5$, $\omega_p = 2$. The subject perceives quite differently between these two added dynamics. The difference in peak magnitude is more than 30dB.

This phenomenon only happens at the lowest frequency set. As shown in Figure 18, at other frequency, the difference due to the switch of natural frequency of pole and zero are negligible comparing to the first two data points.

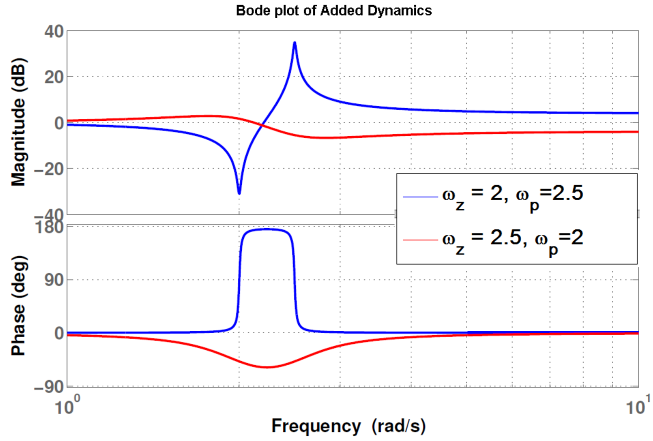


Fig. 20. Critical Case for Lead/lad and Lad/lead Added Dynamics

To compare to the 2.5/2 and 2/2.5 rad/s case, Figure 21 shows the critical cases of the added dynamics with $\omega_z = 3$, $\omega_p = 3.75$ and added dynamics with $\omega_z = 3.75$, $\omega_p = 3$. It is clear that in this case, the two added dynamics are almost symmetric to each other, which is as expected.

The unexpected data, however, is not due to measurement error or by coincidence. Because this happened for both motion conditions. It is believed that at this frequency, the natural frequency of pole and zero has an effect on pilot's perception on added dynamics.

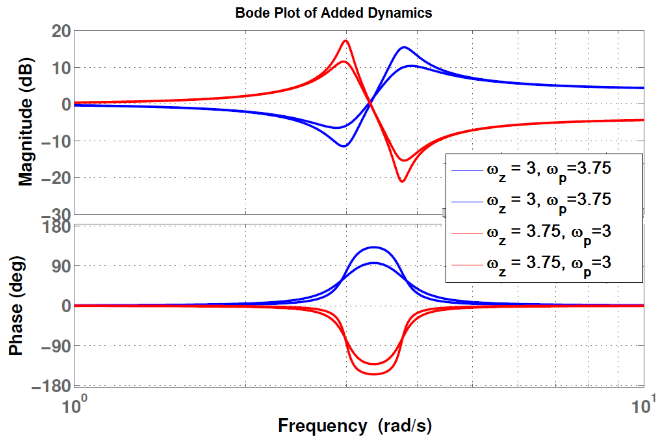


Fig. 21. Critical Case for Lead/lad and Lad/lead Added Dynamics

The reason behind this phenomenon can also be the subject, who might be very insensitive to a phase lead in low frequency. With current data, it cannot give a conclusion. However, at least two points can be pointed out: firstly, the added dynamics at low frequency consistently affect the pilot's perception, and secondly, this effect is independent of motion. For future research, more attention should be paid to the selection of these added dynamics, since just switching poles and zeros can have larger effects than just asymmetry.

6.4 Comparison to other Envelopes

Figure 22 and 23 shows the Allowable Error Envelopes developed based on the data captured in this study. The amount of data was enough to get a complete shape of envelopes over the studied frequency range. However, with only one subject and two conditions, the envelopes did not give much information.

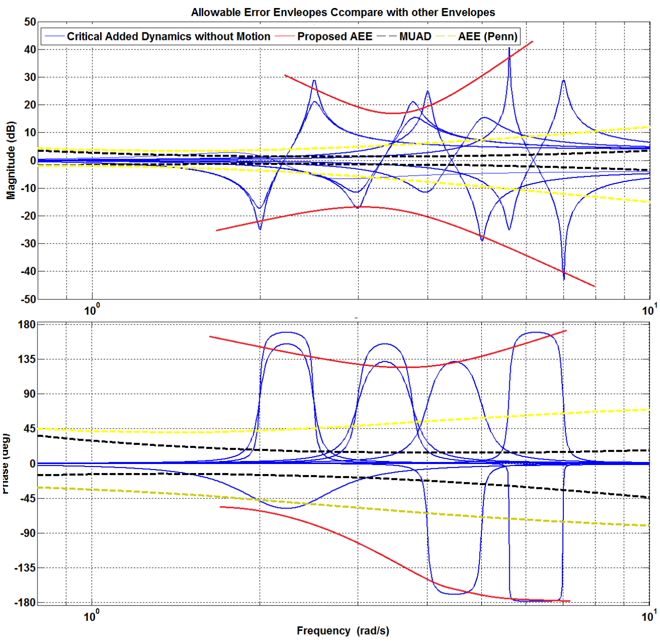


Fig. 22. Proposed AEE compare to MUAD without Motion

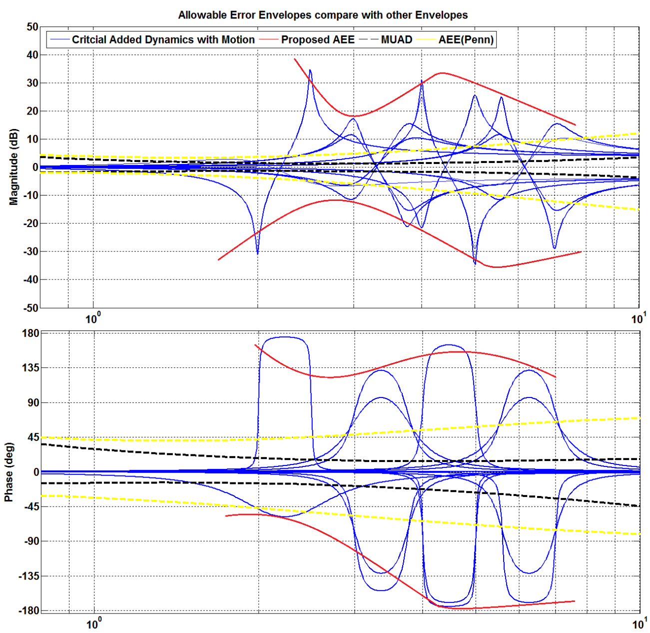


Fig. 23. Proposed AEE compare to MUAD with Motion

The original MUAD Envelopes are plotted in the figure. Comparing to the critical added dynamics in the experiment as well as the proposed AEE, the MUAD Envelopes and AEE Envelopes proposed by Penn [10] are too stringent in this case. It also shows that Penn's AEE is wider than MUAD but much narrower than the proposed AEE in this study.

6.5 Discussion on Experiment Design

The procedure of the experiment was smooth and went according to plan. The most important difference between the proposal and the real experiment was, in the proposal, two subjects are considered. It was also proposed to have two motion conditions, this means a complete two by two matrix experiment could be done. The motion condition was reduced to only one: with and without motion, although there were noticed differences between the pre-designed filters. However, the trade off between time consumption and experiment complexity had to be done. A more practical plan is hence proposed.

On the other hand, there is some other modification to reduce the time consumption of the experiment. Firstly, the added dynamics is reduced from 12 sets to 8, by removing the very low frequency 1.2 to 1.5 rad/s and very high frequency set from 8 to 10 rad/s. These frequency are removed based on the result from Penn's study. However, the experiment result shows that the interesting area is either in very high frequency or very low frequency.

The most important modification of experiment procedure is to define the damping ratio in a preliminary experiment. In this way, only 5 damping ratio are tested for each set of added dynamics. It saves lots of time on searching the boundaries. The pre-defined damping ratio is also useful for different subjects. The advantage of this method is not only save time, but also make the experiment more rigorous. However, the disadvantage is that the selected damping ratios may not be transferable completely between subjects, an experiment with more subjects should be performed in the future to investigate the workability of this method.

Quality of Data

Two subjects participated in this study, while only one set of data was used. However, the quality of this data was considered as good. All the 16 sets of data were consistent since the ratings deteriorated consistently with increasing added dynamics as shown in Table9. And the task performance were steady and met the requirements.

With this data, it is possible to develop an AEE as shown in Figures 22 and 23. But to investigate the effect of motion and D.O.F of added dynamics, the envelope alone does not provide sufficient information..

The consistency of data had benefited from the modification of experiment procedure. With a preliminary test, the pre-defined damping ratios were expected. To ensure the data making sense, two sanity checks were used for each set of added dynamics.

Noticeability Rating Scale

The performance requirement is one of the control variable in this experiment, so the assumption behind the rating scale is that: the task can be performed with a constant performance. The subject works well with the rating scale. He was not confused by the rating scale, and was confident with every given score. However, there is not enough information to conclude that the rating scale is a useful tool with only one subject.

The ANR is based on Penn's rating scale [10], while unlike HQ rating, or SFR, this rating scale is not validated. There is a need for a validated tool to assess pilot's perception on simulator model dynamics. A validation could be done by assessing pilot's control behaviour, to make sure that the pilot perceives a change when he says he does.

7 CONCLUSION AND RECOMMENDATION

This paper presents the result of the experiment to study the effect of motion cues and helicopter D.O.F on AEE. However, with limited data, there is not enough confidence to answer the research question clearly.

The motion effects pilot's perception on high frequency. The pilot gets more sensitive to high frequency added dynamics with motion. But there is no special pattern found in the other frequency range to confirm that motion has an effect on AEE.

The natural frequency of pole and zero of the Added Dynamics does have an effect on pilot's noticeability of added dynamics. Different forms of added dynamics needs to be studied in the future. With the current data, it is impossible to make a strong statement. But there is confidence to say that the added dynamics has an influence on AEE.

In conclusion, both hypothesis proposed in this paper are rejected. Hence a further study on this topic is necessary.

For future research, there are some recommendations:

- The experiment can be performed with different forms of Added Dynamics. To figure out the effect of parameters of added dynamics to pilot's perception, the type of gain and natural frequency can become the independent variable in the future experiment. The number of poles and zeros can also be an independent variable.
- The effect of helicopter D.O.Fs should be studied by an experiment, with at least two conditions: added dynamics on pitch, and added dynamics on roll. In this study, added dynamics were applied on pitch, it was quite difficult to compare the result with previous research, because a different experiment design was used.
- The experiment can be performed with a wider range of frequencies. However for one experiment, it is better to just focus on one short range of frequency, with a higher resolution, for example form 5 to 8 rad/s, and get 10 sets of added dynamics within this range.
- The quality and quantity of pilots are very important to this study. It is better to perform an experiment with multiple pilots.
- To investigate the effect of motion, different motion filters need to be tested. An experiment with multiple motion conditions can be performed. By focusing on one or two sets of added dynamics, the time consumption of the experiment can be controlled.

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Part II

Literature Review

Chapter 1

Introduction

Background Information

The use of flight simulator for pilot training has become more and more popular [1]. As mentioned by Moroney et al. [2], training using a Simulator Training Device (STD) has the following advantages: training of pilots with minimum risk, training device with good availability, training with extreme conditions like system failure, reduction of cost and environmental impact. [2].

The risk of an accident with a helicopter is much higher than with a fixed wing aircraft [3], indicated by statistics that the accident is usually caused by human error [4]. Thus more effort should be done to improve pilot training for helicopter. For hazardous conditions which give the highest accident rates, for example, flight in extreme operational environments or system failure, training with STDs has became the most suitable choice [5]. However, the helicopter simulators are not as developed as a fixed wing simulators, due to the complex dynamics behind the model [5]. On the other hand, training with helicopter simulators are relatively less cost efficient because the demand is low. [6]

In order to fulfill the training requirements, qualification is necessary for helicopter simulator training devices. Pavel et al. [7] in 2013 has assessed the qualification standards of helicopter simulation, it points out the current qualification standards for helicopter simulator are still insufficient and may lead to overconfidence in the simulator. Current qualification by meeting certain tolerances applies only to a limited range of aircraft responses, and matching these responses does not necessarily means it fulfills the training requirements. [7] . A method is needed urgently in this field, to find a way of "judging" the fidelity of helicopter simulation.

Problem Statement

Besides the simulator cueing system, like visual system and motion system, the quality of simulator is highly dependent on the mathematical model [8]. The quality of the mathematical model, in other words, model fidelity can be assessed by model validation. However, the main shortcoming of helicopter simulation model validation is inherent: for different operational uses, the required fidelity can differ. So the question becomes how to define the required level of fidelity, or what can be considered as "sufficient" fidelity.

During the research, it is found that the state of the arts of model validation are mainly performance criteria based on time domain tolerance. But besides handling qualities and performance, what does the pilot actually feel about the model? Mitchell et al. [9] attempted to investigate the tolerance based on frequency response analysis, by using the method suggested in [10]. The method is called Maximum Unnoticeable Added Dynamics(MUAD). It defines the boundary in frequency domain that any added dynamics within it will not be noticed by pilots.

In 2006, Mitchell et al. [11] identify the envelopes in frequency domain that define the boundary of acceptable error between a simulation model and a real aircraft. It is assumed that pilot will not feel any difference if the error falls within this boundary. Instead of examining handling qualities, the boundary is based on pilots' perception about the added dynamics in the mathematical model.

To show the specific purpose: ”define the allowable errors in helicopter simulation validation” [11], and to distinguish from MUAD, this envelope is named Allowable Error Envelopes(AEE).

Motivation

As indicated by Mitchell in his own work [11], AEE are dependent on the bandwidth frequency of the baseline model configuration. (roll attitude bandwidth in Mitchell’s experiment.) On the other hand, these envelopes were developed based on simulation data for a single pilot. AEE are not universally applicable for now, but Mitchell suggested the possibility to adjust the envelopes so that they can become an universal tool for simulation model validation by taking different pilots and model configuration into account. [11]

To further investigate the application of AEE, similar experiment were reproduced by Hess [12] in 2009 and Penn [13] in 2013. By testing with the same helicopter model and multiple pilots, Penn indicated that AE Envelopes are dependent on simulator configuration and vary for different pilots. The main recommendations that motivate the current study are:

- AEE may be affected by motion cueing.
- AEE may differ when added dynamics are applied on other axis. Since both Mitchell and Penn did the experiment with added dynamics on roll.

The literature study on helicopter model validation is given. Different assessment of simulation fidelity are discussed, with the focus on the AEE. To investigate the effect pf changing the D.O.F of added dynamics and adding motion, a literature study on helicopter modelling and simulation motion systems is also given in this report.

This Literature review will focus on the studies by Mitchell [11], Hess [12] and Penn [13] about the AEE. The proposed research project is a further investigation of the feasibility of applying AEE on helicopter simulation model validation. Thus the aim of the literature review is to find the relevant studies that can support the proposed research and hence answer the research questions.

Report Layout

The Preliminary Thesis Report contains two parts, in the first part, a literature study on helicopter model validation is given. Chapter 2 will give a brief introduction about the development on STD, and introduce the idea of simulation fidelity, which will be discussed in detail in Chapter 3. Here, different definitions and criteria of fidelity will be introduced, both objective and subjective assessment will be discussed. Chapter 4 will talk about development of MUAD and AEE. In Chapter 5, the helicopter model will be discussed in detail with a study on D.O.F of added dynamics. Chapter 6 will give the literature study on motion cueing of simulator.

Based on the result of the Literature Study, a research proposal is given in the second Part, with the main research question, and a detailed experimental set up, followed by a research plan.

Chapter 2

Develop of Helicopter Simulation Training Devices

The advantages of using flight simulator for training is give by Moroney et al. [2]. Also the safety impact of using STD instead of airborne training, according to Allerton [14] is mentioned:

- Reduction of the training cost, specific in operation rate.
- Reduction damage of the training equipment, like jet engine.
- Reduction pollution to the environment.
- Reduction the risk of injury of pilot during training.

In this Chapter, a brief background information about Simulation Training Devices(STD) will be given, section 2.1 will talk about the historical development on STD, section 2.2 will discuss the difference of simulation between fixed wing aircraft and helicopter, and the challenge in helicopter simulation, and finally, section 2.3 will introduce simulation fidelity.

2.1 Using of STD on Training

The development on flight simulation for pilot training started in early 1900s [15], as shown in Figure 2.1, the pilot experienced the effect of control by the motion provided by instructors, the so called on-ground training device could only give trainer a quite limited experience of flight [14].

Figure 2.1: circa simulator in 1911(The Library of Congress) [15]

The demand for pilot training increased after World War One [15] due to the rapid expansion on aviation industry. This led to the evolution of simulation training devices. During the late 1920s, Edwin Link [16] developed a flight training device that for specific training requirement.

He tilted the devices by compressed air, as shown in Figure 2.2. The simulator he developed is well known as ”Blue Box” [17], which is a big step in the evolution of flight simulators. With the following reasons [14]:”He exploited specific engineering technologies to produce a flight training device, which is developed to meet specific training requirement.” It mentioned that Link is the founder of the modern flight simulator because his investigation proved that effective training can also take place on the ground. [15]

Figure 2.2: Link simulator in 1930 [14]

Modern aircraft are getting more and more complex, the flight simulation training devices are also getting more advanced with the development of analogue computing and digital computing. The microelectronic revolution in the 1980s gave a huge improvement on flight simulator with the semiconductor computer [18]. It provided the opportunity to represent the complex dynamics of aircraft, and access high resolution visual system.

Figure 2.3 give the structure of the modern flight simulator, it consists of different components. While the most important one is the Equation of Motion(EOM), which represents the dynamics of the aircraft itself. The EOM determine the states of the simulator, by taking input from the dynamic model and give output to the simulator systems like visual system or motion system. It works as a computer of the simulator, which calculate and update continually.

The aerodynamics model is also a critical component for a flight simulator, it represent the aerodynamics force and moment of the aircraft. Usually the data comes from flight test or Computational Fluid Dynamics (CFD) results. Engine model and gear model are also implemented to reproduce the real flight.

Visual system is another important subsystem, as visual is the primary sense for a human being [19]. The quality of visual system is mainly depend on display resolution and its refresh rate [15]. Other subsystems like control loading also help simulation perform closer to a real aircraft.

The motion system, however is more critical for the current study.It replicates the physical movement of the real aircraft, and hence provide pilot a physical sense of motion. In Chapter 6, motion will be discussed in detail.

The STD nowadays is developed and operated widely. In 1992, International Civil Aviation Organisation (ICAO) gave the guidelines called Manual of Criteria for the Qualification of Flight Simulators (MCQFS) [15], which shows that: using of flight simulator as training is accepted internationally, while an international standard for STDs is established, and different levels or categories of STDs are defined. [20].However, these standards are applied for fixed wing aircraft. The development of helicopter STDs are still lacking behind.

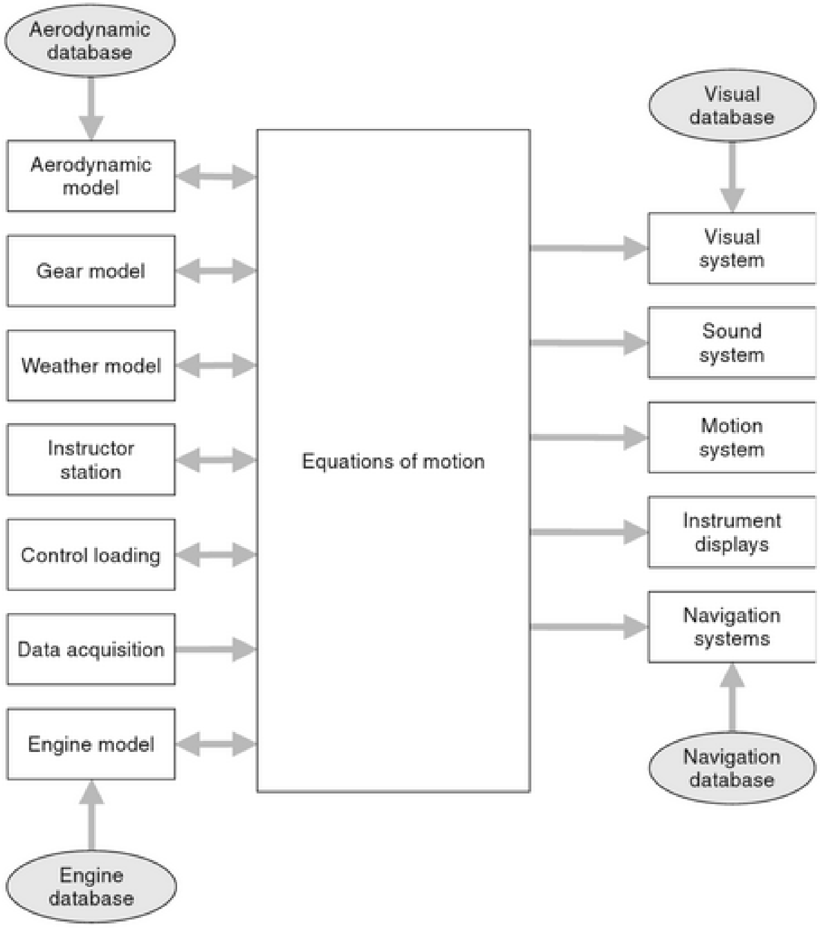

Figure 2.3: Modern Flight Simulator Structure [21]

2.2 Challenges: Fixed Wing vs Rotorcraft

The use of flight simulator for fixed wing aircraft is playing an important role in pilot training [2], however, the helicopter simulator is not as developed as the fixed wing [5]. A short literature study will be given to analyse the reasons for this mismatch and the current challenges of helicopter simulators.

According to [6], the most important differences between simulation of a fixed wing aircraft and a rotary wing aircraft, which are leading the lack behind of development on helicopter simulator are: cost, technical issues, practical issues, certification and qualification.

Training Cost

Training pilots for helicopters has usually less demand compare to fixed wing aircraft. Hence using helicopter simulators for training pilots is less cost efficient. On the other hand, the purchase cost for helicopter simulator is higher, due to the complex dynamics and more developed software. More importantly, near-ground operations place more stringent requirements on visible details, like texture. [6]

Technical Issues

The mathematical model of a helicopter is much more complex than a fixed wing aircraft. There are much more moving parts in a helicopter which results in a very complex dynamics and aerodynamics model. And its physical interactions and cross-axis dynamics make the helicopter complicated.

The lack of computer power used to be the reason that left helicopter modelling behind [5]. Even if nowadays, the computer is sufficiently powerful for simulating the complex dynamics, to reach the similar level of fidelity, its cost on software develop is still higher than a fixed wing aircraft [6].

Finally, for a helicopter pilot, downside view is quite important since near ground operation is needed during the flight. In this way, the visual system for helicopter is usually more elaborate than for a fixed wing simulator. Usually helicopter simulators require a larger field of view.

Practical Issues

During the use of helicopter STD, there are some practical issues:

- The utilization of helicopters is usually lower than for fixed-wing aircraft. This lead to the possibility of performing training in ”non-utilized time”.
- The operational task for a fixed-wing aircraft is usually more straight forward, compare to their rotary counterparts [6].
- Centralized training facilities are developed for fixed-wing operators, but not for helicopter operators yet.

Certification and Qualification

As mentioned by Pavel et al. [7], the qualification standards for helicopter simulator should be improved. The current qualification is based on certain tolerances on limited aircraft responses, and matching responses may not guarantees similar handling qualities. The most important reason, as indicated by Timson [22], simulator tolerance for helicopter are derived from fixed-wing counterparts. The proper engineering base behind these tolerances is not sufficient.

The qualification based on aircraft responses should be supplemented with handling qualities and pilots’ perception on aircraft dynamics [22]. To achieve this, two things are needed: more knowledge of impact of simulation cues like motion on training effectiveness, and the method to assess handling qualities and pilots’ perception. To understand these, a study on simulation fidelity is necessary.

The fundamental challenge for helicopter simulator is to find out a criteria that a simulator is of sufficient quality for the required purpose. In other words, what simulation fidelity is needed for helicopter simulator to fulfill the training requirements. The following section gives a brief introduction of simulation fidelity.

2.3 Training and Simulation Fidelity

The term Simulation Fidelity was described by Allen in 1980s [23]. He mentioned that simulation fidelity represents how a simulation can perform a real aircraft. The criteria however, is not quantified by a metric, as it can only be described as a ”high fidelity” or ”low fidelity”. Thus, after 20 years, a more detailed category of simulation fidelity is investigated by A.T.Lee [24]. Lee also mentioned that the simulator should provide pilot an experience of flight but not aim to reproduce the complex physical dynamics, thus the approach for simulation fidelity is not only focus on the ”physical flight environment" anymore, simulator attributes like Motion and Visual will also define the fidelity.

Figure 2.4 shows that increasing in the complexity of simulator will results in an increasing of development cost as well as operation cost, the higher cost on the other hand does not necessary means a higher effectiveness of training, it will result in a stagnation or maximum point that further investment could even reduce the fidelity [25]. As pilot may be affected by other simulator cueing, results in a decrease in fidelity for the training purpose.

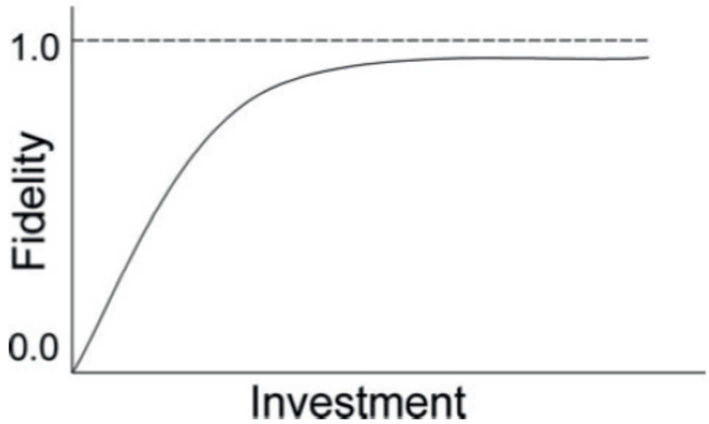

Figure 2.4: Fidelity vs Investment [25]

Visual fidelity [19], suggested by Rinalducci, describes the simulation fidelity as the reproduction of the visual and audio of the real flight. It not only provide the visual environment for a pilot, but also the sounds like vibration [19]. This fidelity is quite useful as the visual cueing is the most straight forward sensor by a pilot [19]. However, Schroeder stated that reproducing the visual does not guarantee the training effectiveness [26], and he suggested another fidelity based on the motion cueing of a simulation, motion fidelity.

Motion Fidelity [27] is the fidelity based on the motion cueing of the simulators, the early work on motion system of simulation is published by Sinacori [28]. As another important physical fidelity, motion fidelity is defined as the degree to which a simulator can replicate motion of the aircraft's dynamic response. The modern flight simulators have a six degree-of-freedom motion-base which can translate and rotate in all directions. High-frequency motion components can usually be simulated quite well, whereas loadings due to sustained accelerations can not be simulated.

There are a lot of definitions of simulation fidelity, while the problem is which fidelity should be used for a specific task of training, and what is the metric to measure the fidelity or what is the criteria for simulation fidelity? It will be discussed in the next Chapter.

Chapter 3

Assessment on Simulation Fidelity

This chapter discusses in detail the simulation fidelity of helicopter and the assessment on the fidelity. Section 3.1 gives a short introduction to the development on helicopter simulation fidelity. While Section 3.2 and 3.3 introduces some methodologies for fidelity assessment.

3.1 Challenges on simulation fidelity

The study of simulation fidelity consists of two main questions: what is fidelity, and how to measure it. Simulation fidelity measures the quality of simulator. On the other hand, simulation fidelity depends on to what extent training goals are satisfied by using the simulator. To effectively train a pilot, it is very important to understand which subsystems are required, ie. a motion system is not necessary if the pilot uses STD only for training how to work with the cockpit.

The first question to get understanding the simulation fidelity is hence: what is fidelity? As indicated by Liu et al. [29], a clear and agreed-upon definition of fidelity is very difficult to find. Liu et al. mentioned in [29] that there are some general issues on simulation fidelity:

- 1. no universal and unambiguous definition
- 2. inevitable and uncontrolled subjectivity
- 3. no quantified method of measuring fidelity
- 4. no referent for simulation fidelity

The first issue is to find out a clear definition of what is meant by simulation fidelity. The following section discusses about it in detail.

3.1.1 Definition of fidelity

There are more than 20 different definitions of simulation fidelity in the literature:

- Simulation fidelity: degree to which device can replicate actual environment, or how "real" the simulation appears and feels. [25]
- Physical fidelity: degree to which device looks, sounds and feels like actual environment. [23]
- Visual-audio fidelity: replication of visual and auditory stimulus. [30]
- Equipment fidelity: replication of actual equipment hardware and software. [31]
- Motion fidelity: replication of motion cues felt in actual environment. [26]
- Psychological-cognitive fidelity: degree to which device replicates psychological and cognitive factors. [26]
- Task fidelity: replication of tasks and maneuvers executed by user. [32]

- Functional fidelity: how device functions, works and provides actual stimuli as actual environment. [23]

It is stated in [29] that a common-agreed definition of fidelity is difficult. The subdividing definitions make it more confusing. More importantly, the listed traditional definitions of fidelity are mainly physical fidelity: they describe how simulator can replicate the physical flight environment. The main shortcoming for these definitions is that human behavior and perception are not taken into account.

On the other hand, Lee [24] indicated perceived fidelity based on the human-machine integration. Perceived fidelity, according to [13] is far more comprehensive than physical fidelity, as it does not only replicate the physical flight environment, but also takes pilot's perception and human-machine interaction into account.

In my words, simulation fidelity can be defined as how close pilot feels the simulation is similar to real condition. As human behavior is difficult to quantify objectively, the pilots' feeling about fidelity is hence subjective. The problem is then how to measure the simulation fidelity?

3.1.2 Measurement of fidelity

The other challenge on simulation fidelity is to find out a quantified method of measuring fidelity. In this section, some general issues is discussed, and in Section 3.2, a few fidelity assessment techniques are given in more detail.

Physical fidelity vs Perceived fidelity

As mentioned before, the traditional definition of simulation fidelity are mainly based on physical fidelity. They describe how good the simulator can replicate the physical flight environment. To measure such a fidelity, Federal Aviation Administration(FAA) categories of flight simulator define the measuring of physical components of a flight simulator for training.

However, pilots' perception is not taken into account. A different approach, so-called perceived simulation fidelity has become more popular. [13]. Not only to understand the physical components of flight simulator, but also study the pilot behavior, perceived fidelity has shifted the academic research attention from dynamics model to human-machine system and manual control cybernetics. [24]

When pilot's behavior is taken into account, the measurement of fidelity gets more complex. Compare to examine the performance of the simulator, pilot's experience and feeling will be more important in this case. The biggest challenge is that human behavior is hard to predict, and difficult to quantify.

Objective vs Subjective

The fidelity assessment can be done in two different ways, objectively and subjectively. For a traditional physical fidelity assessment, an objective approach is assumed to be sufficient to determine the fidelity [33]. As discussed before, perceived fidelity is a more comprehensive approach. However, it is difficult to assess pilots' perception objectively, hence a subjective assessment is used.

The most straight forward approach for objective assessment is to compare the performance from a real flight test and simulator. An example will be hover, climb performance defined by FAA.

A perceived fidelity is usually processed by a subjective assessment. An example will be subjective handling quality approach, which is discussed in section3.2. During the subjective assessment, the pilot will give comments on the difficulty of performing the task and give a rating numerically based on the rating scale. With the assumption that handling quality ratings can represent the pilots' perception on simulator, this rating can assess the fidelity to a certain extent. [34]

Time domain vs Frequency domain

In a normal regulation like FAA, the performance criteria is based on time domain tolerance. It is easier to understand, and allows predictions and regression models for the signal.

However, according to [35], some handling qualities aspects are difficult to be analyzed in time domain. An frequency domain analysis is hence a suitable way for validation. Frequency domain analysis is also a more suitable tool where processes like filtering, amplifying and mixing are required. Due to the transformation, frequency response analysis is hence more difficult to collect in a flight test, and require more calculation effort [36].

3.2 Subjective Fidelity assessment techniques

The second question when study the simulation fidelity is how to measure fidelity, when pilot's perception is taken into account. In this section, some subjective assessments are briefly introduced.

3.2.1 Handling Quality Rating

Using handling quality ratings to assess fidelity is a common method.To understand this assessment, a short introduction to handling quality is given.

Handling quality is defined as "Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role [35]". For further understand handle quality, some general terms needs to be discussed:

ADS-33E
ADS-33E [37] is the handling quality standards for military helicopter, it defines response types required to achieve different levels of handling qualities with different mission task element.

Mission Task Element
Mission Task Element (MTE) are the manoeuvres defined in ADS-33 [37], like hover, bob-up. There are three different types of MTE: Good Visual Conditions (GVE), Degraded Visual Conditions (DVE) and Instrumental Meteorological Conditions (IMC).

Usable Cue Environment
Usable Cue Environment (UCE) is one of the important factor that influence the handling quality. It is used to measure the quality or usefulness of the visual cueing.

Response type
It is the required response to achieve the certain level of handle quailty, examples are Rate Command (RC), Attitude Command and Attitude Hold (ACAH) and Translational Rate Command and Position Hold (TRCPH).

The Cooper and Harper Handling Quality Rating (HQR) [34] is a subjective measurement of handling quality. It is also commonly used to assess simulation fidelity. The pilot is asked to analyse the workload and difficulty of the task by going through a decision tree.

The question tree of HQR is shown in Figure 3.2. 10 pilot ratings are available after going through the decision tree, the less rating, the better handling quality, ie rating 1 is the best. Compare with ADS-33 HQ requirement, a level 1 handling quality can be achieved with rating 1 to 3. Level 2 handling quality is related to rating 4 to 6, and rating 7 to 9 will end up with level 3. A rating 10 which is the worst means the task cannot be performed according to the specified requirements.

Figure 3.1 shows the relationship among MTE, UCE and response type. When UCE decrease, pilots get worse visual aid, the response type to hold level 1 of hanling quality also changes.

MTE	UCE = 1		UCE = 2		UCE = 3	
	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
Required Response-Type for all MTEs. Additional requirements for specific MTEs are given below.	**RATE**	**RATE**	**ACAH**	**RATE + RCDH**	**TRC+RCDH + RCHH+PH**	**ACAH**
Hover			RCDH + RCHH			RCDH + RCHH
Landing			RCDH			RCDH
Slope landing			RCDH			RCDH
Hovering turn			RCHH			RCHH
Pirouette			RCHH			RCHH
Vertical Maneuver			RCDH			RCDH
Depart/Abort			RCDH + RCHH			RCDH + RCHH
Lateral Reposition			RCDH + RCHH			RCDH + RCHH
Slalom	NA	NA	RCHH			RCHH
Vertical remask			RCDH			RCDH
Acceleration and deceleration			RCDH + RCHH			RCDH + RCHH
Sidestep			RCDH + RCHH			RCDH + RCHH
Turn to target			RCDH + RCHH			RCDH + RCHH
Divided attention required	RCDH + RCHH + PH		RCDH + RCHH			RCDH + RCHH

Figure 3.1: Typical ADS-33E requirement [37]

Based on HQR, Hess et al. develop a method called Handling Quality Sensitivity Function (HQSF) [38], it measured how handling quality rating affect the fidelity. The basic idea of HQSF is to figure out which aspect gives the most effect on the fidelity of a simulation.

The handling quality can be measured both subjectively and objectively. An example of objective handling quality is predicted handling quality measurement. However, a high handling qualities does not necessarily means a good fidelity. Because it only shows the response type necessary for a desired level of HQ in a certain task. A match of handling qualities only shows that similar response types are required which is not sufficient to prove the fitness for purpose [7]. This results that assess fidelity with handling qualities is not a good way.

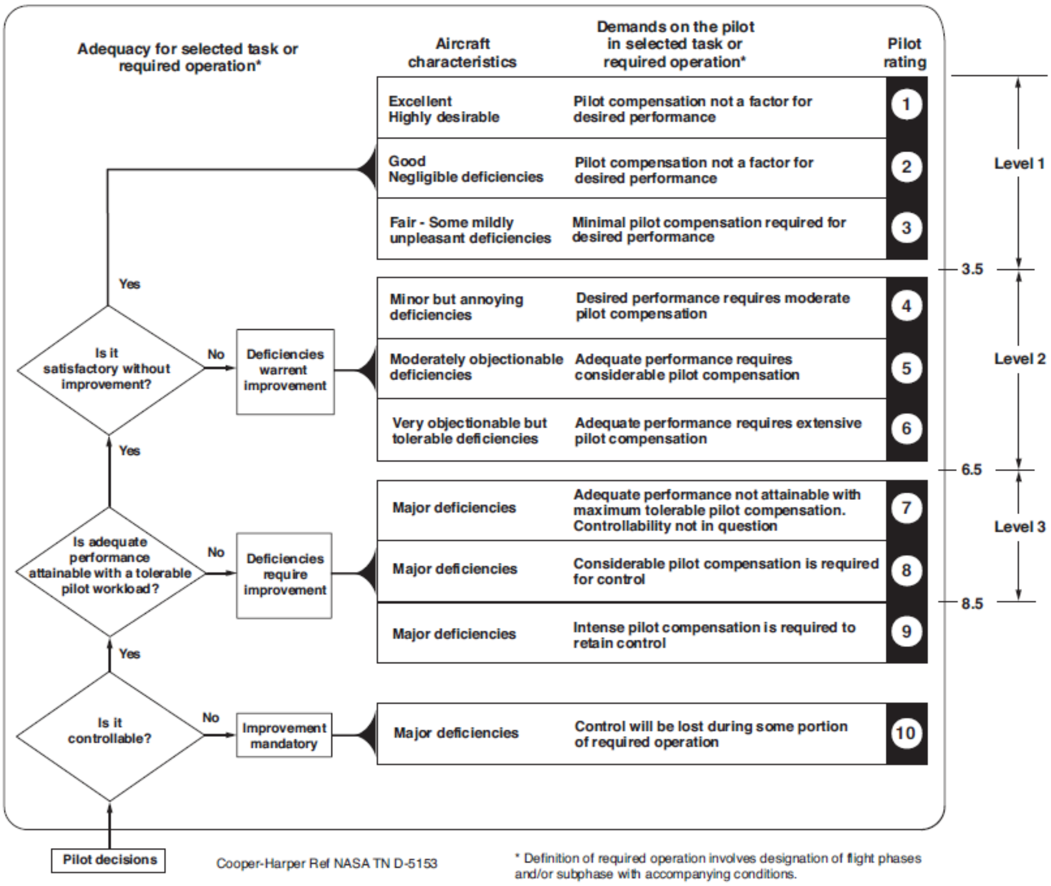

Figure 3.2: Cooper Handling Quality Rating [34]

3.2.2 Motion Fidelity Rating

Motion Fidelity Rating (MFR) is investigated by Schroeder [27], it is a much simpler method compare to HQR, by giving three different category:

- low MFR, the difference can be noticed easily from the simulation and real flight and objectionable.
- Mid MFR, the difference is still noticed but not objectionable.
- High MFR, no difference, motion is exactly like real flight.

It is a simple method however, it only focus on the motion cueing. A simulator can be bad in motion but still provide good handling quality [26]. And there is no proved statement that shows the direct relationship between motion and simulation fidelity.

3.2.3 Simulation Fidelity Rating Scale

In 2008, a metric called Simulator Fidelity Rating (SFR) for helicopter fidelity is developed by Timson [22]. This method is not focus on handling quality, but on the training requirement for the simulator. It measures how the simulator is capable for the training task, with four different levels [39]:

- Level 1, the training on simulator is sufficient for a pilot to perform same task on aircraft.
- Level 2, some additional training is still required before a pilot can do it on aircraft.

- Level 3, simulator is not suit for this task.
- Level 4, simulator cannot provide the training for this task at all.

The assessment on simulation fidelity rating scale is quite similar to HQR. It takes the pilot strategy into account as well. Figure 3.3 shows the decision tree to assess SFR scale. Similar to HQR, rating 1 to 10 is given, the lower rating, the better. To match the listed 4 level of fidelity, score 10 will leads to level 4, score 7 to 9 is level 3, score 4 to 6 is level 2 and score 1 to 3 is related to level 1 fidelity.

The main difference between HQR and SFR is , the fidelity rating for SFR is dependent on both performance and strategy. The task performance is defined similar to the HQR. While in SFR, the pilot will not only be asked the difficulty to maintain the performance, but also the adaptation of strategy. For example, a pilot can attain the representable performance, however, excessive adaptation of strategy is required to complete the task. In this case, a rather low rating should be given.

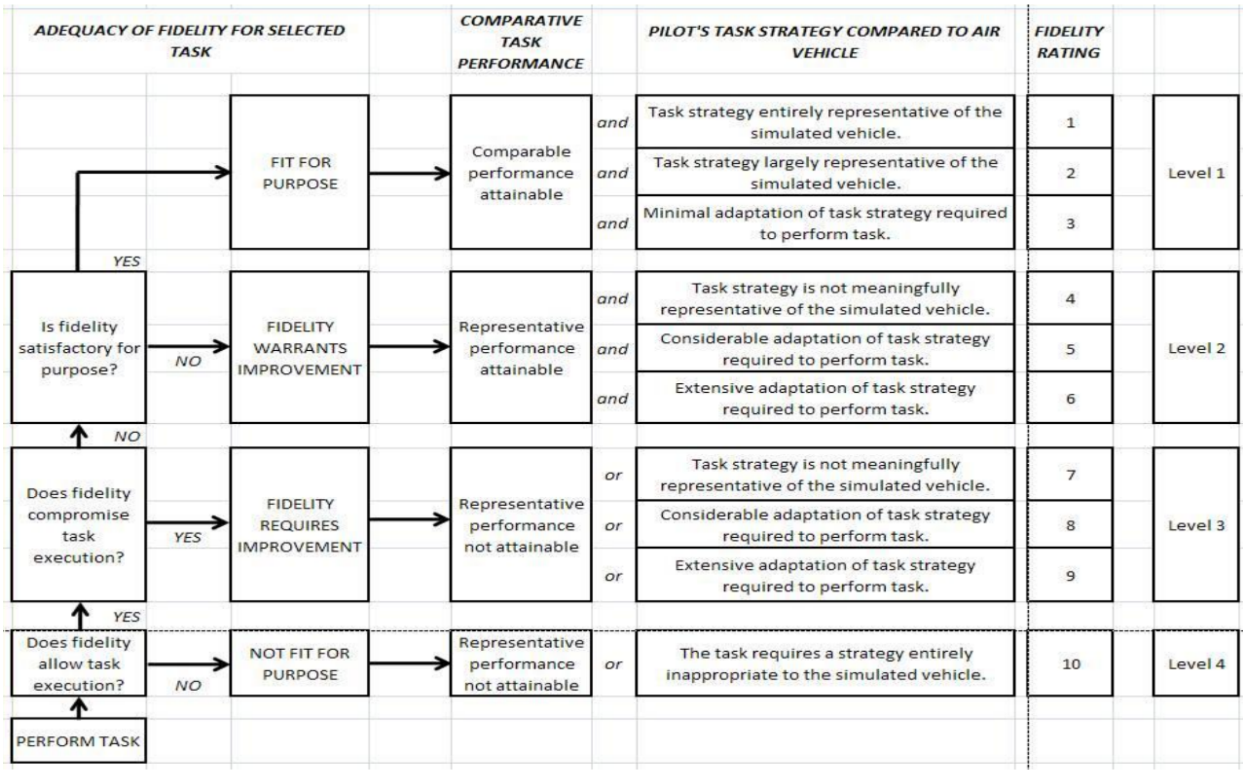

Figure 3.3: Simulation Fidelty Rating [40] [36]

3.3 Objective Fidelity assessments techniques

In this section, an example of traditional objective fidelity assessment is discussed in detail. After that a new method called allowable error envelopes is introduced, which will be further analyzed in the next chapter.

3.3.1 Predicted Handling Quality Measurements

Handling quality can also be assessed in an objective way, an example will be predicted handling quality measurements. It is a boundary based on the bandwidth and phase delay of the frequency response.

The responses of aircraft can be classified in terms of frequency and amplitude. As showed in Figure 3.4, the stability and agility of the aircraft is determined by both frequency and amplitude. The shape shows the trade-off relationship between stability and agility, and forms the so-called operational flight envelopes.

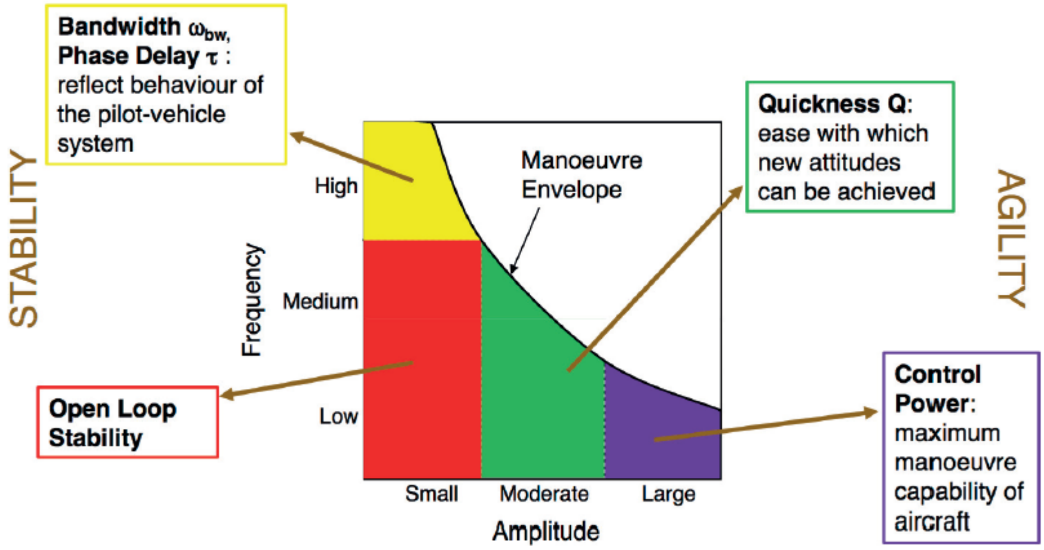

Figure 3.4: Response characteristics [36]

The interesting areas which are shaded with different colors are in the corner of the envelope. It also shows the handling quality criteria for different type of response:

- High frequency, small amplitude: Bandwidth and phase delay
- Low frequency, large amplitude: Control power
- Low frequency, small amplitude: Open loop stability
- Medium frequency and amplitude: Quickness

For the response of high frequency with small amplitude, the handling quality criteria for this region is bandwidth and phase delay. The phase bandwidth frequency is defined as the frequency where the phase crosses the 135 degree. The gain bandwidth frequency is defined as the frequency where the gain margin is 6 dB. The phase delay can be shown in Figure 3.5.

An example for the HQ requirement is shown in Figure 3.6, the requirement is based on ADS-33. The level of handling quality is corresponding to the requirement on ADS-33, with the two dependent measurements: bandwidth and phase delay. The boundaries are defined depending on MTE. In a helicopter operational flight envelope, the showed region corresponds to the pitch axis in hover/low speed for target acquisition and tracking. [37]

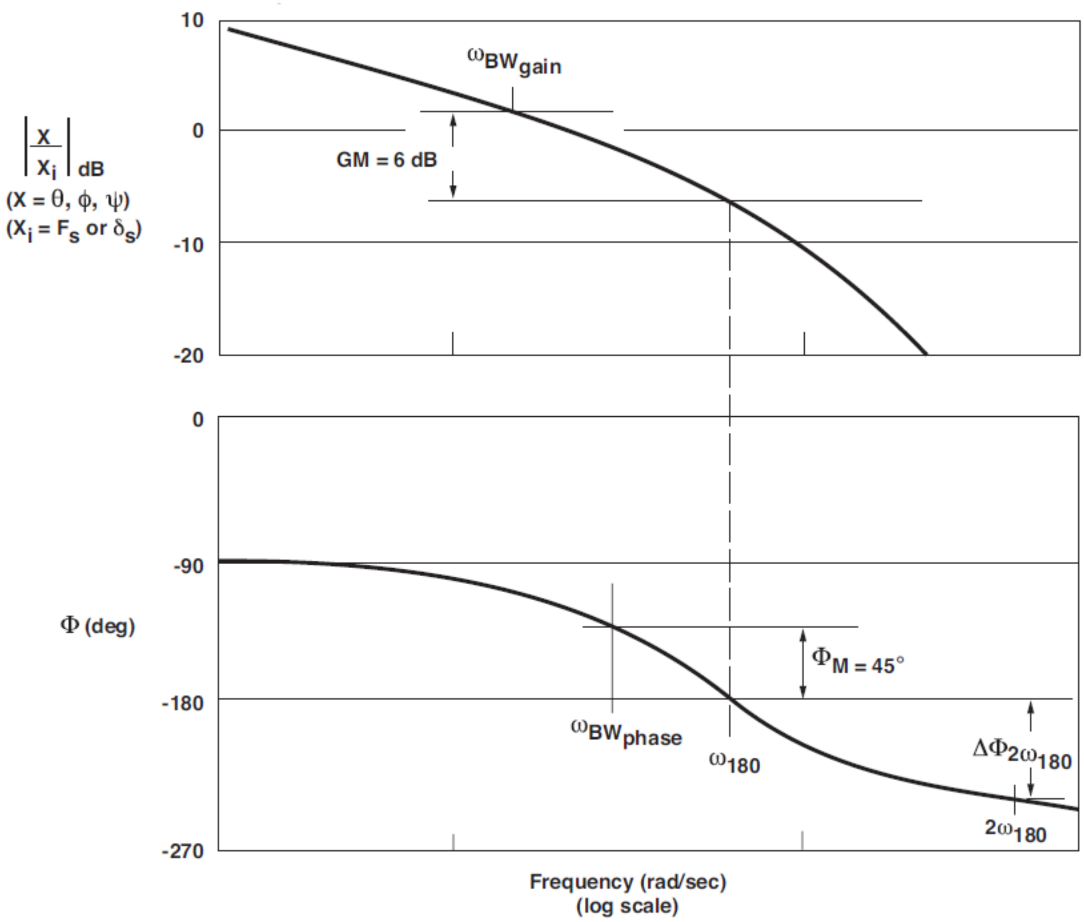

Figure 3.5: Phase Bandwidth shown in Bode plots [41]

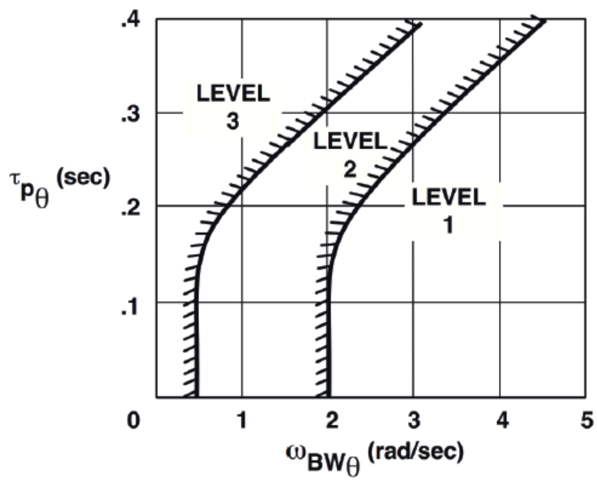

Figure 3.6: Handling quality requirement for bandwidth and phase delay [37]

3.3.2 Allowable error envelopes

By reviewing the different fidelity assessment techniques in the literature, the following requirements are summarised to design a new assessment on simulation fidelity.

- A frequency domain analysis
- Take pilots' perception into account
- A quantifiable method of measuring
- As objective as possible

Mitchell et al. [11] tried to find out an approach that full fill these requirements. By verifying the possibility to define a boundary on simulation error in frequency domain, he developed the Allowable Error Envelopes(AEE) as a validation criteria for helicopter simulation model. This approach is based on the method called Maximum Unnoticeable Added Dynamics(MUAD) which will be discussed in Chapter 4.

The main idea of AEE is to use the Bode plots of added dynamics applied to the simulation model to identify the boundaries between unnoticeable and noticeable dynamics. Based on pilots' evaluation, it assumes that any added dynamics with in this boundary will not be noticed by the pilot. These boundaries form the envelopes that shows the maximum allowed mismatch between the simulation model and the real aircraft. In next chapter, this approach and the theory behind it will be discussed in detail.

Chapter 4

Development of Allowable Error Envelops

Allowable Error Envelopes(AEE) are based on theory of Maximum Unnoticeable Added dynamics(MUAD), while the origin of MUAD is the equivalent system approach [42]. This chapter discusses how AEE is developed.

Section 4.1 reviews the origin of this method: equivalent system approach, and explains the importance of the mismatch criteria. Section 4.2 describes how MUAD is developed as a mismatch criteria for equivalent system. In section 4.3, early work on application of this mismatch criteria is discussed. And AEE investigated by Mitchell et al. [11] is then reviewed. Finally, section 4.4 reviews the further research on application of AEE to model validation.

4.1 Low Order Equivalent System

Low Order Equivalent System(LOES) [43] is the approach to match the higher order augmented model with a lower order system. The development of this approach is due to the growth of highly augmented aircraft. This increases the difficulties on handling qualities analysis because of the high order of the augmented system. The idea behind LOES is to use a lower order system to approximate the high order augmented system(HOS) so that the classical flight quality can be assessed easily.

The basic principle of LOES is that the lower order system should show the similar behavior of dominant mode response of the reference aircraft. The dominant modes can be the Eigen mode like phugoid or short period. Additional to this, a time delay is necessary to represent the delay in control system like actuator. [44].

Figure 4.1 shows the High Order System(HOS), LOES, and LOES with a time delay on the Bode plot. The system are described in equation 4.1 4.2 and 4.3. [43]

$$HOS = \frac{s+0.7}{(s^2+4s+4)(s^2+16.8s+144)} \tag{4.1}$$

$$LOES(without \quad \tau) = K \cdot \frac{s+0.7}{(s^2+4s+4)} \tag{4.2}$$

$$LOES = K \cdot \frac{s+0.7}{(s^2+4s+4)} e^{-0.12s} \tag{4.3}$$

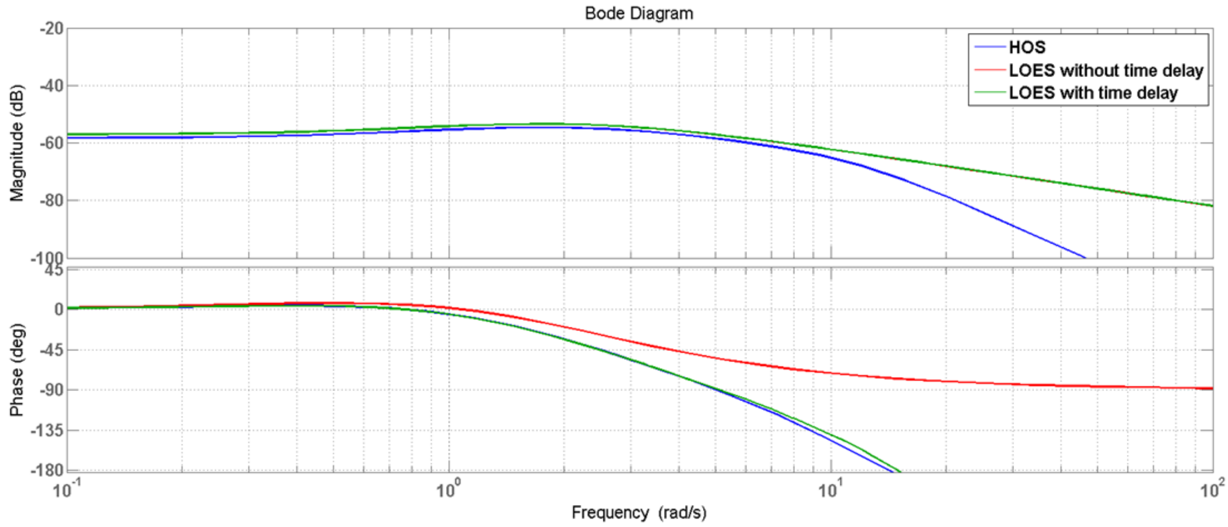

Figure 4.1: Low order equivalent system

As showed in Figure 4.1, the phase lag in the high order system is fixed with a time delay. This term represent the effectively time delay due to all the sources from the high order augmented system like delay in actuators or computational delay. It is believed that the approach with time delay showed "much better matching results compared to picking one dominant mode" [45].

4.1.1 Challenge: allowable mismatch

After understand the principle of LOES, the main challenge is hence to find out the acceptable level of mismatch between HOS and LOES. This criteria can define to what extent the low order system can replicate the high order system. One of the method is to develop a cost function that shows the mismatch between two systems, the other is to define a boundary in frequency domain. Both methods are reviewed in the next section.

Determine mismatch by cost function

A straight forward way is to calculate the mismatch with a cost function. For example in [46], a simple least-squared cost function is used as shown in equation 4.4. This cost function is just sum up the squared error for both magnitude and phase with n numbers of frequencies.

$$Mismatch = \sum_{\omega_1}^{\omega_n} \left[(G_{HOS} - G_{LOES})^2 + \alpha(\Phi_{HOS} - \Phi_{LOES})^2 \right] \tag{4.4}$$

With a transfer factor α, the error in phase (deg) can be adjust to be proportional to the magnitude in dB. In this way, the mismatch error for the chosen range of frequency can be calculated. According to [46], the number of frequency is usually chosen to be 20 and the mismatch under 12 will be acceptable.

An example of calculating mismatch in [13] and [46] is shown in Figure 4.2. In this case, the control force (F_s) to pitch rate ($\dot{\theta}$) response is represented by a LOES. The original HOS is a 11 order augmented system, and the approximate LOES is only a second order system.

It is showed on the figure that LOES does not match the HOS perfectly, the mismatch is varied for different frequency. By using the cost function mentioned in equation 4.4, the mismatch is calculated to be 18.1.

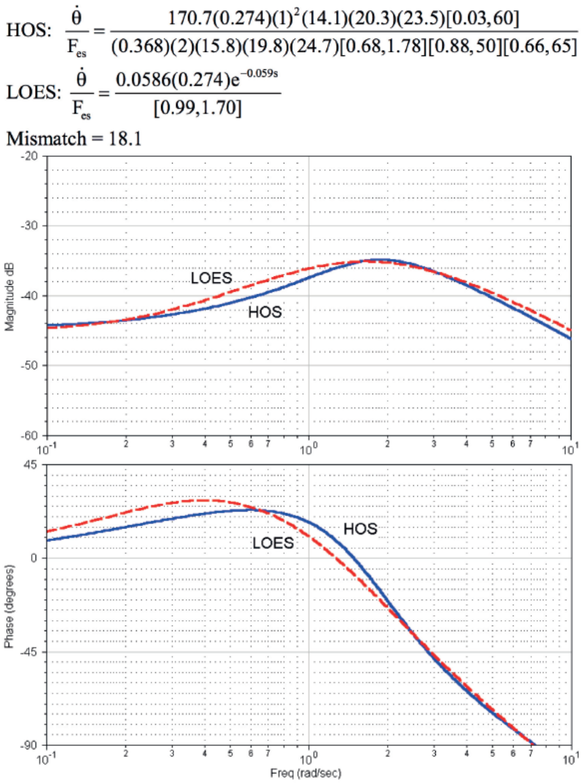

Figure 4.2: Example of Mismatch Cost Function [13] source: [46]

Although the cost function can calculate the mismatch in a numerical way, the function is dependent on the number of frequencies used. Also the cost function itself does not show any understanding of the aircraft model, it is purely based on mathematical process. The pilot's opinion on if the LOES can represent the original aircraft is also very important in this case. To show the engineering behind the LOES and add pilot's perception into consideration, the boundaries for the acceptable mismatch is investigated, which is reviewed in Section 4.2.

Boundaries for allowable mismatch

To ensure that the LOES can represent the original system, the acceptable level of mismatch is needed to be defined. An approach is to define a boundary that if the mismatch error fall within this boundary, the LOES can be considered to have similar handling quality as HOS. In the 1980s, engineers at McDonnell Douglas Crop.(Boeing) carried out the study to investigate the envelopes that define the acceptable mismatch [44]. This leads to the basic idea of Maximum Unnoticeable Added Dynamics, the MUAD [11] is the envelops on frequency domain formed by Bode plot of magnitude and phase angle.

The basic idea behind MUAD is that the added dynamics which is added to the aircraft within the boundary, will not be noticed by a pilot. To further analysis this approach, Section 4.2 will review the development of MUAD as well as the limitation of this method.

4.2 MUAD

In this section, the development of MUAD is reviewed. First part introduces the history of MUAD, following that, an example of determination of MUAD is given. Finally the application of MUAD and shortcoming of applying MUAD is discussed.

4.2.1 Neal-Smith program

The earlier work on MUAD is taken by Wood and Hodgkinson. [44]. They selected data from the Neal-Smith experiment [47], and draw the envelopes of MUAD. According to Mitchell et al. [48], the publish of flight data of Neal-Smith program leads to the development of MUAD.

The basic idea behind Neal-Smith program is adding dynamics to a reference model. It is assumed that the added dynamics can represent the effect of the higher order terms. The pilots were asked to give a handling quality rating, in this case a Cooper-Harper HQ rating which is discussed in Chapter 3. The rating is giving for both baseline system and the system with added dynamics. By compare the HQ rating, the critical added dynamics is determined.

In [47], the critical added dynamics is defined as the last set of added dynamics that the pilot's HQ rating is not degrading. The MUAD envelopes is based on the critical added dynamics cases in Neal-Smith program, by plotting the critical added dynamics on Bode plot for both magnitude and phase.

4.2.2 Procedure of determine MUAD

To review the methodology of MUAD, a replication work of determine MUAD is presented. The basic system is a pitch response of a linear helicopter model, as described in equation 4.5. Where δ_b represent the control input from cyclic and θ is the pitch angle.

$$H = \frac{\theta}{\delta_b} = \frac{1}{s(s+3)} \tag{4.5}$$

The added dynamics is chosen from the experiment data of [12] and [13]. The form of added dynamics will be discussed later, and a detailed analysis of added dynamics will be given in Chapter 5. In this case, the added dynamics can vary in intensity by adjusting the damping and frequencies as showed in Equation 4.6 [11].

$$Added\,Dynamics = K\frac{s^2 + 2\zeta w_{nz}s + w_{nz}^2}{s^2 + 2\zeta w_{np}s + w_{np}^2} \tag{4.6}$$

Critical added dynamics

The used added dynamics are shown in Table 4.1. By keeping constant frequency range, the amplitude of added dynamics is dependent on the damping ratio. This process of determine critical added dynamics is then repeated for different range of frequencies.

As shown in the Figure 4.3, case 1 to 3 and baseline response is plotted. The highlighted added dynamics is the critical case. It means at this frequency, this is the maximum allowable added dynamics. To determine the envelopes, the boundary is formed by the critical cases along the

Table 4.1: Added dynamics cases from [13] and [12]

Added dynamics	ζ	w_{nz}	w_{np}	Noticeability
case 1	0.4	2	2.5	Noticed
case 2	0.65	2	2.5	Unnoticed (Critical)
case 3	0.9	2	2.5	Unnoticed
case 4	0.2	3	3.75	Noticed
case 5	0.4	3	3.75	Unnoticed (Critical)
case 6	0.75	3	3.75	Unnoticed

frequency range.

Same procedure is applied to case 4 to 6. By plotting the added dynamics, the boundaries can be found. As shown in Figure 4.4, the boundary define the area that describe the acceptable added dynamics. It means the mismatch error fall within these area will not be noticed by pilot, hence can represent the reference dynamics.

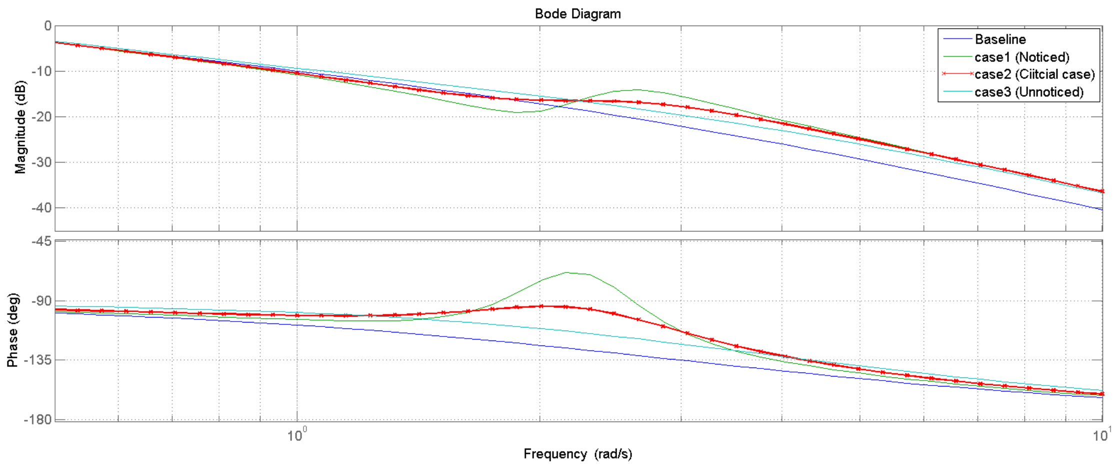

Figure 4.3: Added dynamics on reference system

Figure 4.4 shows a very smaller part of the MUAD envelopes. A tangent line is drawn across the peak position of the critical added dynamics. If enough data points are provided, a full, detail set of boundaries can be determined.

The full shape of MUAD envelopes is formed by 4 such kind of boundaries, describe the upper and lower limit for both magnitude and phase. This is discussed in the next section in more detail.

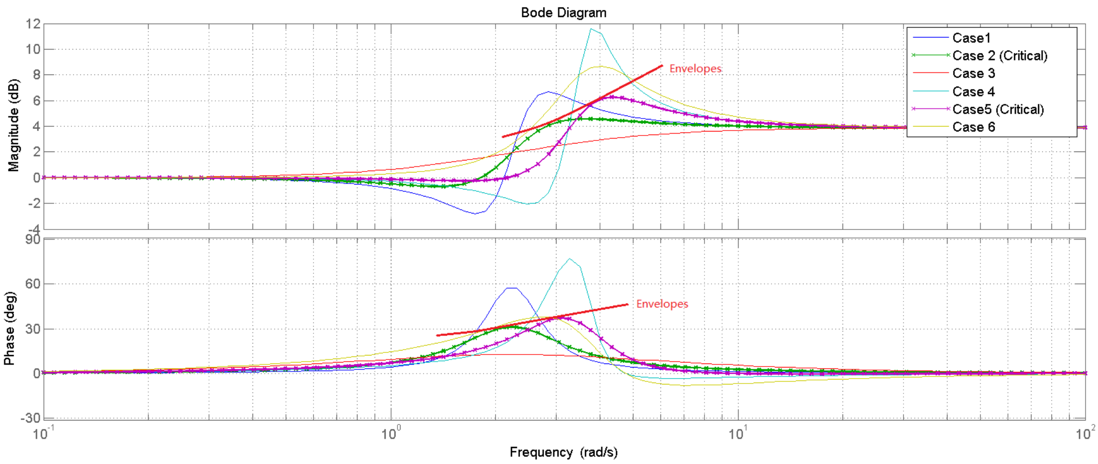

Figure 4.4: Determine of MUAD

MUAD Envelop

By repeating the steps of determine critical added dynamics for all the interesting range of frequency, the envelops of MUAD can be drawn. As shown in Figure 4.5, the shape of MUAD envelopes like a hourglass. The red dash line indicate the frequencies associated with manual control, from 0 to 5 rad/s [49]. It is clear that MUAD envelopes are narrower at these frequencies, therefore pilots are more sensitive to added dynamics in this region. At either end of the envelopes, the shape get wider. This means beyond and below these frequencies, pilots barely excite vehicle dynamics at those frequencies, hence less sensitive to the added dynamics.

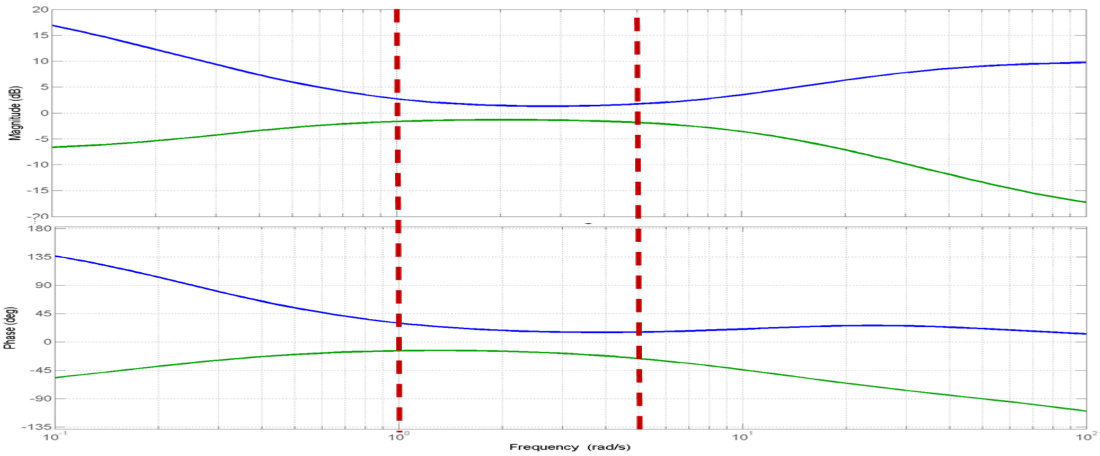

Figure 4.5: Envelopes of MUAD

4.2.3 Application of MUAD

The concept of MUAD is simple and comprehensive. The use of MUAD is getting popular over the years, not only for the LOES approach, but also the application to simulation model validation.

The early application of MUAD envelopes was in 1996 proposed by Tischler [10]. During the development of the simulation model of XV-15 tilt rotor craft, the MUAD envelopes was used as a tool for model validation. In this case, MUAD is used as a mismatch criteria between the flight data and the simulation data.

As pointed by Mitchell in [11], the MUAD envelopes are not verified tools, the effectiveness of these envelopes are still questionable. In 2006, Mitchell et al. [11] replicated the experiment by reapplying MUAD envelopes to the full set of Neal-Smith Data.

The result of such a replication shows that MUAD is not effective for simulation validation. Mitchell et al. [11] proposed a new experiment with a helicopter simulator, to verify MUAD and more importantly, investigate the applicability of it. This experiment is reviewed in Section 4.3.

4.3 Allowable Error

The most important characteristic of the MUAD envelope is that, the boundaries are defined by the handling qualities. However, how the pilot's perception about the added dynamics is not taken into account. Mitchell et al. [11] proposed an experiment to study the pilot sensitivity to variations in the helicopter dynamics. Instead of determining critical added dynamics by degrading of handling quality, the boundaries are formed by the pilots' rating on the noticeability of the added dynamics. This experiment is reviewed in detail in this section.

4.3.1 Mitchell's experiment

Mitchell's experiment is the main foundation of the current study since it is where AEE is defined. There are three main objectives of Mitchell's experiment:

- Determine sensitivity of pilot due to the added dynamics in helicopter model
- Verify MUAD as a tool for simulation model validation.

The experiment set up is similar to Neal-Smith program. A fixed-base helicopter simulator is used, with a linear augmented model. According to [11], the model is chosen to be as simple as possible. Further review of the helicopter model is given in Chapter 5.

The flight task is the Hover Mission Task Element(MTE)defined by ADS-33E-PRF [37], which is reviewed in Chapter 5. During the experiment, the pilot is asked to fly both the baseline model as well as the model with added dynamics.

The most significant difference between Mitchell's experiment and early work is that, the standard handling quality procedures are not used. Instead of assessing Cooper and Harper HQ rating, the pilots were asked if the change of dynamics is noticeable compare to the baseline model, and if this change affect the performance.

The result of Mitchell's experiment is shown in Figure 4.6. In this figure, the original MUAD envelopes is compared with the experiment data. The boundaries shows the envelopes based on the handling quality, while the added dynamics shows on figure are the unnoticed dynamics. These added dynamics, according the the pilot opinion, is not noticeable or not affect the task performance.

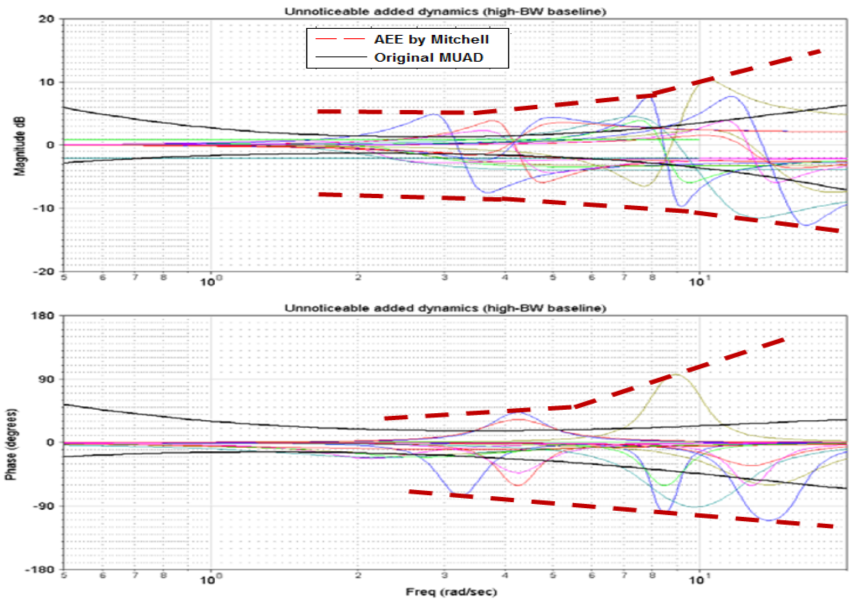

Figure 4.6: Result of Mitchell's experiment (MUAD envelopes compared with unnoticed added dynamics from simulation) [11]

It is clear that the original MUAD is way too stringent for this case. Most of the unnoticed added dynamics violate the boundaries. According to [11], at least a "roll control of a hovering helicopter on a fixed-based simulator" is not applicable for the original MUAD. It concludes that MUAD envelopes is not a universal tool, it is dependent on the model configuration, flight task and aircraft types [11]. In this way, MUAD is not verified to be a suitable tool for helicopter model validation.

4.3.2 Allowable Error Envelops

Although MUAD envelopes is not fit for the simulation setting in Mitchell's experiment, the result of the experiment is useful. With the added dynamics that considered to be unnoticed by the pilot, it is possible to find out another acceptable envelops that define the maximum allowable error for simulation validation.

As shown in Figure 4.6, though the added dynamics violate the traditional MUAD envelope, with this Bode plot, a new boundary can be drawn. The highlighted dash line define the possible boundaries that based on pilots' noticeability of added dynamics. It can assume that the error between simulation model and reference aircraft will not be noticed, if it falls within the boundary.

Mitchell et al. [11] defined the new boundaries "Allowable Error Envelopes " (AEE). A different name is given to be distinguished from traditional MUAD envelopes. More importantly, the new term AEE has a different purpose. Instead of using as a mismatch criteria for equivalent system, AEE is used to define the allowable error in simulation model validation. [11]

AEE seems to be a more reasonable tool for model validation than MUAD. Since the pilot's perception is taken into account. However, AEE is still not universally applicable, yet. It is dependent on the configuration of baseline model, for example the bandwidth of baseline model.

In Figure 4.7, the AEE for different model configurations(bandwidth of baseline model) are plotted. Although Mitchell proposed a way to normalised the AEE, there is some differences especially in phase.

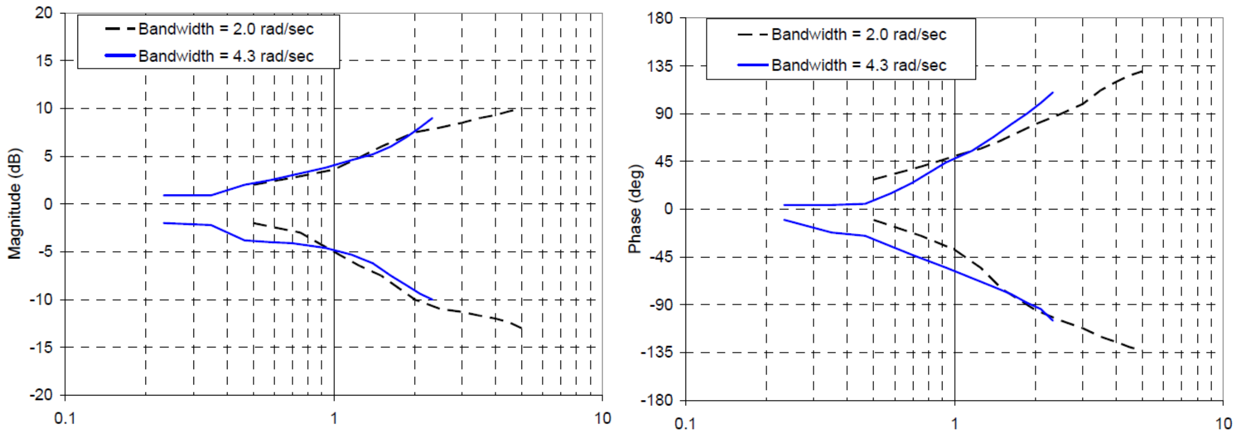

Figure 4.7: Normalized AEE [11]

Mitchell et al. [11] believed that there is a way to adjust AEE so that AEE can be used as an universal tool. In this study, he suggested some improvements that can be tested in the future research on this topic:

- AEE should be verified by multiple pilots
- AEE should be developed for added dynamics on other axis
- A method independent of baseline dynamics should be found

4.4 Further application

As recommended by Mitchell et al. [11], a further study on AEE is required. Single simulator and single pilot was used, and the tests were not well structured. It is believed that there is space for improvement on AEE.

In 2013, Penn proposed to replicate Mitchell's experiment, to further investigate the effect of multiple pilots and multiple simulators on the AEE. [13] The main objectives in this study is to reproduce the AEE proposed in [11], and investigate the effect of multiple pilots on AEE.

Compare to Mitchell's experiment, Penn proposed an experiment using two different simulators with multiple pilots. By keeping other variable controlled (same model and flight task), the experiment is the extended research on this topic.

4.4.1 Penn's experiment

The simulation set up is similar as Mitchell's experiment. Same helicopter model is used, to replicate the experiment as much as possible. Due to the dependency of AEE on model configuration, in Penn's experiment, only one model configuration is used. It means all the model parameters are fixed in this case.

Two different simulators are used, one is the fixed-base Helicopter Pilot Station(HPS) at National Aerospace Laboratory of The Netherlands (NLR)and the other one is moving based SIMONA Research Simulator(SRS) at the Delft University of Technology. The forms of added dynamics are identical to Mitchell's experiment, and same hover task is used.

During the experiment, 3 pilots were asked to fly the baseline model as well as the added dynamics model. After each flight, pilots were asked to go through the noticeability rating scales. This noticeability rating scales is developed by Penn. [13] on a base of Simulation Fidelity Rating. Same procedure repeated on the other simulator. By recording the rating, the critical added dynamics is determined. Based on these critical cases, AEE is hence generated.

An example of result from Penn's experiment is shown in Figure 4.8. Note that with 3 pilots and 2 simulators, a total number of six conditions are analyzed in Penn's report. Finally, the most stringent case is chosen as the normalized AEE.

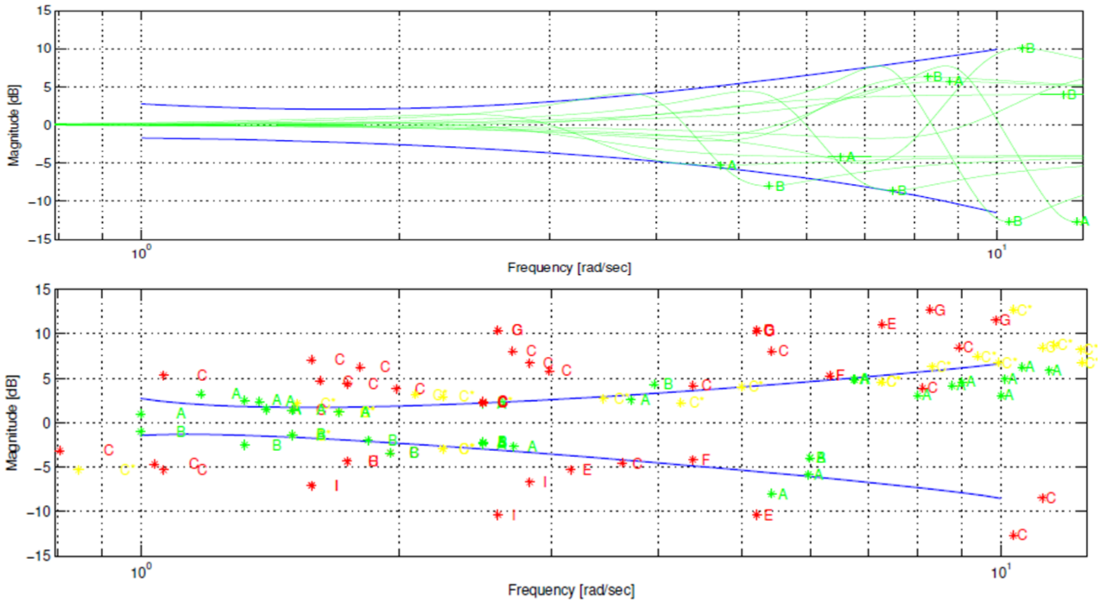

Figure 4.8: AEE produced by Penn [13]

The first part of Figure 4.8 shows the critical cases for one condition, the AEE is drawn as a tangent curve across the peak point of each case. To verify this strategy, Penn proposed to check the envelopes with all the data set in this condition. As showed in the second part of the figure, the points show the peak position of all the added dynamics tested in this condition. Score A and B are considered as unnoticed, while B is the critical case. The result shows that the envelopes are acceptable, however, it differ from subjects and simulator platforms.

The pilot's sensitivity analysis of Penn's experiment shows that the AEE is dependent on the simulator as well as pilot. [13] He also made some suggestions for the further research on AEE. Firstly, since two simulators are used, while there are many differences between these two simulator. One needs to investigate which differences between the two simulators contributes more to the effect on AEE. Also the added dynamics can be applied on other axis to investigate if there is a effect on AEE.

4.4.2 Proposed research

The main objectives of Mitchell's experiment is to: firstly verify MUAD. Secondly investigate pilot sensitivity to added dynamics and finally define an acceptable envelopes. While the purpose for Penn's research it to investigate the effect of simulators and pilots on AEE.

With the consideration of suggestions by Mitchell and Penn, a research is proposed by the author. The proposed research is to investigate the effect of D.O.F of added dynamics and motion cueing on AEE. By using single simulator while the motion can be isolated, the effect of other simulator particularities is then minimized.

The main difference among Mitchell's study, Penn's study and the proposed research is shown in Table 4.2. The helicopter model and flight task are identical to previous experiments, while the added dynamics is applied on pitch axis. Another factor is a single simulator is used while the motion cueing can be isolated.

Table 4.2: Brief information on application of AEE

	Mitchell'experiment	Penn's experiment	Proposed research
helciopter model	first order linear	first order state linear	first order state linear
simulator	fixed-base	fixed-base and motion-base	motion-base(non-motion condition)
added dynamics	roll axis	roll axis	pitch axis
subject	single pilot	multiple pilots	multiple pilots
configuration	multiple	single	single
flight task	hover MTE	hover MTE	hover MTE

It is clear now that the two main independent factors are: D.O.F of added dynamics and motion cueing. In next Chapter, a detail literature review and preliminary analysis on these two topic is given.

Chapter 5

Helicopter Simulation Model

To investigate the effect of D.O.F of added dynamics on AEE, a review on helicopter model is given in this chapter. As mentioned in Chapter 4, one of the two important independent variables in the proposed research is the added dynamics.

Section 5.1 reviews the helicopter model used in the experiment. The extension of model like added dynamics is also explained. In this section, a preliminary analysis on added dynamics is proposed to investigate the effect of added dynamics.

Section 5.2 gives a literature review on difference between longitudinal and lateral dynamics of the helicopter. As the added dynamics is applied on pitch instead of roll axis, the difference and expected affect is analyzed. Firstly, a handling quality analysis is given. After that, the difference between pitch and roll axis is analyzed by a cybernetic approach [49].

5.1 Helicopter Modelling

The helicopter model used in the proposed research is identical to Mitchell and Penn's experiment. To replicate the experiment and compare the result, it is reasonable to use the same model. Besides the dependent variable, the simulation set up should be as similar as possible.

A first order state space system is showed in equation 5.1 5.2 5.3 and 5.4. The 8 states represent velocity in three axis, angular velocity and angular rate. [11]

There are four control inputs. δ_B is longitudinal cyclic, δ_A is lateral cyclic, δ_C is collective and δ_P is pedal input. Note that these control inputs are dimensionless, they present the ratio of the maximum control inputs.

$$\dot{x} = Ax + Bu \tag{5.1}$$

$$u = \{u,\ w,\ q,\ \theta,\ v,\ p,\ r,\ \phi\ \}^T \tag{5.2}$$

$$x = \{\delta_B,\ \delta_C,\ \delta_A,\ \delta_P\}^T \tag{5.3}$$

$$A = \begin{bmatrix} X_u & 0 & 0 & -g & 0 & 0 & 0 & 0 \\ 0 & Z_w & U_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_q & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & Y_v & 0 & -U_0 & g \\ 0 & 0 & 0 & 0 & 0 & L_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & N_r & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Z_{\delta_C} & 0 & 0 \\ M_{\delta_B} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & L_{\delta_A} & 0 \\ 0 & 0 & 0 & N_{\delta_P} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.4}$$

The stability derivatives are showed in Table 5.1. U_0 is the trim airspeed and g is the gravity. Note that these stability derivatives are mass or moment normalized. These derivatives are from [11] except the yaw damping N_r. It was tuned and tested by Penn in his study [13] .

Table 5.1: Model Parameters [12]

Derivatives	Value	Unit
X_u	-0.01	1/sec
Z_w	-1	1/sec
M_q	-3	1/sec
Y_v	-0.02	1/sec
L_p	-5	1/sec
N_r	-0.625	1/sec
Z_{δ_C}	-7	ft/sec2
M_{δ_B}	-0.7	rad/sec2
L_{δ_A}	2	rad/sec2
N_{δ_P}	-3	rad/sec2

The helicopter model is designed to be as simple as possible. According to Mitchell et al. [11] the nonlinear element will affect the pilot more than the added dynamics.

The model is designed without any cross-axis coupling. Based on the model, the longitudinal and lateral dynamics are independent. The derivatives that define low frequency oscillation are neglected like phugoid motion. Hence the term M_u and M_q are setting to be zero in the model.

More importantly, the model is an augmented model. It is designed to represent a hovering rate-augmented helicopter. It means the bandwidth can be changed by tuning the roll damping L_p or pitch damping M_q. As mentioned before, the bandwidth is not going to be changed in the experiment, hence these derivatives are fixed.

The model is only valid around hover. This means the trimmed velocity is zero. However, in the flight task, the helicopter is not initially at hover. Instead, some ground speed is needed. The flight task will be explained in later chapter. Therefore, the model has to be trimmed at beginning of experiment.

5.1.1 Trim condition

In the model, the trim term U_0 is set to be 0 during hover. To provide the helicopter a ground speed at beginning, the model is trimmed such that an initial pitch and roll angle is given.

As showed in equation 5.5 and 5.6, at trim condition, the acceleration is zero. The initial velocity in x direction is u_i which is calculated based on the initial ground speed. In this way, the initial pitch is determined.

$$\dot{u} = X_u \cdot u_i - g \cdot \theta_i = 0 \tag{5.5}$$

$$\theta_i = \frac{X_u \cdot u_i}{g} \tag{5.6}$$

It is same for lateral axis. Equation 5.7 and 5.8 shows how the initial roll angle is calculated. Note that r_i is zero.

$$\dot{v} = Y_v \cdot v_i + g \cdot \phi_i - U_0 \cdot r_i = 0 \tag{5.7}$$

$$\phi_i = \frac{-Y_v \cdot v_i}{g} \tag{5.8}$$

5.1.2 Added dynamics

The added dynamics are second order lead/lag and lag/lead filter. This form is identical to Mitchell's experiment. The advantage of using dipole pairs is that it is very easy to shift the peaks of added dynamics, both vertically and horizontally. In this way,it is easier to design the added dynamics for the interested range of frequency.

The added dynamics can be written as equation 5.9. Where K is the gain and ζ is the damping ratio. w_{nz} and w_{np} are the natural frequency for zeros and poles.

$$Added\,Dynamics = K\frac{s^2 + 2\zeta w_{nz}s + w_{nz}^2}{s^2 + 2\zeta w_{np}s + w_{np}^2} \tag{5.9}$$

The other advantage for these added dynamics is that by adjusting the poles and zeros, the peaks of added dynamics can shift between positive and negative. In this way the AEE can be determined in both direction.

To get further understanding the added dynamics, some preliminary offline simulation is proposed to investigate how the following factors affect the added dynamics:

- Gain K
- Damping ratio ζ
- Natural frequency w_n
- Distance between pole and zero.

Effect of K

K is the gain, which added directly to the magnitude in frequency domain in dB. Increase K will shift the magnitude upwards while phase will remain constant. However according to [13], the gain should be tuned so that the added dynamics can surpass the narrow area of the envelopes.

Two types of gain is tested, firstly to achieve the steady state gain at high frequency, a unity gain 1 is used. For lower frequency, the second type gain is determined. As shown in equation 5.10 both types of gain are determined with final value theorem and initial value theorem separately.

$$K_{type1} = 1 \qquad\qquad K_{type2} = \frac{w_{np}^2}{w_{nz}^2} \tag{5.10}$$

To investigate the effect of gain, other factors is keeping constant. So the same damping ratio as well as natural frequency is used.

Figure 5.1 shows the added dynamics with two different types of gain. It is clear that for type 1, the unity gain is achieved at higher frequency. While at lower frequency, the steady state unity gain can be achieved with type 2.

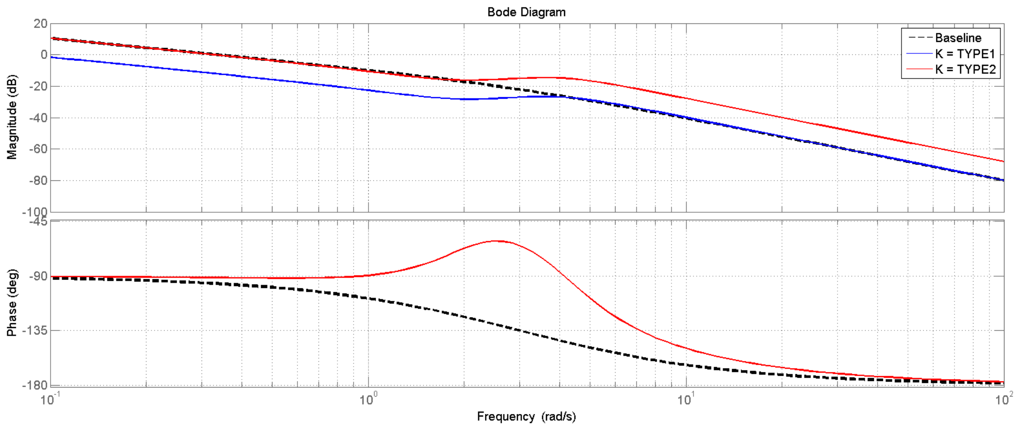

Figure 5.1: Effect of Gain K on added dynamics

During the experiment, type 2 gain is used. As in this case, pilots are more likely to notice the added dynamics at lower frequency, so the unity gain is chosen to be achieved at lower frequency. This is also confirmed by Penn [13].

Effect of damping ratio

Adjusting the damping ratio is the most straight forward way to change the height of peaks of added dynamics. Figure 5.2 shows three different added dynamics with a increasing damping ratio from 0.2 to 0.6. It is clear that high damping ratio has a smaller peak and flat hyperbolic shape.

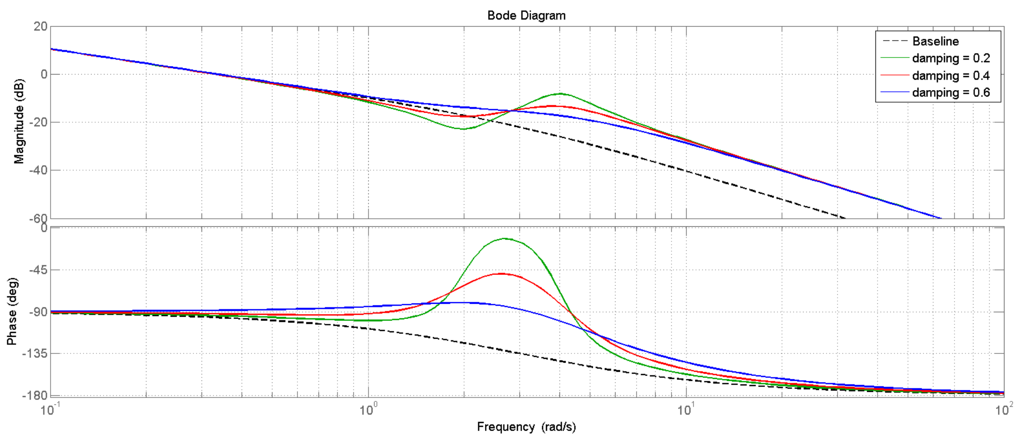

Figure 5.2: Effect of Damping on added dynamics

During the experiment, the intensity is hence shifted by tuning the damping. With this knowledge, it can also help to check the feasibility of the result. For example, in the same set of frequency, if pilot noticed dynamics with very high damping but ignore the ones with small damping, the result is not reasonable.

Effect of natural frequency

One advantage of using the dipole pair as added dynamics is by change the natural frequency of poles and zeros, the frequency of added dynamics can be adjusted easily.

Three sets of natural frequencies are tested, by keeping the same gain and damping, the distance between the pole and zero is also constant(in logarithm). Figure 5.3 shows the three added dynamics with different sets of natural frequencies.

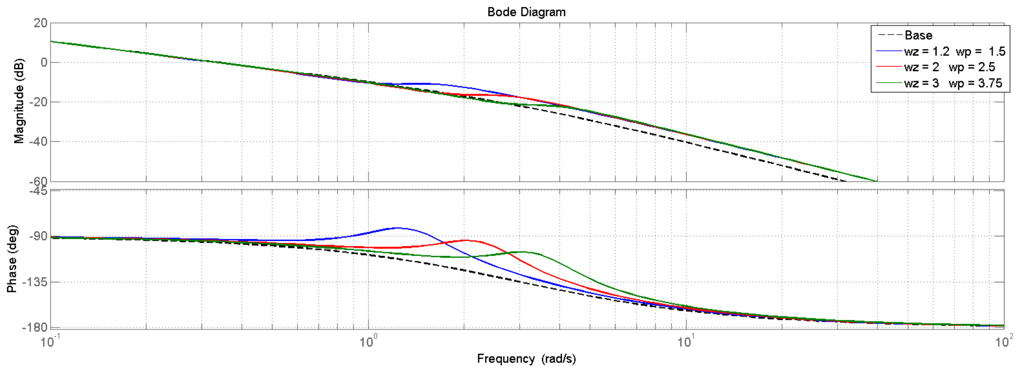

Figure 5.3: Effect of natural frequency on added dynamics

It is clear that the frequency of the peak of added dynamics shift to right. And the frequency of added dynamics falls within the range between natural frequency of pole and zero. It is noticed that if the natural frequency of zero is higher, the added dynamics will be negative.

Studying the effect of natural frequency will help the design of added dynamics for the experiment. Since by giving different sets of natural frequency, one can apply the added dynamics to the interested range of frequency.

Effect of distance between pole and zero

As showed in Figure 5.4, with constant natural frequency on zeros. Shifting the natural frequency of poles will increase the mismatch in the high frequency. If type 1 gain is used, the mismatch will be in low frequency. The change in distance also shift the peak of added dynamics. This is because the frequency of added dynamics falls somewhere in between the natural frequency pole and zero.

In conclusion, by changing the gain, damping and natural frequency, the added dynamics can be designed to fit for the purpose of the current study.

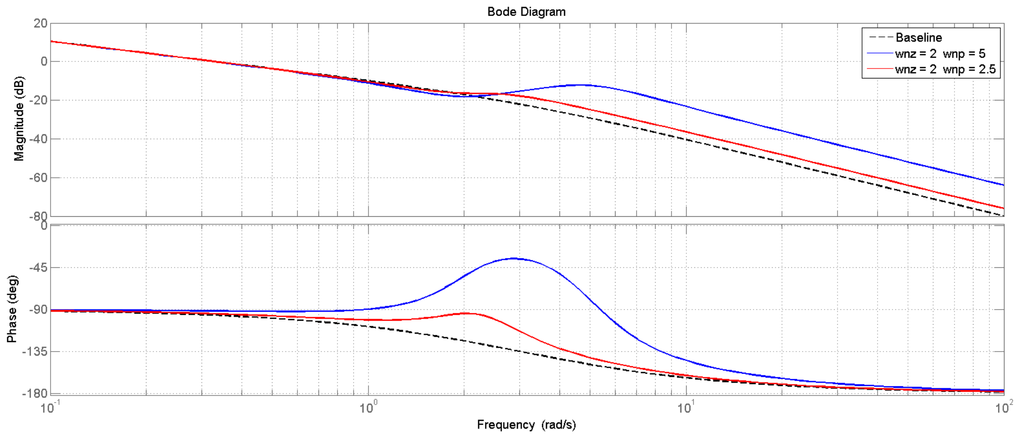

Figure 5.4: Effect of distance between pole and zero on added dynamics

5.2 Difference Between Roll and Pitch

One of the difference between proposed research and early work is that, instead of applying added dynamics on roll axis, the added dynamics is applied on pitch axis. To investigate the effect of added dynamics on AEE, the difference in longitudinal and lateral dynamics of helicopter is analyzed.

Simulator cueing can cause the difference between longitudinal and lateral control for the pilot. For example, due to the different optical flow [19], the visual cueing can be very different when pilot is doing pitch or roll. The vestibular system also gives different feeling to pilot with motion cueing.

More importantly, the difference between longitudinal and lateral axis of helicopter needs to be analyzed based on the model of the flight dynamics. A predicted handling quality assessment is firstly introduced to show the difference in handling quality for pitch and roll dynamics. Secondly, this issue is analyzed with a cybernetic approach, by building the cross-over model [49] for both pitch and roll dynamics.

The second approach will show more understanding on predicted pilot behavior than handling quality. As the main objective of this analysis is to find out how these differences (between longitudinal and lateral) affect the noticeability of pilot on added dynamics. it is more reasonable to take the pilots into the loop and investigate their perception and response.

5.2.1 Handling quality analysis

The handling quality requirement defined by ADS-33 are different for pitch and roll control [37]. Handling quality metric is also introduced with combination of flight parameters like turn rate or climb rate. Two methods are briefly discussed in this section. One is using attitude quickness to describe the handling quality. The other is predict handling quality measurement which explained in Chapter 3.

Attitude Quickness

Quickness is one the important handling quality metric defined by ADS-33 [37]. The main idea of quickness it to define the pitch, roll and yaw response of a helicopter at hover or low speed.

Quickness is a measure of the agility in attitude of the helicopter. It can be calculated with peak angular rate divided by peak attitude change. It is not saying that the higher quickness the better.

For a pilot, a high quickness may give a feeling that the helicopter is way too sensitive. To find out the difference in handling quality for pitch and roll, the quickness for both axis are determined.

A small experiment is proposed by using the flight data from a BO-105 helicopter simulation model on Simona Research Simulator [50]. During the experiment, the pilot was flying a pulse input in an augmented BO-105 helicopter during hovering. The rate response for pitch and roll as well as the attitude change are recorded.

The results are showed on Figure 5.5. Based on the metric, to achieve level 1 handling quality, for roll response the required quickness is higher than pitch. During the experiment, all sets for pitch quickness full-fill the requirement of level 1 handling quality. While for roll response, the influence of performance is larger. Some sets fall in the the level 2 category.

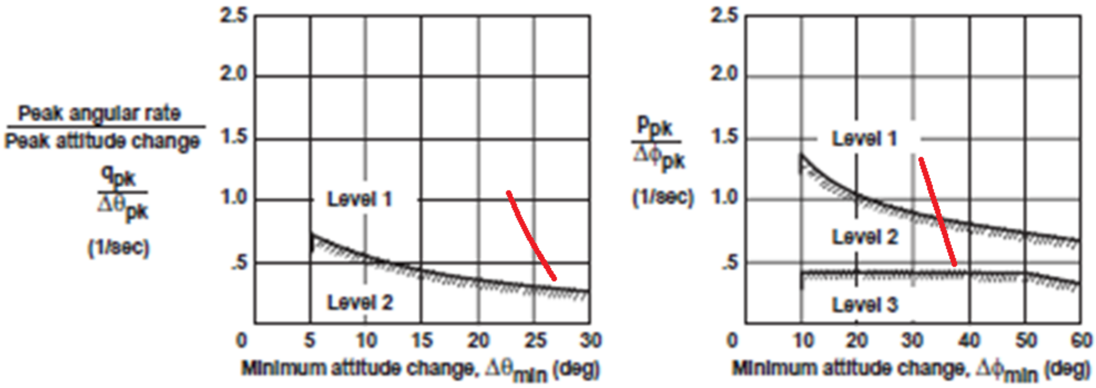

Figure 5.5: Quickness on pitch and roll

A general remark on this experiment is that a higher quickness on roll response is expected. Pilots might be more sensitive to roll dynamics. However, this experiment is based on a full augmented non-linear helicopter model. The cross-axis coupling as well as the non-linear element may affect the result.

predicted HQ

As mentioned in Chapter 3, the predicted handling quality can also be assessed by the bandwidth and phase lag for a high frequency and small amplitude response. These is also the interested region for the hover MTE in the proposed research.

Based on the model, the bandwidth ω_{BW} is derived from the frequency response. By further investigating the model, the frequency bandwidth is determined by the damping factor. The ω_{BW_θ} is determined by pitch damping M_q and ω_{BW_ϕ} is dependent on L_p.

Figure 5.6 shows the predict handling quality measurement for both pitch and roll. Note that for a open loop analysis, the phase lag can not be determined since the phase does not across the -180 degree. However, this open loop analysis can still show something. The bandwidth for roll ω_{BW_ϕ} is 5 rad/s and for pitch ω_{BW_θ} is 3 rad/s instead.

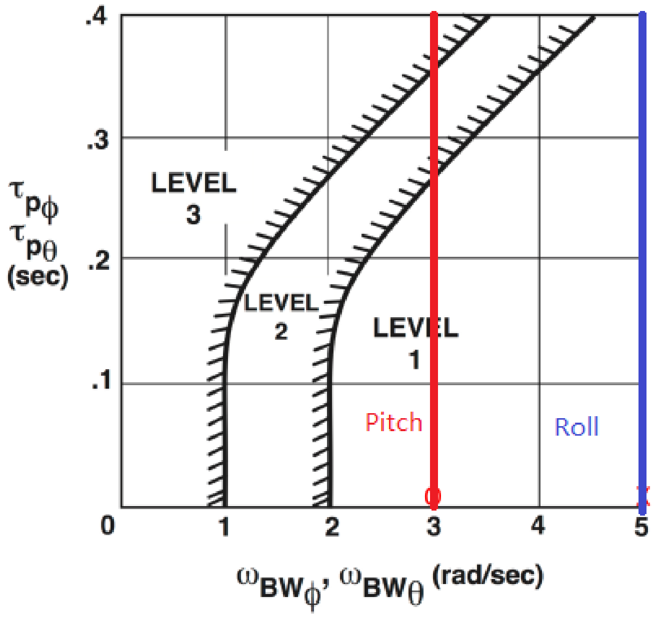

Figure 5.6: Predicted handling quality measurement on pitch and roll

The two highlighted line shows the pitch and roll response on the handling quality metric. For a small phase delay, both pitch and roll can achieve level 1 handling quality. However, when the delay increased, roll and pitch will have different performance. Based on the graph, the degrading of handling quality for pitch will happened when the time constant is around 0.25 second. Further more, when phase delay is reaching 0.35s, the handling quality will degrade to level 3 for pitch. For roll, the handling quality will not degrade even the phase delay is 0.4 second.

It looks like roll dynamics has a higher delay tolerance than pitch. It means the same handling quality on roll can be achieved with higher phase delay. It can also showed from a Bode plot that roll response has a higher phase margin than pitch.

5.2.2 Model based analysis

An important improvement from MUAD to AEE is that, instead of considering the handling quality, the pilot's perception is taken into account. The previous analysis are based on handling quality of the two axis. But how does the pilot perceive the difference between pitch and roll?

To predict the human behavior, a manual control cybernetic approach is hence used. The basic of this approach is the cross-over model [49]. A cross over model can be described as in Figure 5.7.

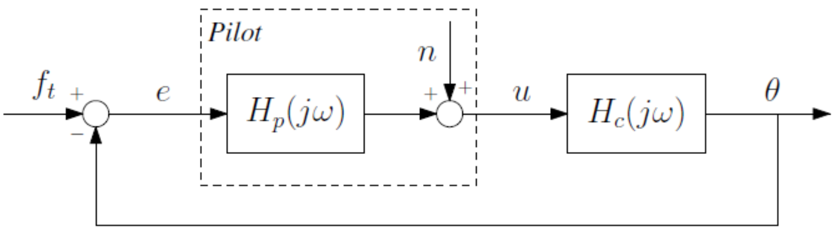

Figure 5.7: An example of cross over model [49]

A simple cross model consists of pilot H_p and control element H_c. The idea of cross over model is that the human controllers adapt their control characteristics to the dynamics of the controlled element, in such a way that the open loop system dynamics mimic those of a well-designed feedback system [49].

To apply this approach, the two main elements are needed: pilot model and controlled element model. The controlled element model can be represented by the transfer function of pitch or roll response. As showed in equation 5.11 and 5.12.

$$\frac{\theta}{\delta_B} = \frac{M_{\delta B}}{s(s - M_q)} = \frac{-0.7}{s(s+3)} \tag{5.11}$$

$$\frac{\phi}{\delta_A} = \frac{L_{\delta A}}{s(s - L_p)} = \frac{2}{s(s+5)} \tag{5.12}$$

By neglecting the magnitude gain, the two response transfer function are influenced by the their break-off frequencies. Figure 5.8 shows the open loop response of these kind of dynamics. The magnitude is dropping with slop of -20dB. After break frequency, the dropping rate increases to -40dB.

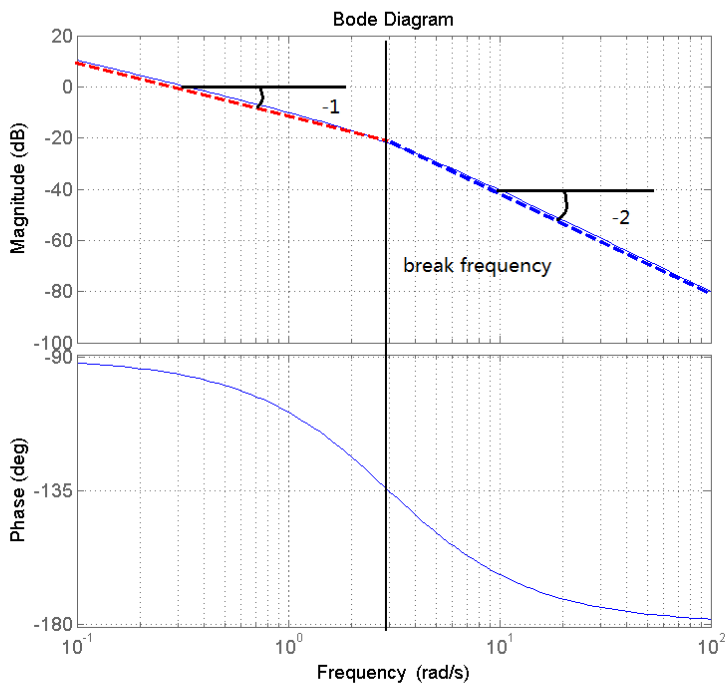

Figure 5.8: Response of open loop dynamics

The break frequency is dependent on the damping of the dynamics. Based on the model, a pitch dynamics has a break frequency at 3 rad/s while the roll is at 5 rad/s. It means for frequency lower than 3 rad/s or higher than 5 rad/s, pitch and roll will perform identical to each other. The interested region is hence the frequency between 3 to 5 rad/s.

To investigate the effect of the open loop dynamics on pilot's behavior, the pilot is adding into the loop. According to McRuer [49], the pilot model can be described in equation 5.13 [49]. Where K_p is the pilot gain, τ_L and τ_I are the time constant in lead and lag. τ_e is the effective time delay.

$$H_p(j\omega) = K_p \frac{\tau_L j\omega + 1}{\tau_I j\omega + 1} e^{-j\omega\tau_e} \tag{5.13}$$

One of the important rule to use cross over model is that the pilot model should be adjusted to achieve the -20dB/decade slope of the open loop transfer function. As the controlled element is a double integrator, according to McRuer, pilot model needs to generate a lead [49]. So the pilot model for this case is then a first order lead as described in equation 5.14.

$$H_p(j\omega) = K_p\left(\tau_L j\omega + 1\right)e^{-j\omega\tau_e} \tag{5.14}$$

By applying verbal adjustment rule, the pilot model can be determined for both pitch and roll response. The pilot response for pitch and roll are plotted in frequency domain on Figure 5.9.

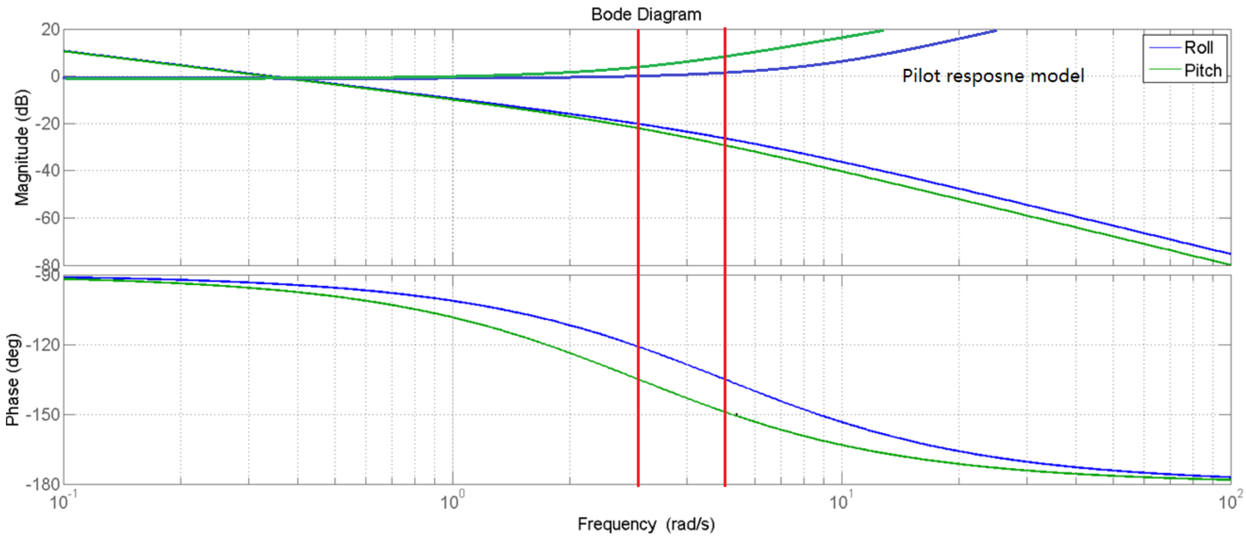

Figure 5.9: Pilot model on pitch and roll

The interested region (between 3 to 5 rad/s) is highlighted with the vertical line on the figure. Any frequency lower than 3 rad/s, pilot is doing a zero order gain control. While for frequency higher than 5 rad/s, pilot is generating a first order lead to keep the open loop dynamics a -20dB decade. However, inside the region, a pilot is doing a gain control for roll dynamics while has to provide a lead for pitch dynamics. From the point of view of pilot, inside this region, a pitch is expected to be more challenging to control.

Conclusion of analysis on model

Based on the result of the analysis, in the interested region, it is assumed that the workload and effort that pilot has to put for a pitch control is higher than roll in the interested frequency range. According to [11], configuration with lower break frequency will be more tolerant to to added dynamics since the aircraft itself will attenuate the effects of added filter. It is assumed pilot will be more sensitive to added dynamics on roll.

It conclude that between 3 rad/s to 5 rad/s, pilots are expected to be more sensitive to the added dynamics on roll, which means the shape of the AEE generated with added dynamics on pitch is expected to be wider than the ones with added dynamics on roll.

Chapter 6

Helicopter Motion Cueing

One of the main objective of the proposed research is to investigate the effect of motion cueing on pilot's noticeability of added dynamics. In this chapter, a short literature review on helicopter motion system is given.

Section 6.1 gives a introduction to simulator motion cueing, by discuss the vestibular system. Section 6.2 reviews how the motion affect AEE by using a cybernetic approach. Finally a preliminary analysis on motion filter is given in Section 6.3.

6.1 Simulator Motion System

The motion system of the simulator is to replicate the physical movement of the real aircraft, and hence provide pilot a physical sense of motion. Human being have different sensors to perceive the motion of body [51]:

- The neuromuscular system, sense the loads on limbs and body and contact forces in a proprioceptive way.
- Eyes, perceive the motion visually by the change of position and optical flow.
- The somatosensory system, detect skin pressure.
- The vestibular organ, sense the physical movement of body directly.

In general, those sensors work together to perceive the motion. In a simulator, different cueing can provided information to different sensors so that a pilot can feel the motion similar to real aircraft.

Visual cueing provide information to the eyes, while control loading gives haptical feeling. Vestibular system sense the motion directly from the translational and angular acceleration of body, which will be provided by the motion cueing system.

6.1.1 Vestibular system

There are two parts of vestibular system, the otolith organ and the semi circular canals. Both systems are located in the inner ear of the body.

The otolith system is tiny calcite crystal on a gelatinous substance, with embedded sensitive hair cells [51]. It is a translational acceleration sensor. More accurately, it is sensitive to specific force.

The otolith system can be modelled as equation 6.1. Based on physiological measurements, the parameters are determined [51] : $K = 3.4$, $\tau_n = 1s$, $\tau_1 = 0.5s$ and $\tau_2 = 0.016s$. The input is specific force while the output is afferent firing rate.

$$H_{OTO}(s) = K \cdot \frac{1 + \tau_n s}{(1 + \tau_1 s)(1 + \tau_2 s)} \tag{6.1}$$

The transfer function is plotted on Figure 6.1. Due to the threshold, the interested range of frequency is around 0.1 to 10 rad/s. As showed on the figure, within this range, the otolith model can be presented by a pure gain. So the human will still perceive specific force (acceleration) but not rate.

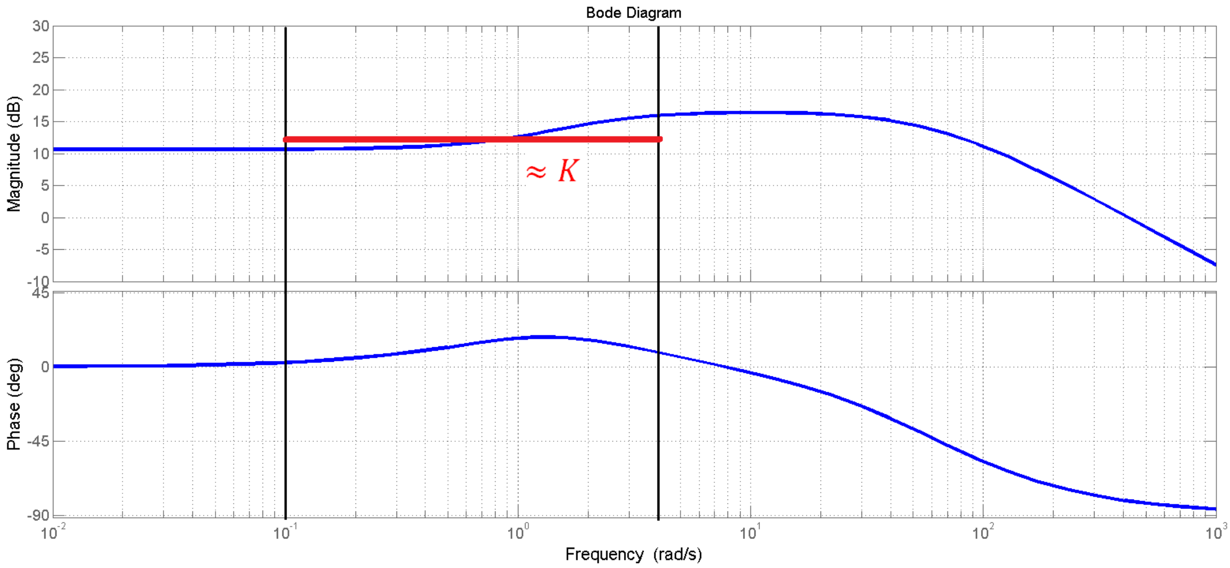

Figure 6.1: otolith model

The three semi circular canals are the sensors for rotational acceleration around three axis. They are canals filled with liquid and a cupula which contains sensitive hair cells [51]. The approximated linear model for a semi circular canal is described in equation 6.2. Figure 6.2 shows the Bode plot of the transfer function H_{SCC}

$$H_{SCC}(s) = K \cdot \frac{1 + \tau_L s}{(1 + \tau_1 s)(1 + \tau_2 s)} \tag{6.2}$$

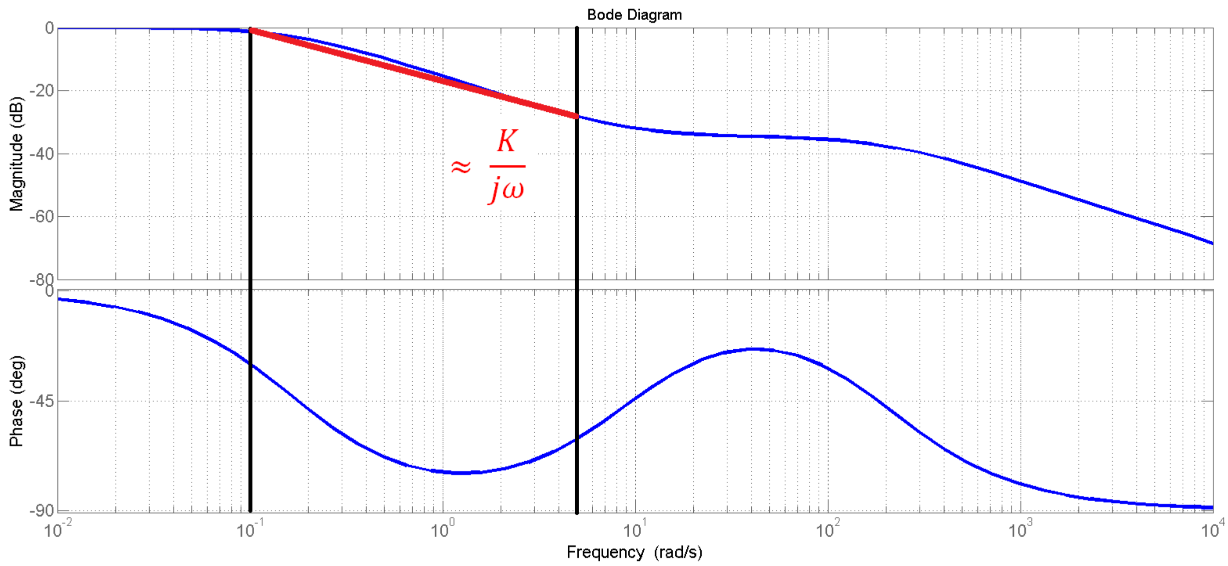

Figure 6.2: Semicircular canals model

The parameters in H_{SCC} are also defined by [51]: $K = 1$, $\tau_L = 0.1097s$, $\tau_1 = 5.924s$ and $\tau_2 = 0.005s$. With a range form 0.1 to 10 rad/s, the semi circular canal can be approximated to a first order integrator. It means what human will perceive is not acceleration, but rotational velocity.

By understanding the principle of vestibular system, the remained question is how it affects the pilot's noticeability of added dynamics and hence the shape of AEE. In next section, the effect of motion is analyzed by a cybernetic approach.

6.2 A Cybernetic Approach

During the literature review on the topic of simulator motion system, lots of study were found with opposite conclusion. The remark of the literature review is that the effectiveness of motion is dependent on task, purpose of simulator and of course the cost.

To investigate the effectiveness of motion for this specific task, a pilot's perception on motion cueing is hence needed to be analyzed. To approach that, a manual control cybernetic approach is a reasonable tool.

By reviewing on the cross over model explained in Chapter 5, the pilot is divided into two parts: pilot with visual response Y_{Pvis} and pilot with vestibular response Y_{Pvest}. Figure 6.3 shows the cross over model when motion response is added.

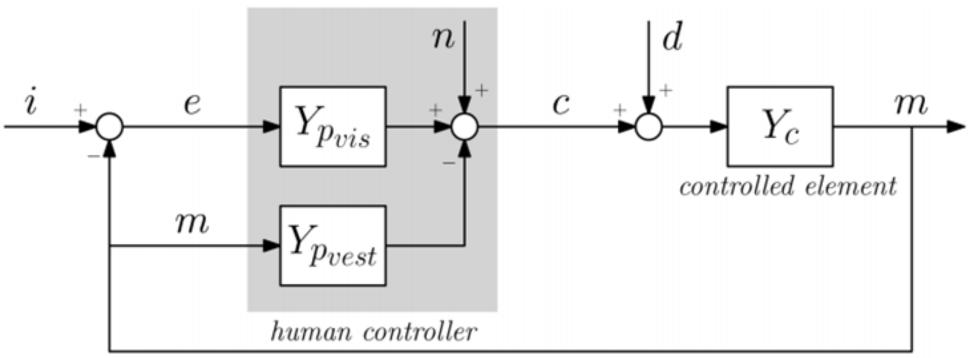

Figure 6.3: cross over model with motion [52]

In this case, the visual and vestibular system is working together to keep the open loop dynamics with a -20 dB decade. As mentioned before, the model of ototith works as a pure gain, the output is still specific force. While the semi circular canals works as an integrator, the output is integrated into velocity. Hence the H_{SCC} is the dominating term in the vestibular system.

The combination of visual and vestibular response for pilot model is shown in Figure 6.4. The eyes of human is assumed to be a perfect sensor, hence the dynamics of sensor is a unity gain. For a second order integration system, the pilot with visual response needs to proved a lead. As shown in the figure, the equalization dynamics for visual is a first order lead function.

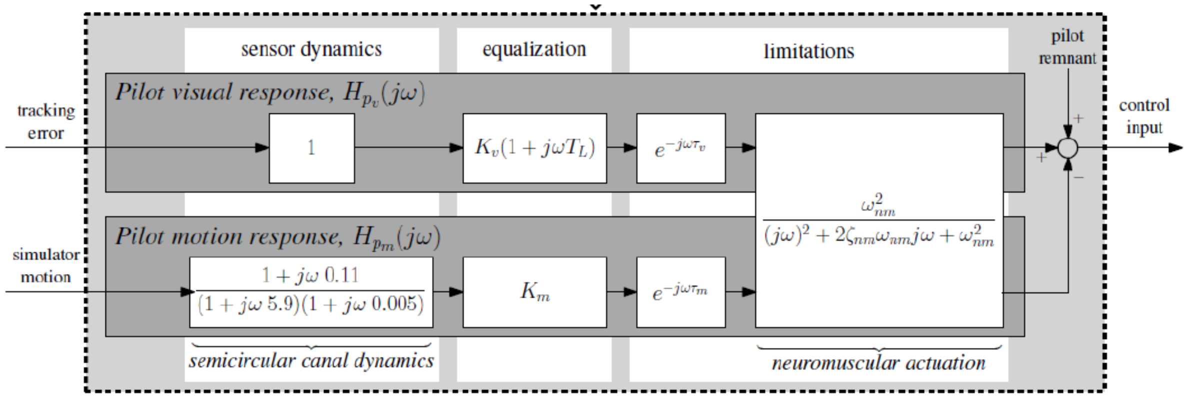

Figure 6.4: Multimodal Pilot with motion [53]

The pilot with vestibular is different. The sensor dynamics of vestibular system is dominated by semi-circular canal. In the range of frequency associated with manual control, the sensor dynamics is approximated to be a first order integrator. It replaces the lead provided by visual system. Thus for pilot with vestibular response, only a gain is needed for the equalization dynamics.

It gets complex when the two systems work parallel. The information given by the two systems are different, so does the feedback. According to [51], the visual and vestibular responses are integrated by human through weighting and summation.

Figure 6.5 shows the Bode plot of pilot model with and without motion. The left part is the pilot model with only visual response. It is identical to Figure 5.9 in previous chapter. To achieve an open loop dynamics with -20dB decade, Y_{Pvis} needs to generate a visual lead after the break frequency.

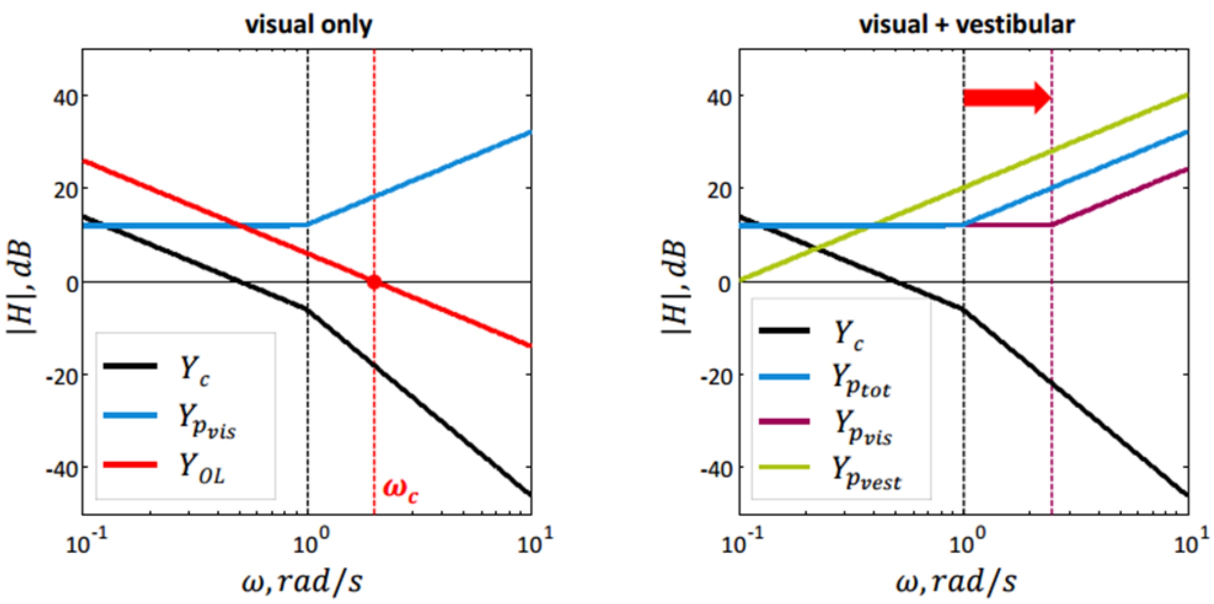

Figure 6.5: Pilot response with motion source: [51]

While when the vestibular system is added into the loop, like the right part of Figure 6.5. Vestibular response can be used as an alternative lead, which can replace the lead generated by pilot. Graphically, it will shift the pilot model with visual response to right. It means the pilot only needs to generate lead for higher frequency.

This also means the time constant for pilot model decrease. As according to [51], perception delay for vestibular system is smaller than 150 ms which is much less compared to visual rate (around 350 ms).

Conclusion of analysis on motion

This change in pilot response is expected to influence the noticeability of added dynamics as well. Since the pilot only needs to perform a first order lead control at higher frequency. That means for a longer range of frequency, the pilot do a gain control. It is more "easier" for pilot to control, while pilot is expected to be more sensitive to added dynamics.

It is also noticed that the lead effect is only valid with frequency higher than break frequency. Because at any frequency lower than break frequency, pilots are only control a gain no matter motion is involved or not.

The expected influence of shape of AEE is that the stringent part of the envelope will be longer after the break frequency, 3 rad/s in this case. This means the bottle neck of the AEE will shift to right (higher frequency).

To test the analytical result, the experiment is designed to investigate the effect of motion on AEE. In the experiment, AEE will be determined for condition with and without motion. The problem is how to set the motion and what is the quality of motion applied in the experiment. For a simulator, the motion cueing is adjusted by setting the motion filter. Next section gives a review on motion filter design.

6.3 Motion Filter Design

One of the challenge on simulator motion system is that the quality of motion provided by simulator can not be perfectly match the real aircraft. The aircraft flies through the air without any limitation, while the simulator has a limited workspace.

A way of transforming real aircraft motion to a reduced version is developed. The algorithms behind this idea is using a motion filter with a washout effect. Only scaling down the motion directly is not a very practical approach due to the limited space.

The specific force can be described as the summation of gravity and the body acceleration. To assess the translational specific force, a high pass filter is used. This is because low frequency elements are the main cause of the excursions. A typical second order high pass filter can be described in equation 6.3.

$$H_{HP}(s) = \frac{k \cdot s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{6.3}$$

The higher order terms determine the washout effect. During the simulation, the simulator will return to neutral position slowly without being noticed by pilot. In some cases like heave motion, a third order term is needed for even larger washout effect. Since a sustained vertical motion such as during take off is difficult to represent by a simulator.

For the rotational acceleration, the simulator can replicate the attitude of real aircraft to a large extend except the yaw. However, a filter is still needed to prevent from false cueing. For example, during a coordinated turn, the specific force on sway (y axis) should be zero. Unfiltered roll motion will generate the force on sway so that pilot will perceive the false cueing.

A high pass filter is also used for rotational motion. However, simulator can not provide a sustained acceleration in low frequency. This can be replicated by a tilt coordination. For example, during take off, the aircraft is accelerate in surge axis continuously . Since the otolith can not distinguish the difference between tilt and translation acceleration. With a rate lower than the threshold of semi-circular canals, the simulator can be tilted in pitch so that pilot will feel the same acceleration.

This tilt coordination can be achieved by a low pass filter. Equation 6.4 shows a typical second order low pass filter. Note that output of the low pass filter is the low-frequency content of the specific force signal..

$$H_{LP}(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{6.4}$$

One challenge on tilt coordination is that pilot should not feel the rotational motion. In this way, the tilt is rate limited. Tilt coordination is also only valid for surge and sway, since simulator can only tilt pitch and roll.

The classical motion filter structure is described in Figure 6.6. In general, three channels are defined. First channel is specific force channel. It filters the specific force from aircraft with high pass filter and transform to inertial frame. The second channel is angular rates channel. It transfer angular rate in body frame to Euler angle rate. The third channel is the tilt coordination channel. It is a low pass filter that transfer specific force on surge and sway into pitch and roll angle.

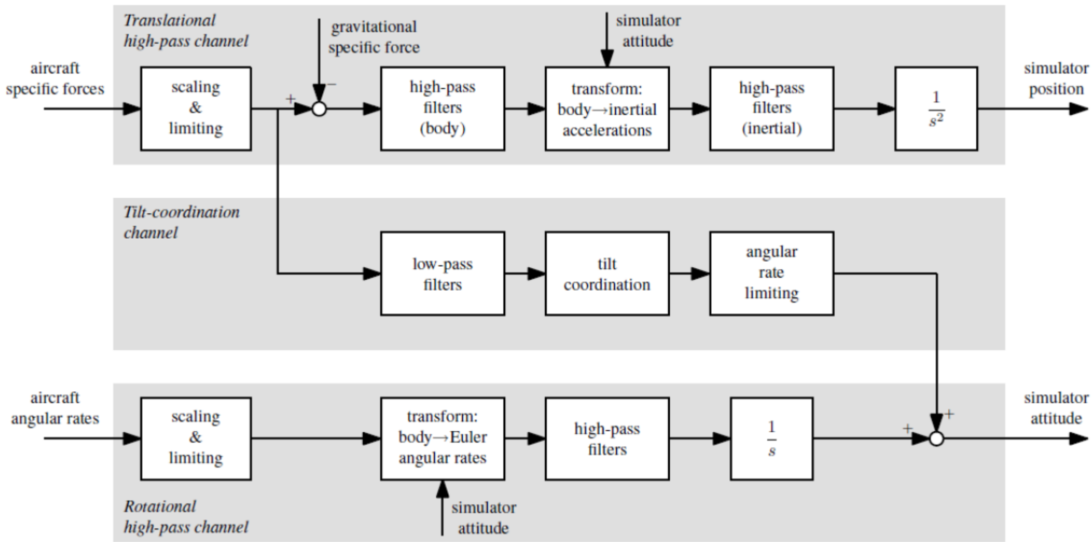

Figure 6.6: classical motion filter structure : [53]

The result from specific force channel is hence integrated to simulator position. For SRS simulator, the acceleration in inertial frame are directly used. The outcome from tilt coordination channel and angular rate channel is adding up. Different from the figure, in SRS simulator, the output from tilt coordination will transfer to Euler rate after the rate limiter. The Euler angle rate is added with output from angular acceleration channel. The simulator will use of Euler angle rate directly.

6.3.1 Preliminary consideration

With some knowledge of the motion filter, a suitable motion filter is required to be designed for the experiment. Here, a preliminary consideration on motion filter design is given.

The motion filters can be adjust by the following parameters:

- The order of filter
- The gain K
- The washout ω_n (2nd order)or ω_b (1st order)

For a preliminary test, the only reference motion filter setting for the similar experiment is in [13]. Table 6.1 listed the motion filter setting used by Penn. In the experiment, identical second order filter is used for rotational axis as well as surge and sway. A third order filter is used for heave. Since with tilt coordination, a second order filter is enough to complete wash out the position after a step on specific force.

Table 6.1: Motion Filter Setting from Penn's Experiment [13]

Filter	Order	K	ζ	ω_n	ω_b
translation (surge and sway)	2	0.7	0.9	2	-
Heave	3	0.5	0.9	2.5	0.1
rotational	2	0.7	0.9	2	-
roll and yaw	1	0.7	0.9	-	1.5
pitch	1	1	0.9	-	1.5

Since simulator usually can match the rotational motion of aircraft more closely. For example the SRS simulator can replicate the pitch and roll motion exactly same as real aircraft. Hence an extra set of first order filter for Euler angle is also analyzed in preliminary consideration.

Motion fidelity criteria

To assess the performance of the motion filter in Table 6.1, Sinacori fidelity criteria is used [27] [26]. The criteria is defined by the gain and phase shift of the motion filter at 1 rad/s as shown in Figure 6.7.

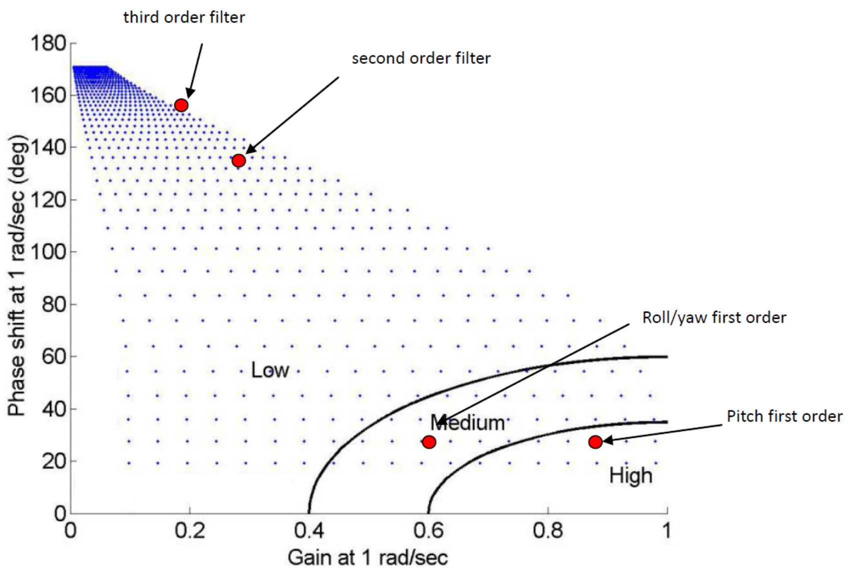

Figure 6.7: Sinacori Motion Fidelity Criteria

The listed motion filter is assessed by this criteria. As shown on the figure, the edge of the criteria is defined by the work space limitation, the actuator length, and the actuator speed. The first order filter has much higher fidelity, based on Sinacori criteria. While with unity gain, the pitch filter is shifted horizontal to the right, which means higher fidelity. The third order filter has the worst performance.

Conclusion of preliminary consideration

The remarks of the preliminary consideration of motion filter are:

- The first priority of setting motion filter is to keep simulator within the limits.
- The limits are defined by the size of work space, length, speed and acceleration of actuators.
- The lower the order, the higher the fidelity.
- The higher the gain, the higher the fidelity.
- The lower the frequency, the smaller washout effect, hence the higher fidelity.
- The filter setting for all D.O.F should be balanced as much as possible.
- The filter setting should be cooperated with the task mission.

6.3.2 Tuning based on simulation

Based on the result of preliminary consideration, a test tuning is proposed by simulating the helicopter model as well as motion filter offline. The helicopter model is built identical to Mitchell's model by setting the added dynamics to zero. The motion filter is simulated with same structure discussed above.

To simulate the pilot's control input in the hovering mission, the flight data from Penn's experiment [13] is captured. Figure 6.8 is an example of control input for this specific mission. The data is from one subject flying with baseline model (without added dynamics) in SRS simulator with motion.

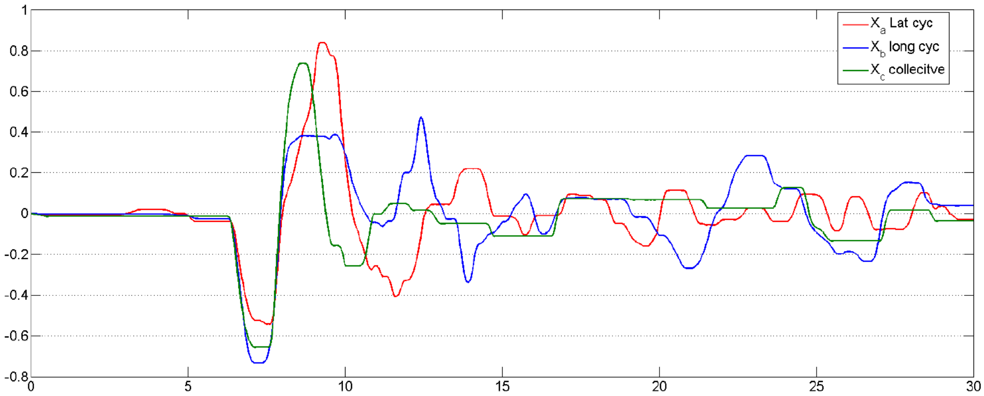

Figure 6.8: Example of Control input in Hover MTE for baseline model [13]

Three inputs signal are generated, while there is no pedal input hence no yaw dynamics is involved. Notes that these input are normalized and dimensionless.

The baseline motion filter setting, shown in Table 6.5 are based on [13] and result from preliminary consideration. The original setting is in favor of roll attitude, while to keep it balanced, same filter is used for surge and sway, and same second order filter is used for pitch and roll.

Table 6.2: Baseline setting for motion filter

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
w_n	2	2	2.5	1,5	1.5	1.5	-
w_b	0	0	0.1	0	0	0	-
$w_n lp$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

The heave filter is different from other two (surge and sway). Since for surge and sway, the low pass filter for tilt coordination results in a addition of an order. Hence a second order washout is enough for surge and sway. For heave, extra washout effect is required.

The break frequency for rotational filters are designed to be as lower as possible but within the limit of simulator. The upper boundary of break frequency is set by the critical frequency of the mission. In this case, the critical frequency is the frequency where added dynamics applied.

The simulation result is shown on Figure 6.9. Six graphs represent the output of three translational motion as well as three rotational motion. In the figure, the filtered motion is compared with the reference motion, which is calculated by the helicopter dynamics.

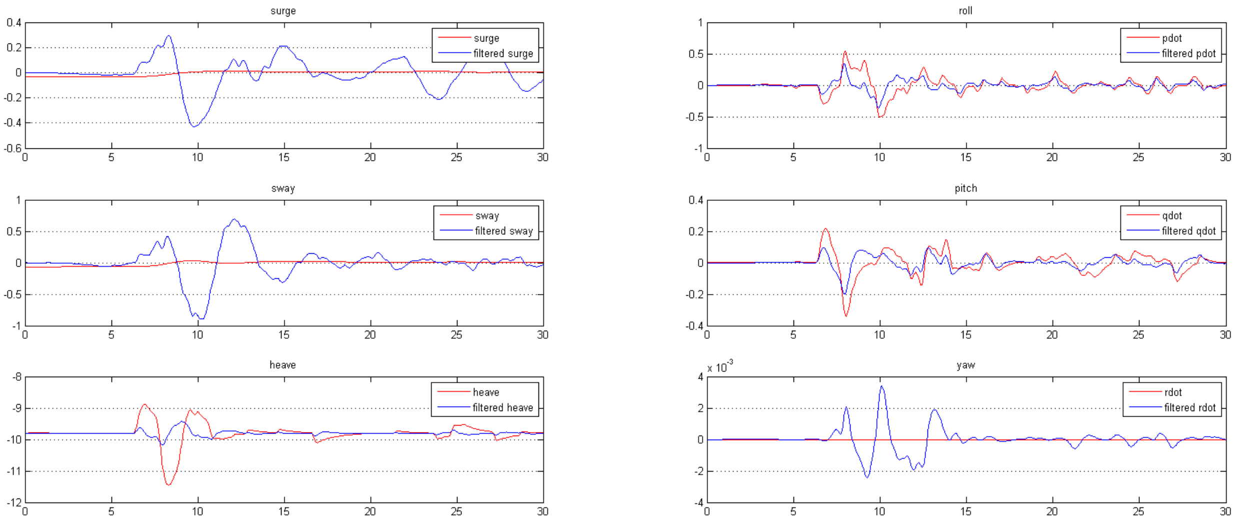

Figure 6.9: Simulation result for baseline filter

The output for specific force and angular acceleration before and after the filter are plotted. Note that the pitch and roll in this case is considered as good, but still can be improved. There are false cueing on surge and sway.

The second check is to check the actuator length to see if the motion is out of the work space of simulator. Based on graph in Figure 6.10, all six actuators are not reaching the maximum length. The speed of actuator is not calculated yet, based on the slope and frequency, the speed is also safe.

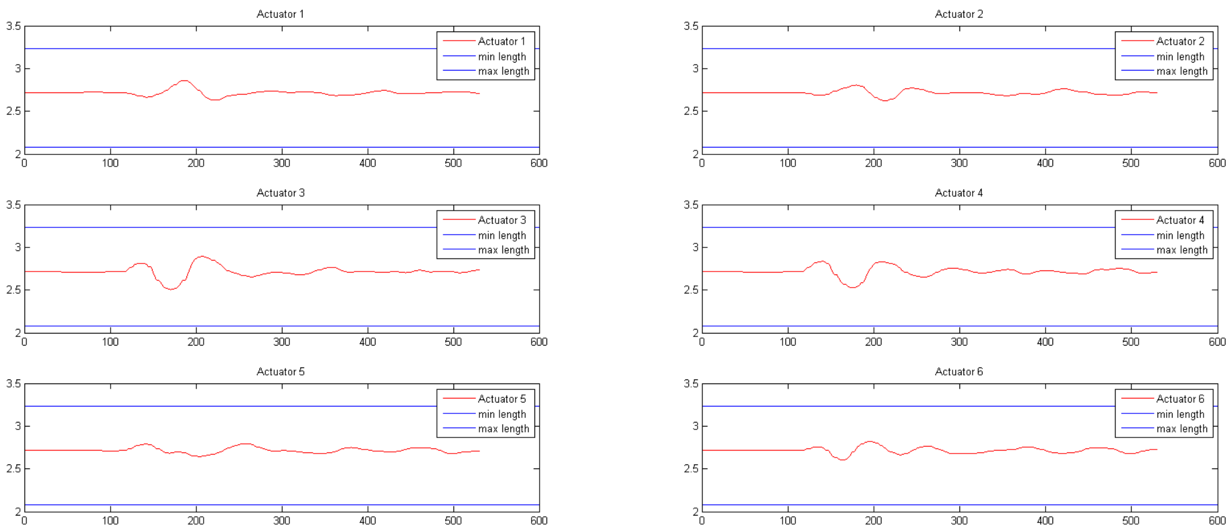

Figure 6.10: Actuator length check

The focus of the tuning is to achieve a good performance in pitch, since for the experiment, the added dynamics are applied on pitch axis. However, during the tuning, the pitch will generate false cueing on surge, the better pitch will trade off in worse surge.

As shown in Figure 6.11, The surge cueing is based on the body acceleration and effect of gravity. Both attributes are plotted. Base on the graph, the gravity (based on pitch) dominating the false cueing while the body acceleration is trying to work against the false cueing, hence improve it.

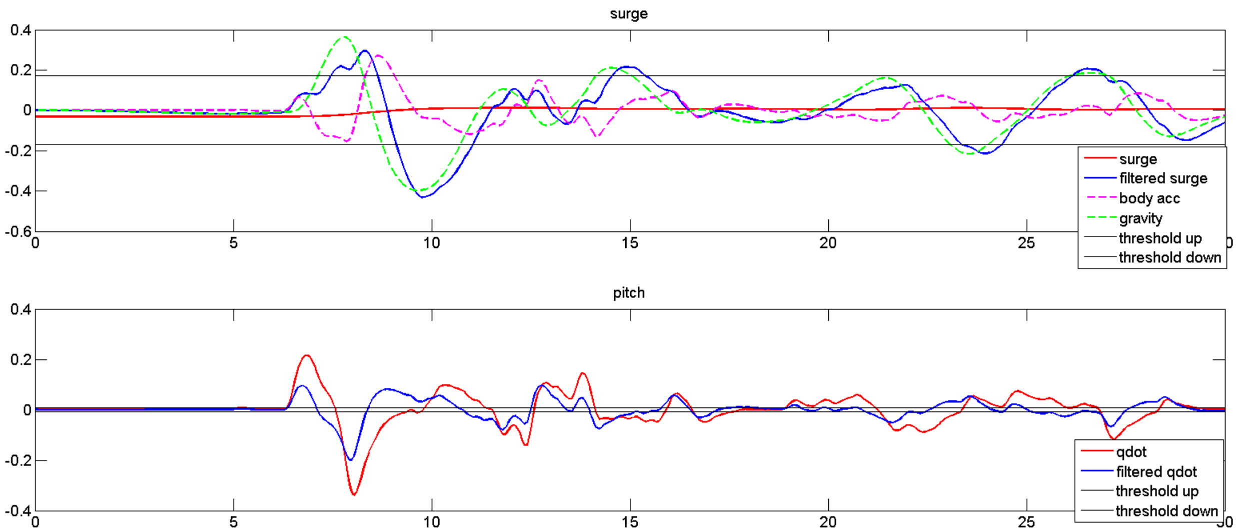

Figure 6.11: Surge and Pitch

To fix the false cueing, it can either increase the cueing from body acceleration (HP surge) or decrease the cueing on pitch. Note that there may be a point that if the pitch is too small that body acceleration will dominating the false cueing.

The similar effect can be observed in sway and roll. The false cueing on sway is also dominating by the roll attitude. Either decrease this cueing or increase body acceleration should help Showing on Figure 6.12.

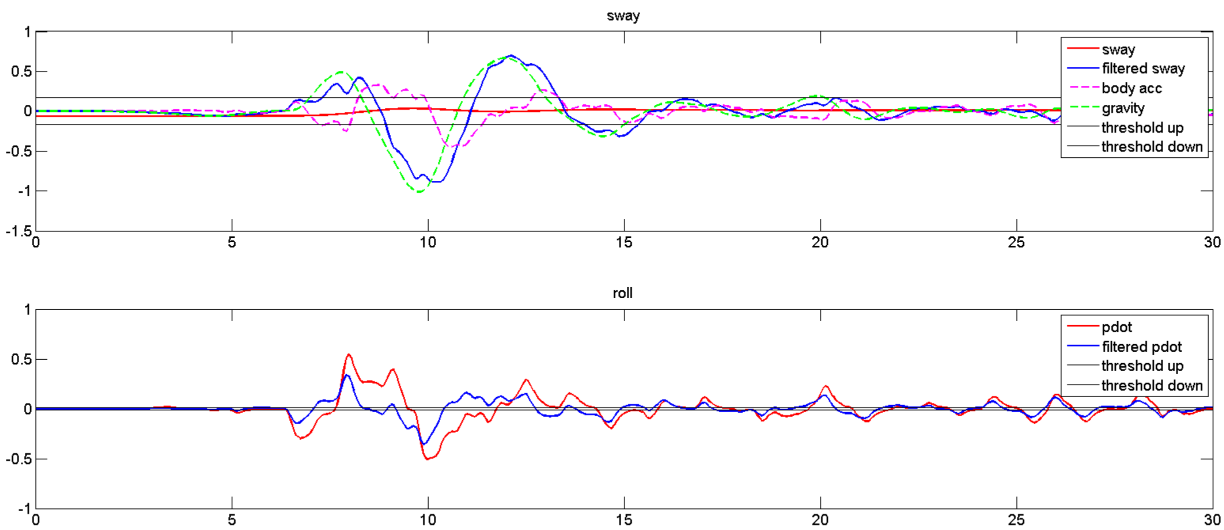

Figure 6.12: Sway and Roll

To conclude, there is some general remarks on the baseline filter:

- There is trade off relationship between surge/pitch as well sway/roll. To fixed the false cueing on surge or sway, either pitch/roll should degraded or surge/sway increased.

- The objective of the motion filter is to suit the experiment, the added dynamics is applied on pitch, it is expected to have a good pitch.
- The objective for a motion filter tuning is hence find a balance between good pitch performance and minimize false cueing on surge/sway.

After some off-line simulations, due to the trade off relationship between surge and pitch, one objective of the test is to find out the effect of false cueing on surge on the flight task. And it should determine the number of motion conditions used in the further experiment as well. Hence three cases are selected.

Case1: Focus on Pitch

This is an extreme case, with perfect pitch and no surge. This filter is in favor of pitch, a scaling down is used without any washout. The surge and tilt coordination is off. In this case, the pitch is considered as perfect, while the false cueing on surge is very large as well. It is one extreme case with maximum false cueing.

Table 6.3: Case1: focus on pitch

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
w_n	2	2	2.5	1.5	0	1.5	-
w_b	0	0	0.1	0	1.5	0	-
$w_n lp$	4	4	0	0	0	0	-
switch	0	1	1	1	1	1	0

As showed in the table, a first order filter is used for pitch , while surge is removed. The result is shown on Figure 6.13. The pitch is improved while the false cueing on surge get larger.

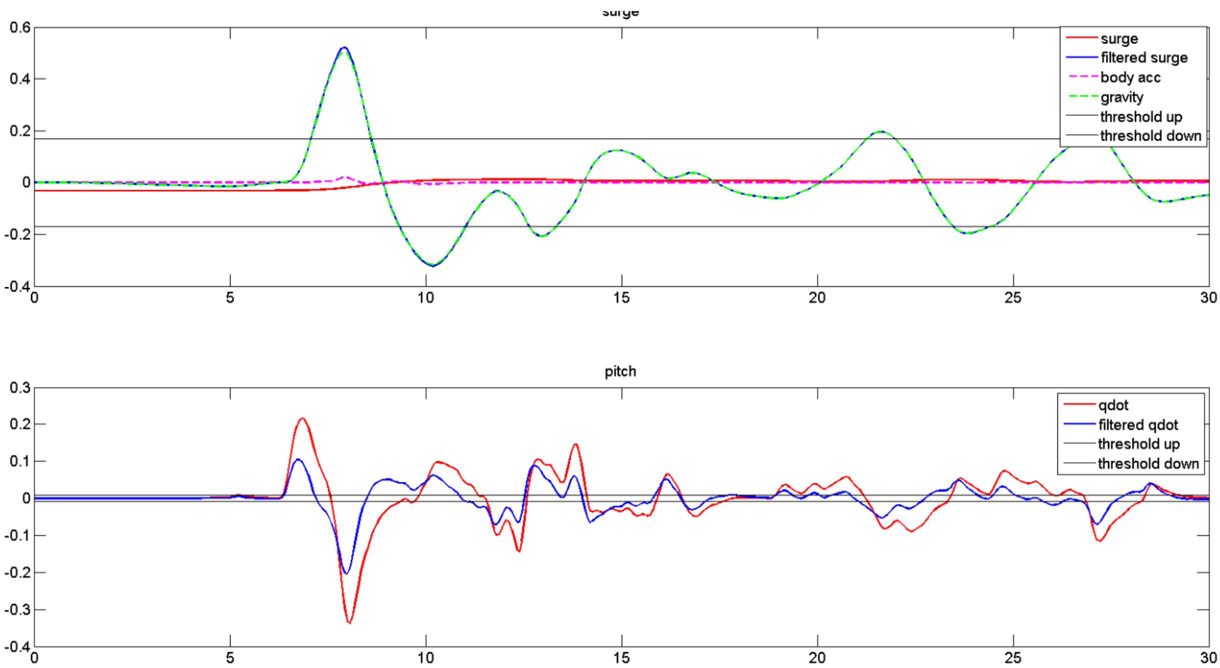

Figure 6.13: Surge and Pitch for Case1

Adding surge can reduce the false cueing, moreover, degrading pitch by increase the break frequency can also reduce the false cueing. The problem is, the break frequency for pitch should not be higher than 2 otherwise the added dynamics will be washed out.

This case is an extreme case for pitch, regardless of false cueing on surge. In next section, the extreme case on the other side will be analyzed as well.

Case2: Focus on Reducing false cueing

With a degraded pitch, but false cueing are fixed. Second order on rotational axis while first order is used for translational axis. It looks like the motion is in favor of surge and sway. However in this case, the false cueing on surge and sway are under threshold. The pith and roll are very bad instead. This is considered as another extreme case that there is no false cueing.

Table 6.4: Case2: focus on surge

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
w_n	0	0	2.5	1.5	1.5	1.5	-
w_b	1.5	1.5	0.1	0	0	0	-
$w_n lp$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

Figure 6.14 shows the result of the filter in this case. The false cueing is almost under threshold. This can be regarded as a second extreme case that false cueing are minimized while pitch are worst.

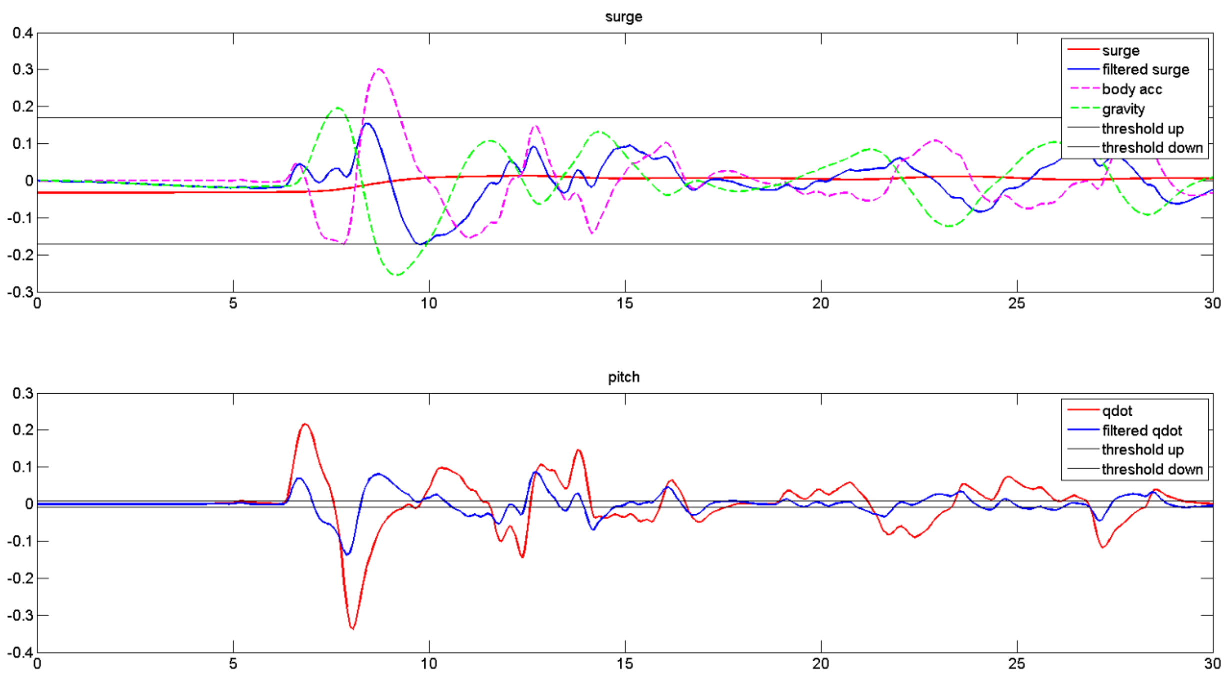

Figure 6.14: Surge and Pitch for Case2

Case3: A balance for all D.O.F

This is the case that balanced for all D.O.F, and first order filter is used for both translational and rotational axis. The false cueing is not significant while moderate pitch and roll is achieved.

Table 6.5: Case3: harmonised case

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
w_n	0	0	2.5	0	0	0	-
w_b	1.5	1.5	0.1	1.5	1.5	1.5	-
$w_n lp$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

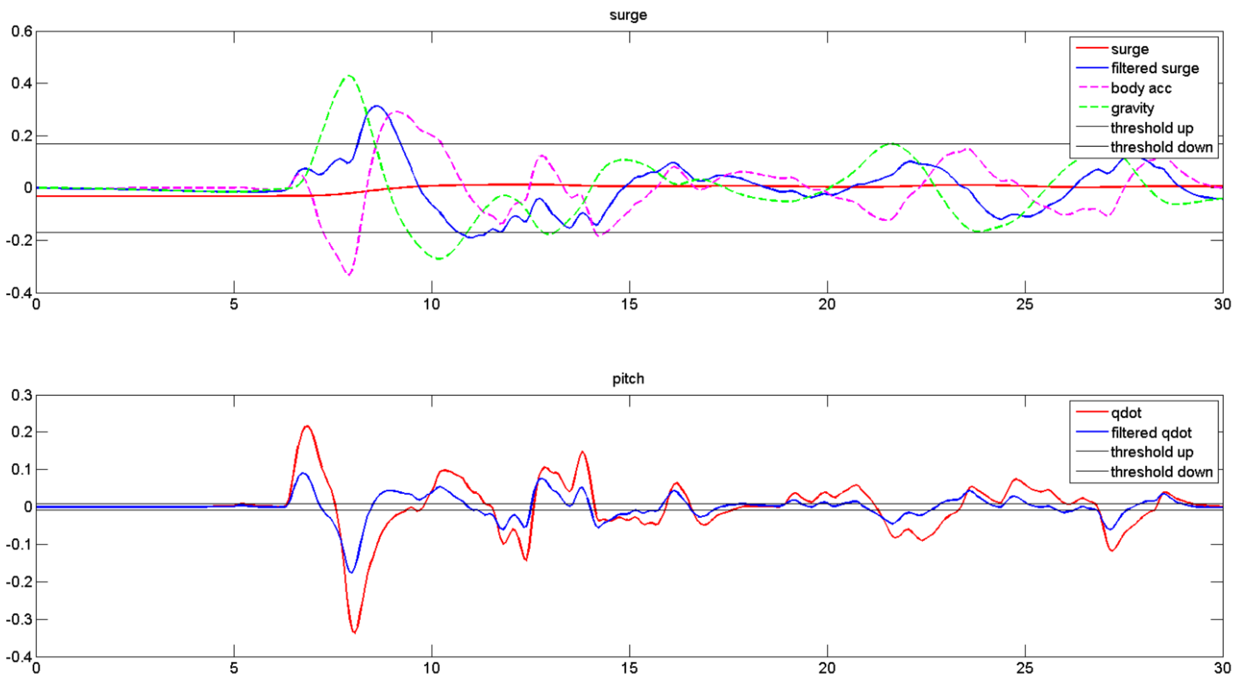

Figure 6.15: Surge and Pitch for Case3

Figure 6.15 and 6.16 shows the simulation result of pitch and roll response. As mentioned, this is a balanced case between a perfect pitch and minimized false cueing.

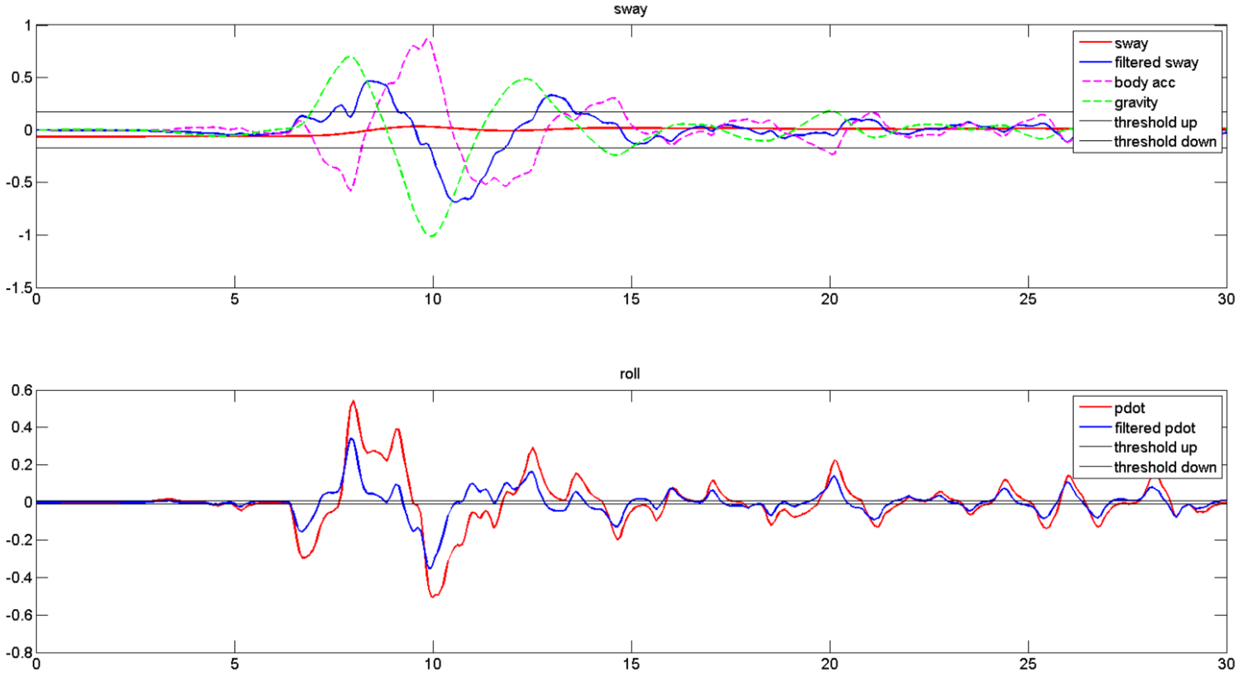

Figure 6.16: Sway and Roll for Case3

6.3.3 Recommendation

The tuning based on simulation is the first step of preliminarily tuning of motion filter. The pilot's opinion and comments are critical during the tuning. Hence a test with pilot is still necessary for the tuning.

Some remarks to the proposed test based on the simulation result:

- The threshold needs to be further tested with a pilot. Since even in a balanced case, the false cueing may not be noticed.
- If pilot feels significant difference between the three cases, to figure out if false cueing affect the AEE, a third condition may be needed for the proposed experiment.
- Similar process should be done for other axis (heave and yaw) to get a more balanced filter on all D.O.F.

Chapter 7

Research Plan

After the literature review, a research is proposed. This chapter gives a proposal for the research. Section 7.1 states the research problem and hence gives a main research question. Section 7.2 briefly introduce the experiment set up to answer the research question. Finally Section 7.3 gives a detail plan for the research project.

7.1 Research Question

Flight simulator nowadays are used as a fundamental tool for research, pilot training and development of any new aircraft design. In 2006, Mitchell et al. [11] proposed an boundary criteria called Allowable Error Envelopes (AEE) in frequency domain to define the allowable errors in the mathematical model for simulation validation.

This research is to further test the applicability of AEE to helicopter simulation model validation, by using same experimental set-up in the SIMONA research simulator at TU delft. The investigation will focus on the effect of helicopter response axis on shape of AEE, and the effect of Motion as well.

Based on the literature review in first part of this report, the preliminary consideration on D.O.F of helicopter dynamics and effect motion are analyzed as well. A research question is formulated:

What is the effect of motion and D.O.F of added dynamics on AEE for helicopter simulation model validation?

With the result from the analysis discussed in first part of the report, some hypotheses for the research question can be formulated:

- Hypothesis 1. The shape of AEE for added dynamics on pitch is wider than those on roll between frequency 3 to 5 rad/s.
- Hypothesis 2. The motion cueing will shift the stringent part of AEE will shift to higher frequency (to right).

The first hypothesis is based on the analysis on difference between helicopter pitch and roll dynamics. Between 3 rad/s to 5 rad/s, pilots are expected to be more sensitive to the added dynamics on roll. Because pilot control a gain instead of a lead. This means the shape of the AEE generated with added dynamics on pitch is expected to be wider than the ones with added dynamics on roll.

The second hypothesis is based on the preliminary consideration of motion system. The cybernetic approach shows that motion cueing can use as an alternative lead and more advantageous for the human. With higher frequency than the break frequency (3 rad/s), the shape of AEE will be more stringent. This means the narrow part of AEE shifts to higher frequency.

To test the above hypotheses, a experiment is designed. In next section, the experiment set up is given in detail.

7.2 Experiment Setup

An experiment is designed to investigate the research question stated in Section 7.1. The general set up is similar to Mitchell's and Penn's experiment. [11] [13] The simulation model is implemented on SIMONA Research Simulator, two different motion conditions are tested.

7.2.1 Helicopter Model

The helicopter model that will be used in the experiment is discussed in Chapter 5 in Part One. The added dynamics are adapted from [13] and [11]. With a interested frequency range from 1 to 10 rad/s, the added dynamics is selected within this range. With the focus on the range between 3 to 5 rad/s, extra sets of added dynamics are applied in this region.

There are 12 sets of added dynamics along the frequency range plotted in Figure 7.1. Only half of the sets are showed as the other half is just opposite by switching the natural frequency of poles and zeros. The difference/distance between natural frequency for zero and pole are keeping constant as $10^{0.8}$. The detail experiment matrix is explained later.

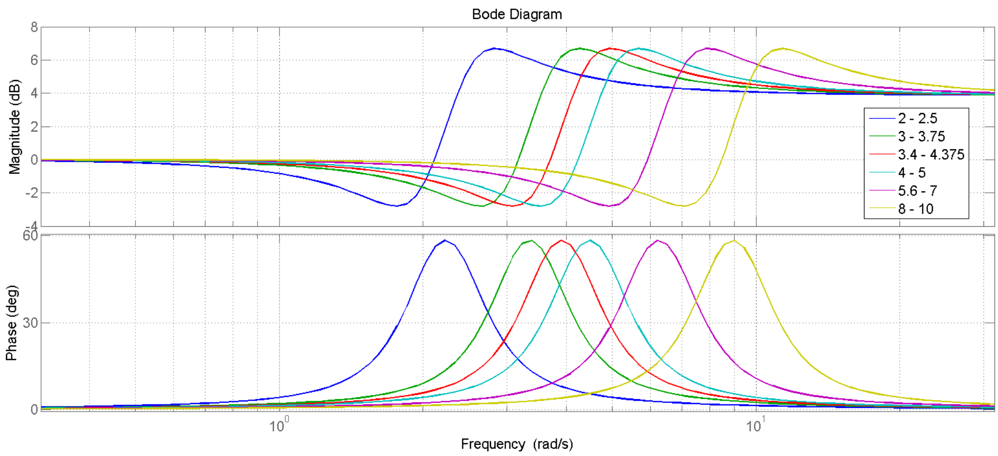

Figure 7.1: Designed Added dynamics

The Bode plot of added dynamics shows the interested range of frequency for this experiment. Note that the number of data between 3 to 5 rad/s is larger. Added dynamics with too low or too high frequency are not used in the experiment. As by studying the research by Penn [13], those added dynamics are not critical to the shape of AEE.

7.2.2 Flight Task

The flight task that will be performed in the experiment is also identical to Penn's experiment [13]. To compare the result, it is logical to keep the set up as similar as possible. Also the task can represent the performance on both longitudinal and lateral dynamics of the helicopter, it is suitable for the research on added dynamics on pitch.

The flight task is Hover MTE defined by ADS-33E PRF [37]. Initially, pilots are flying at a ground speed of between 6 and 10 knots, at an altitude less than 20 ft. The target hover point is oriented approximately 45 degrees relative to the heading of the rotor craft with ground reference and it is repeatable.The task is to fly the helicopter to that point and hover it with the following requirements:

- 1. Attain a stabilized hover within 8 seconds of initiation of deceleration.
- 2. Maintain a stabilized hover for at least 30 seconds.
- 3. Maintain the long. and lat. position within ±6 ft of a point on the ground.
- 4. Maintain altitude within ±4ft.
- 5. Maintain heading within 10 degree.

The desired maneuver is shown in the Figure 7.2.

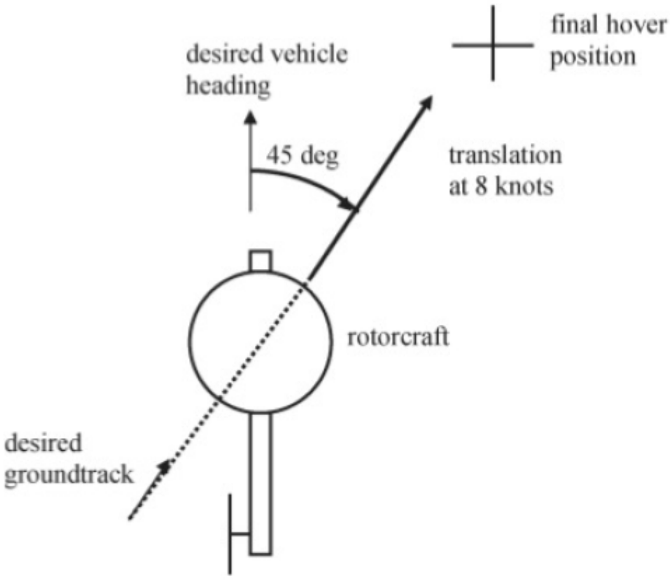

Figure 7.2: Hover Mission Task Element

7.2.3 Experiment Design

Due to the time constrain, the test subjects will be three helicopter pilots. The controlled variables in the experiment will be the model configuration, visual cueing, motion setting and control loading. The control variables is to keep constant during the experiment. To investigate the effect of motion, other simulation cueing like visual and control loading should be identical, this can be achieved by using same simulator. Finally, the task performance should also be controlled, pilots are asked to fly it with desired performance, or if that's not possible, with adequate performance.

The independent variable is hence the added dynamics. The added dynamics can be adjust by tuning the damping and natural frequency. As shown in Figure 7.1, a more structured design of added dynamics is given. The added dynamics is designed based on the frequency. During the experiment, each set will be tested with different damping ratio until the critical case is found.

The designed experiment matrix is described in Table 7.1. This matrix is for one condition, for each condition, same amount of test should be processed. For each condition, there is 8 set of data dependent on the frequency of added dynamics. While s1,s2,s3 represent the three subject, and m1, m2 shows the two motion conditions.

For each set, the pilot will fly randomly the damping ratio for from 0.1 to 0.9. After first round, the scope for searching boundary will be smaller. For example between 0.3 to 0.5. Hence, a second round will be performed in this range. Compare to [13], this approach to search the boundaries is more random and hence has less consistency.

Table 7.1: Experiment Matrix

wz	wp	s1, m1	s2, m1	s3, m1	s1, m2	s2 ,m2	s3, m2
2	2.5	3	1	2	1	2	8
2.5	2	1	8	3	2	5	7
3	3.75	2	7	7	3	7	5
3.75	3	4	5	5	4	6	6
4	5	8	6	6	5	8	1
5	4	5	2	4	6	1	3
5.6	7	6	3	8	7	3	4
7	5.6	7	4	1	8	4	2

The order of the experiment for three subjects are also randomized as much as possible. for each set of experiment, several steps are followed:

- pilots get briefed about the task and procedure
- pilots get familiarize with the simulation setting
- Pilots fly the task with baseline model(without added dynamics)
- Pilots then fly the task with added dynamics model
- The performance has the highest priority
- Pilots are asked to keep the same strategy as much as possible
- After each set, pilots were asked to go though the noticeability rating
- Debriefing

7.2.4 Alteration Noticeability Rating

The only dependent measurement in this experiment is the noticeablility rating. Based on the rating, the critical added dynamics are determined. The noticrability rating used in this experiment is modified based on the Alternation Noticeability Rating (ANR) scale developed Penn [13]. While the origin of ANR is from the Simulation Fidelity Rating Matrix shown in Figure 7.3.

		Comparative Performance		
		Equal	Similar	Dissimilar
Strategy Adaptation	No	A	D	I
	Negligible	B	D	I
	Minimal	C	E	I
	Moderate	F	G	I
	Considerable	F	G	I
	Excessive	H	H	I
	Other	I	I	I

Figure 7.3: Simulation Fidelity Rating matrix [13] source: [36]

The matrix [36] is defined by the performance as well as the strategy of pilot. Score from A to I is giving. According to [13], score A and B can be considered as "Unnoticed". Based on this matrix, ANR is developed, with the same score from A to I. While score B is hence the boundary for critical added dynamics.

However, based on the result and pilot's evaluation on ANR, some further improvement on the rating scale is needed. As mentioned in [13], during the experiment, there is a condition that pilot can feel the added dynamics, while it does not affect the performance and the strategy used. This condition is out of the scope of ANR. Since the Simulation fidelity rating is only based on performance and strategy, but not on the pilot's perception.

This condition is between score B and C which is critical for determining the boundaries. Thus a $C^{\star}$ is used by Penn. To solve this problem, a new noticeablility rating proposed in this research is adapted from ANR as shown on Figure 7.4.

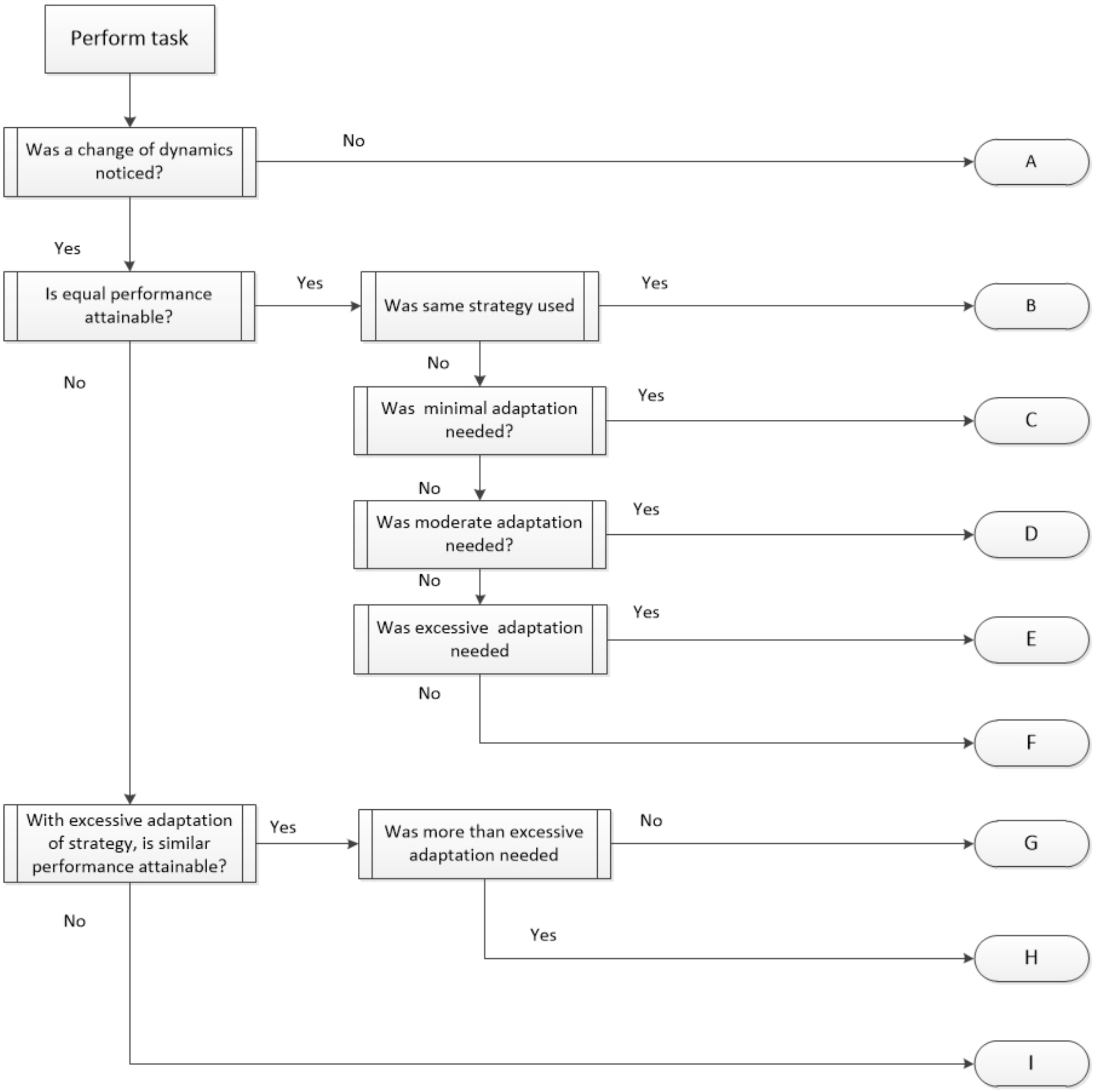

Figure 7.4: Noticeability Rating

The score and level of fidelity are associated with ANR proposed by Penn. It is designed to be like that since the produced AEE can be compared to Penn's result, the rating scale should be as close as possible. The most significant difference is that, the original score A and B are merged to A. Since the pilot does not feel the change of dynamics, further question on performance and strategy is not important. It increases the noise to the result. The $C^{\star}$ is replaced by score B which represent the condition that the added dynamics is noticed, without performance degradation or strategy adaptation.

7.3 Project Plan

The project will be divided into 5 different periods and the Gantt Chart will be shown in Figure 7.5:

- **The Literature Phase**
  The literature Phase is special for Control and Simulation department since literature will be a part of the thesis, in this phase, the literature study is finished, getting understanding of the topic, making project plan.

- **The Preliminary Phase**
  This phase will be end with a preliminary thesis presentation, with the literature study report finished, as well as the experiment set up and plan finished. The topic is further understood and the model and method is reproduced on matlab. Preparation for the experiment should also be done like finding test pilot, reserve SIMONA. The delivery for this phase will be a preliminary thesis report and a presentation.

- **The Experimentation Phase (Mid-term)**
  This phase including the experiment, as well as the preliminary data analysis. Note that setting up the experiment is easy, since a simple model is used, however, tuning the system and motion will take a lot of time. A prelim data analysis can be start even without the result.

- **The Detailed Phase**
  This phase starts immediately after the experiment is done, the data gathering and data analysis will be processed, also the AEE will be developed, the result will also be written into a report. The delivery of this phase will be the final report for Green-Light Meeting.

- **The Wrap Up Phase**
  This is the final phase of the research, the report will be finalized and make the final submission, the presentation for a thesis defence is also completed. The delivery will be the final report and the final presentation.

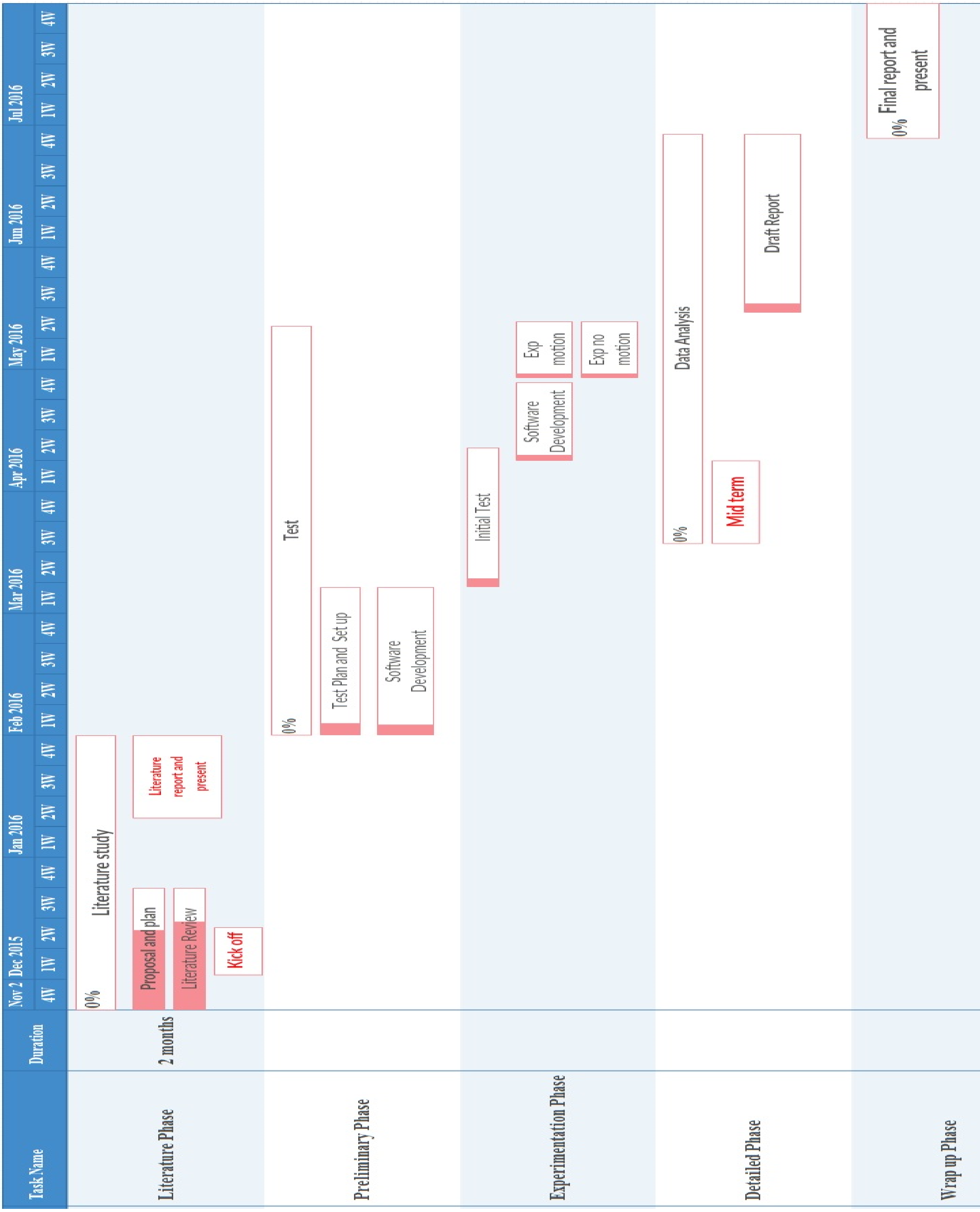

Figure 7.5: Gantt Chart for the Project

Chapter 8

Conclusion and Recommendations

The first part of the report includes a literature study on helicopter simulation fidelity and some preliminary consideration. By reviewing the historical development on simulation training devices(STD), it finds out the general challenges for helicopter simulator compared to fixed wing counterparts. Besides the cost and technical issues, the most important challenge on helicopter simulator is the qualification.

Current qualification standards on helicopter simulator is based on the fixed wing aircraft. Due to the different in dynamics, these standards derived from fixed wing aircraft are insufficient and may lead to over confidence in the simulator [7].

To find out the criteria that defines the sufficient quality of a helicopter simulator, the state of arts of assessment on simulation fidelity is reviewed. There are two main challenges on simulation fidelity, one is to find a universal definition, the other is the measurement of fidelity. The literature study shows that the academical research are shifting from traditional physical fidelity to the perceived fidelity. When the human perception is taken into account, the fidelity is more comprehensive but also more subjective.

After reviewing a few subjective fidelity assessment techniques, a new fidelity assessment method is needed with the following requirements:

- A frequency domain analysis
- Assess the perceived fidelity
- A quantifying method of measurement
- A rather objective approach

A method called Maximum Unnoticeable Added dynamics(MUAD) is proposed firstly as a mismatch criteria for equivalent system approach. The early application of MUAD was proposed by Tischler [10] in 1996. It used for model validation of a XV-15 tilt rotocraft. Mitchell et al. [11] derived the Allowable Error Envelopes (AEE) from MUAD. These envelopes are specifically used to define the allowable error in simulation validation.

The review of the research on AEE shows that: AEE is dependent on pilot and simulation set up. To further investigate the applicability of AEE, a research is proposed by the author. With similar simulation set up, the added dynamics is applied on pitch instead of roll. Different motion conditions are also tested. The research question is hence to find out what is the effect of motion and D.O.F of added dynamics on AEE.

A preliminary analysis on the two independent factors in the research question is given. The cybernetic approach on helicopter pitch and roll dynamics shows that, between 3 rad/s to 5 rad/s, pilots are expected to be more sensitive to the added dynamics on roll. Because pilot control a gain instead of a lead. This means the shape of the AEE generated with added dynamics on pitch is expected to be wider than the ones with added dynamics on roll.

The cybernetic approach is also used to analyse the motion. It shows that motion cueing can be uses as an alternative lead. With higher frequency than the break frequency (3 rad/s), the shape of AEE will be more stringent(narrower). This means the narrow part of AEE shifts to higher frequency.

Finally, based on the result of preliminary consideration, an experiment is designed. Identical helicopter model and flight task from [11] and [13] are used. The SIMONA Research Simulator with different motion conditions is the experiment facility. By replicate Mitchell and Penn's experiment, the AEE proposed in [11] will be reproduced. The result will be also compared to the earier work. Most importantly, the effect of motion and D.O.F of added dynamics on AEE will be determined.

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Part III

Appendix

Appendix A

Qualification on Helicopter Simulation

This Appendix gives a background knowledge on certification standard of helicopter simulator. European Aviation Safety Agency (EASA) certification standard, which is called CS-FSTD(H) is reviewed at first.

FLIGHT SIMULATION TRAINING DEVICE STANDARDS		FFS LEVEL				FTD LEVEL			FNPT LEVEL				COMPLIANCE
		A	B	C	D	1	2	3	I	II	III	MCC	
	1.1 General												
a.1	A cockpit that is a full-scale replica of the helicopter simulated. Additional required crew member duty stations and those required bulkheads aft of the pilot seats are also considered part of the cockpit and shall replicate the helicopter.	✓	✓	✓	✓		✓	✓					
	A cockpit that replicates the helicopter.					✓			✓	✓	✓	✓	
a.2	The cockpit, including the instructor's station is fully enclosed.	✓	✓	✓	✓								
	A cockpit, including the instructor's station that is sufficiently closed off to exclude distractions.					✓	✓	✓	✓	✓	✓	✓	
b.1	Full size panels with functional controls, switches, instruments and primary and secondary flight controls, which shall be operating in the correct direction and with the correct range of movement.	✓	✓	✓	✓	✓	✓	✓					For FTD level 1 as appropriate for the replicated system. The use of electronically displayed images with physical overlay or masking for FSTD instruments and/or instrument panels incorporating instrument controls and switches that replicate those of the helicopter and operate with the same technique, effort, travel and in the same direction may be acceptable.
	Functional controls, switches, instruments and primary and secondary flight controls sufficient for the training events to be accomplished, shall be located in a spatially correct area of the cockpit.								✓	✓	✓	✓	FSTD instruments and/or instrument panels using electronically displayed images with physical overlay or masking and operable controls representative of those in the type of helicopter are acceptable. The instruments displayed should be free of quantisation (stepping).
c.1	Lighting for panels and instruments shall be as per the helicopter.	✓	✓	✓	✓		✓	✓					
	Lighting for panels and instruments shall be sufficient for the training events					✓			✓	✓	✓	✓	

Figure A-1: Example of CS-FSTD (H) standard requirement

Figure A-1 and Figure A-2 shows an example of CS-FSTD(H) requirement. The regulations divide the helicopter training simulator devices into three different categories. As shown on the figure, a Flight and Navigation Procedure Trainer(FNPT) is a fixed base simulator with a simple cockpit. Full Flight Simulator(FFS) on the other hand, has a motion system. There are 4 different levels of FFS

FLIGHT SIMULATION TRAINING DEVICE STANDARDS		FFS LEVEL A	FFS LEVEL B	FFS LEVEL C	FFS LEVEL D	FTD LEVEL 1	FTD LEVEL 2	FTD LEVEL 3	FNPT LEVEL I	FNPT LEVEL II	FNPT LEVEL III	FNPT LEVEL MCC	COMPLIANCE
c.2	Cockpit ambient lighting environment shall be dynamically consistent with the visual display and sufficient for the training event.			✓	✓								
	The ambient lighting should provide an even level of illumination which is not distracting to the pilot.	✓	✓				✓	✓		✓	✓	✓	
d.1	Relevant cockpit circuit breakers shall be located as per the helicopter and shall function accurately when involved in operating procedures or malfunctions requiring or involving flight crew response.	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	
e.1	Effect of aerodynamic changes for various combinations of airspeed and power normally encountered in flight, including the effect of change in helicopter attitude, aerodynamic and propulsive forces and moments, altitude, temperature, mass, centre of gravity location and configuration.	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	Effects of C_G mass and configuration changes are not required for FNPT level I.
	Aerodynamic and environment modelling shall be sufficient to permit accurate systems operation and indication.					✓							
e.2	Aerodynamic modelling which includes ground effect, effects of airframe and rotor icing (if applicable), aerodynamic interference effects between the rotor wake and fuselage, influence of the rotor on control and stabilisation systems, and representations of nonlinearities due to sideslip, vortex ring and retreating blade stall.			✓	✓		✓	✓		✓	✓	✓	
f.1	Validation flight test data shall be used as the basis for flight and performance and systems characteristics.		✓	✓	✓			✓					
	Representative/generic aerodynamic data tailored to the helicopter with fidelity sufficient to meet the objective tests and sufficient to permit accurate system operation and indication.	✓				✓	✓		✓	✓	✓	✓	Aerodynamic data need not be necessarily based on flight test data.

Figure A-2: Example of CS-FSTD (H) standard requirement 2

while level D FFS is the most sophisticated qualification level.

The standard in the figure which is the first part of the certification: Technical specification. It is the technical requirements on simulator hardware like visual, and motion system. While the other part describe the validation test as well functions/subjective test.

Figure A-3 and Figure A-4 shows the second part of the the certification: the validation test. It shows the tolerance of the performance. The validation test requirements are documented based on: Performance, Handling Qualities, Atmospheric Models, Motion System, Visual System and Flight Simulation Training Devices(FSTD) system.

TESTS	TOLERANCE	FLIGHT CONDITIONS	FSTD LEVEL											COMMENTS
			FFS				FTD			FNPT				
			A	B	C	D	1	2	3	I	II	III	MCC	
c. Take-off														
(1) All engines	Airspeed ± 3 kt Altitude ± 20 ft (6·1 m) Torque ± 3% Rotor speed ± 1·5% Pitch angle ± 1·5° Bank angle ± 2° Heading ± 2° Longitudinal control position ± 10% Lateral control position ± 10% Directional control position ± 10% Collective control position ± 10%	Ground/lift off and initial climb	C T & M	✓	✓	✓	C T & M	✓	✓		✓	✓	✓	Time history of take-off flight path as appropriate to helicopter model simulated [running take-off for FFS level B & FTD level 2. Take-off from a hover for FFS level C & D or FTD level 3]. In addition to the airspeed the ground speed should be taken as reference with the same tolerance of ±3 kts until the airspeed is clearly readable. For FFS level B and FTD level 2, criteria apply only to those segments at airspeeds above effective translational lift. Record data to at least 200 ft (61 m) AGL/V_Y whichever comes later.
(2) OEI continued take-off	See 1.c.(1) above for tolerances and flight conditions	Take-off & initial climb	C T & M	✓	✓	✓	C T & M	✓	✓		✓	✓	✓	Time history of take-off flight path as appropriate to helicopter model simulated. Record data to at least 200 ft (61 m) AGL/V_Y whichever comes later.

Figure A-3: Example of CS-FSTD (H) validation test: Take-off

TESTS	TOLERANCE	FLIGHT CONDITIONS	FSTD LEVEL											COMMENTS
			FFS				FTD			FNPT				
			A	B	C	D	1	2	3	I	II	III	MCC	
(3) OEI rejected take-off	Airspeed ± 3 kt Altitude ± 20 ft (6·1 m) Torque ± 3% Rotor speed ± 1·5% Pitch angle ± 1·5° Bank angle ± 1·5° Heading ± 2° Longitudinal control position ± 10% Lateral control position ± 10% Directional control position ± 10% Collective control position ± 10% Distance: ± 7·5% or ± 30 m (100 ft)	Ground/take-off	C T & M	C T & M	✓	✓		✓	✓			✓	✓	Time history from the take-off point to touch down. Test conditions near limiting performance as per aircraft manual. In addition to the airspeed the ground speed should be taken as reference with the same tolerance of ± 3 kts until the airspeed is clearly readable.
d. Hover Performance	Torque ± 3% Pitch angle ± 1·5° Bank angle ± 1·5° Longitudinal control position ± 5% Lateral control position ± 5% Directional control position ± 5% Collective control position ± 5%	In ground effect (IGE) Out of ground effect (OGE) Stability augmentation on or off	C T & M	✓	✓	✓	C T & M	✓	✓		✓	✓	✓	Light and heavy gross weights. May be snapshot tests. Refer to point (b)(4)(ii) below for additional guidance.
e. Vertical Climb Performance	Vertical velocity ± 100 fpm (0.50 m/s) or 10% Directional control position ± 5% Collective control position ± 5%	From OGE hover Stability augmentation on or off	C T & M	✓	✓	✓	C T & M	✓	✓		✓	✓	✓	Light and heavy gross weights. May be snapshot tests.

Figure A-4: Example of CS-FSTD (H) validation test: Hover

Appendix B

Simulation Set up

B-1 Helicopter Model used by Mitchell

$$\dot{x} = Ax + Bu \tag{B-1}$$

$$u = \{u,\ w,\ q,\ \theta,\ v,\ p,\ r,\ \phi\ \}^T \tag{B-2}$$

$$x = \{\delta_B,\ \delta_C,\ \delta_A,\ \delta_P\}^T \tag{B-3}$$

$$A = \begin{bmatrix} X_u & 0 & 0 & -g & 0 & 0 & 0 & 0 \\ 0 & Z_w & U_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_q & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & Y_v & 0 & -U_0 & g \\ 0 & 0 & 0 & 0 & 0 & L_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & N_r & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Z_{\delta_C} & 0 & 0 \\ M_{\delta_B} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & L_{\delta_A} & 0 \\ 0 & 0 & 0 & N_{\delta_P} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{B-4}$$

B-2 Trim condition

The model is only valid around hover. This means the trimmed velocity is zero. However, in the flight task, the helicopter is not initially at hover. Instead, some ground speed is needed. Therefore, the model has to be trimmed at beginning of experiment.

Table B-1: Model Parameters used by Mitchell

Derivatives	Value	Unit
X_u	-0.01	1/sec
Z_w	-1	1/sec
M_q	-3	1/sec
Y_v	-0.02	1/sec
L_p	-5	1/sec
N_r	-0.625	1/sec
Z_{δ_C}	-7	ft/sec2
M_{δ_B}	-0.7	rad/sec2
L_{δ_A}	2	rad/sec2
N_{δ_P}	-3	rad/sec2

In the model, the trim term U_0 is set to be 0 during hover. To provide the helicopter a ground speed at beginning, the model is trimmed such that an initial pitch and roll angle is given.

As showen in equation B-5 and B-6, at trim condition, the body speed derivative is zero. The initial velocity in x direction is u_i which is calculated based on the initial ground speed. In this way, the initial pitch is determined.

$$\dot{u} = X_u \cdot u_i - g \cdot \theta_i = 0 \tag{B-5}$$

$$\theta_i = \frac{X_u \cdot u_i}{g} \tag{B-6}$$

It is same for lateral axis. Equation B-7 and B-8 shows how the initial roll angle is calculated. Note that r_i is zero.

$$\dot{v} = Y_v \cdot v_i + g \cdot \phi_i - U_0 \cdot r_i = 0 \tag{B-7}$$

$$\phi_i = \frac{-Y_v \cdot v_i}{g} \tag{B-8}$$

B-3 Added dynamics

The added dynamics are second order lead/lag and lag/lead filter. This form is identical to Mitchell's experiment. The advantage of using dipole pairs is that it is very easy to shift the peaks of added dynamics, both vertically and horizontally. In this way, it is easier to design the added dynamics for the interesting range of frequency.

The added dynamics can be written as equation B-9. Where K is the gain and ζ is the damping ratio. ω_{nz} and ω_{np} are the natural frequency for zeros and poles.

$$Added\,Dynamics = K\frac{s^2+2\zeta w_{nz}s+w_{nz}^2}{s^2+2\zeta w_{np}s+w_{np}^2} \tag{B-9}$$

The other advantage for these added dynamics is that by adjusting the poles and zeros, the peaks of added dynamics can shift between positive and negative. In this way the AEE can be determined in both directions.

To get further understanding the added dynamics, some preliminary offline simulation is proposed to investigate how the following factors affect the added dynamics:

- Gain K
- Damping ratio ζ
- Natural frequency ω_n
- Distance between pole and zero.

Effect of K

Two types of gain are plotted, firstly to achieve the steady state gain at high frequency, a unity gain 1 is used. For lower frequency, the second type gain is determined. As shown in equation B-10 both types of gain are determined with final value theorem and initial value theorem separately.

$$K_{type1} = 1 \qquad\qquad K_{type2} = \frac{w_{np}^2}{w_{nz}^2} \tag{B-10}$$

Figure B-1 shows the added dynamics with two different types of gain. It is clear that for type 1, the unity gain is achieved at higher frequency. While at lower frequency, the steady state unity gain can be achieved with type 2.

Effect of damping ratio

Adjusting the damping ratio is the most straight forward way to change the height of peaks of added dynamics. Figure B-2 shows three different added dynamics with a increasing damping ratio from 0.2 to 0.6. It is clear that high damping ratio has a smaller peak and flat hyperbolic shape.

During the experiment, the intensity is hence shifted by tuning the damping. With this knowledge, it can also help to check the feasibility of the result. For example, in the same set of frequency, if pilot noticed dynamics with very high damping but ignore the ones with small damping, the result is not reasonable.

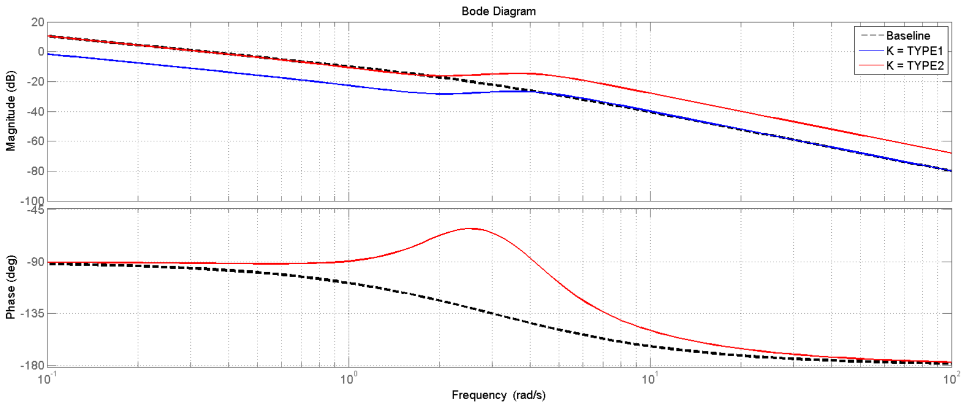

Figure B-1: Effect of Gain K on added dynamics

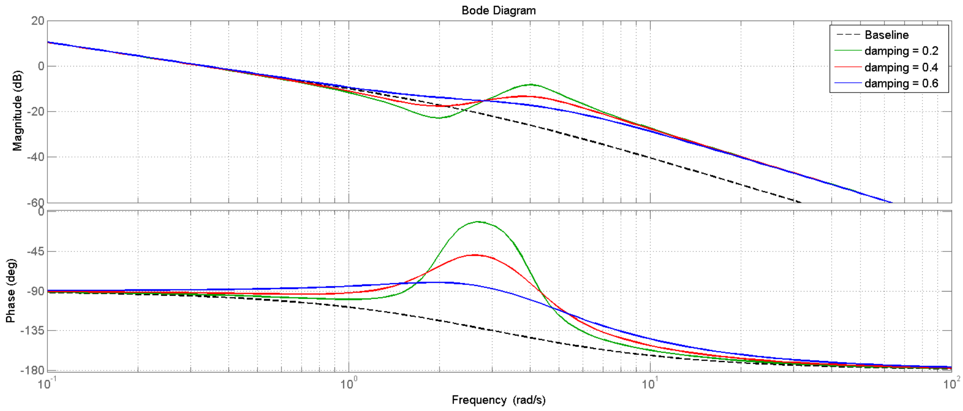

Figure B-2: Effect of Damping on added dynamics

Effect of natural frequency

One advantage of using the dipole pair as added dynamics is by change the natural frequency of poles and zeros, the frequency of added dynamics can be adjusted easily.

Three sets of natural frequencies are tested, by keeping the same gain and damping, the distance between the pole and zero is also constant(in logarithm). Figure B-3 shows the three added dynamics with different sets of natural frequencies.

It is clear that the frequency of the peak of added dynamics shift to right. And the frequency of added dynamics falls within the range between natural frequency of pole and zero. It is noticed that if the natural frequency of zero is higher, the added dynamics will be negative.

Studying the effect of natural frequency will help the design of added dynamics for the experiment. Since by giving different sets of natural frequency, one can apply the added dynamics to the interested

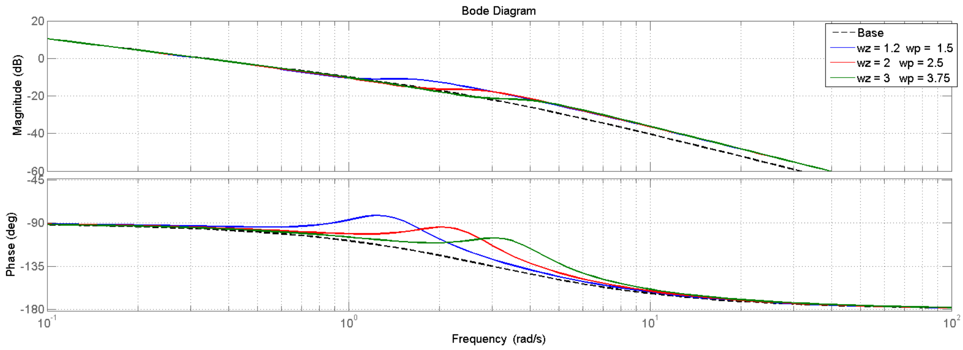

Figure B-3: Effect of natural frequency on added dynamics

range of frequency.

Effect of distance between pole and zero

As shown in Figure B-4, with constant natural frequency of zeros. Shifting the natural frequency of poles will increase the mismatch in the high frequency. If type 1 gain is used, the mismatch will be in low frequency. The change in distance also shift the peak of added dynamics. This is because the frequency of added dynamics falls somewhere in between the natural frequency pole and zero.

In conclusion, by changing the gain, damping and natural frequency, the added dynamics can be designed to fit for the purpose of the current study.

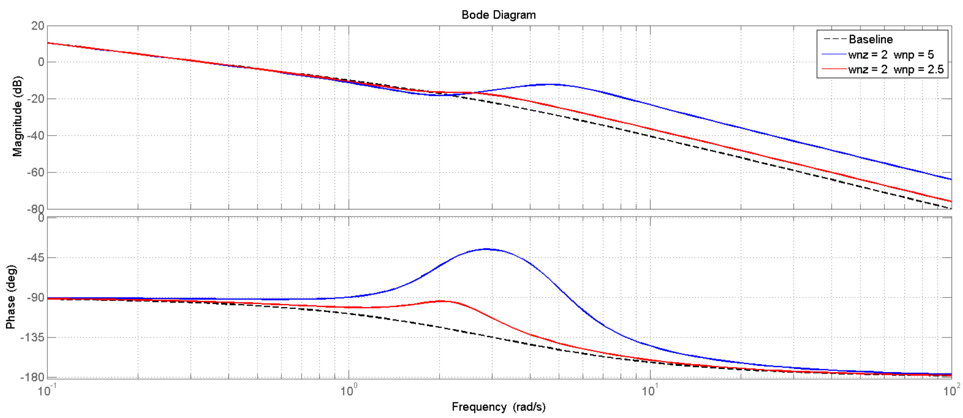

Figure B-4: Effect of distance between pole and zero on added dynamics

Appendix C

Motion Filter Tuning

This Appendix gives a detailed motion filter design and a preliminary motion filter tuning.

C-1 Motion filter design

The motion filter is designed under the following requirements:

- The first priority of setting motion filter is to keep simulator within the limits.
- The limits are defined by the size of work space, length, speed and acceleration of actuators.
- The lower the order, the higher the fidelity.
- The higher the gain, the higher the fidelity.
- The lower the frequency, the smaller washout effect, hence the higher fidelity.
- The filter setting for all D.O.F should be balanced as much as possible.
- The filter setting should be cooperated with the task mission.

A criteria of the motion filter is shown in Figure C-1. Sinacori fidelity criteria is defined by the gain and phase shift of the motion filter at 1 rad/s.

With some knowledge of the motion filter, a suitable motion filter is required to be designed for the experiment. Here, a preliminary consideration on motion filter design is given.

The motion filters can be adjust by the following parameters:

- The order of filter
- The gain K
- The washout ω_n (2nd order)or ω_b (1st order)

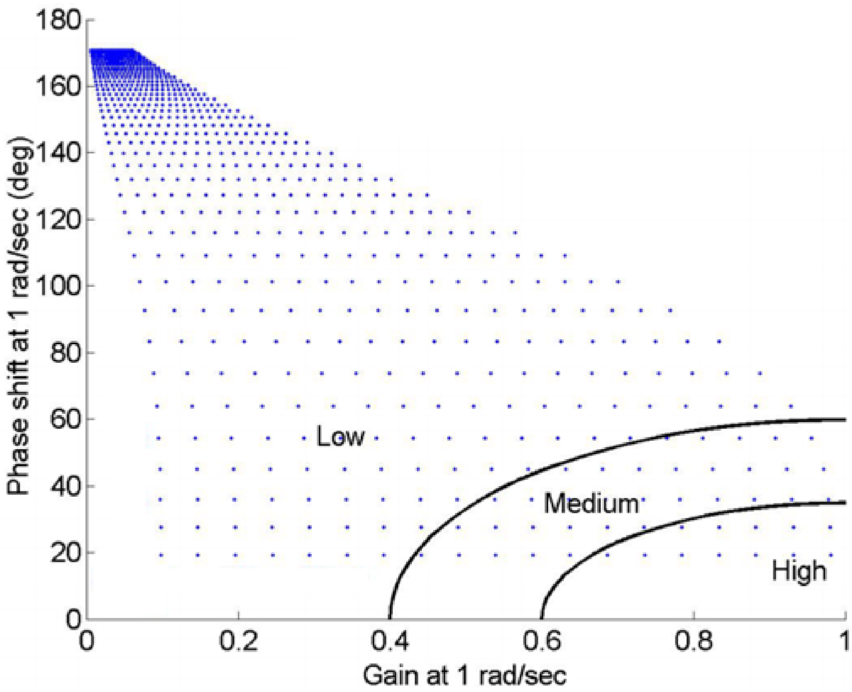

Figure C-1: Sinacori criteria

C-2 Preliminary Tuning

The preliminary tuning of motion filter is based on an offline simulation. The helicopter model as well as motion filter are simulated. By comparing the output of the model before and after the filter, the performance of filter is determined.

To simulate the pilot's control input in the hovering mission, the flight data from Penn's experiment is captured. Figure C-2 is an example of control input for this specific mission. The data is from one subject flying with baseline model (without added dynamics) in SRS simulator with motion.

Three inputs signal are generated, while there is no pedal input hence no yaw dynamics is involved. Notes that these input are normalized and dimensionless.

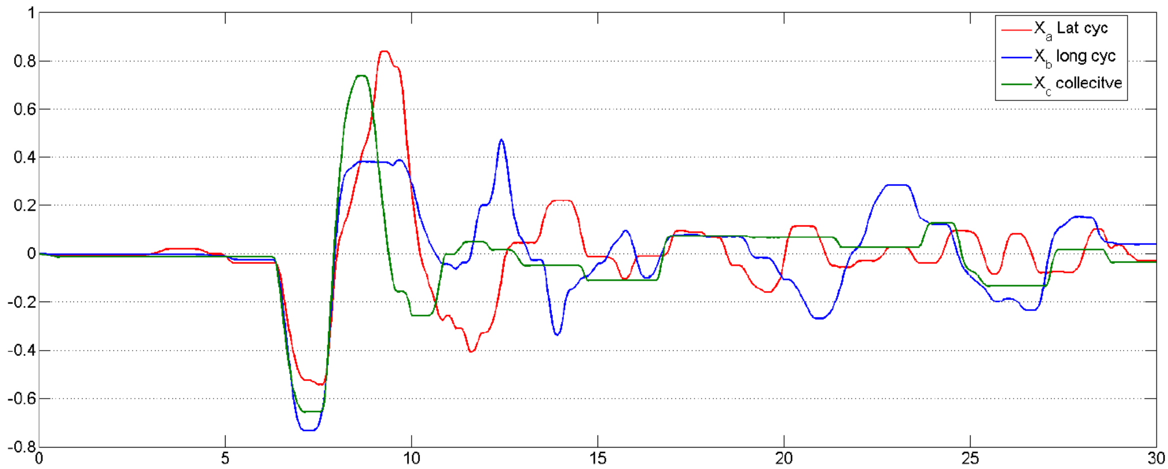

Figure C-2: Example of Control Input

C-2-1 Case 0: Baseline filter

The starting point of the motion filter design is adapted from the motion setting in Penn's experiment. The original setting is in favor of roll attitude, while to keep it balanced, same filter is used for surge and sway, and same second order filter is used for pitch and roll as shown in Table C-1.

Table C-1: Case 0 : Baseline

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	2	2	2.5	1	1	1	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	0	0	0.1	0	0	0	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

The output for specific force and angular acceleration before and after the filter are plotted in Figure C-3. Note that the pitch and roll in this case is considered as good, but still can be improved. There are false cues on surge and sway.

The second check is to check the actuator length to see if the motion is out of the work space of simulator. Based on graph, all six actuators are not reaching the maximum length. The speed of actuator is not calculated yet, based on the slope and frequency, the speed is also safe.

Based on graph, all six actuators are not reaching the maximum length. The speed of actuator is not calculated yet, based on the slope and frequency, the speed is also safe.

The focus of the tuning is to achieve a good performance in pitch, while other axis should not be too bad. However, during the tuning, the pitch will generate false cues on surge, the better pitch will trade off in worse surge.

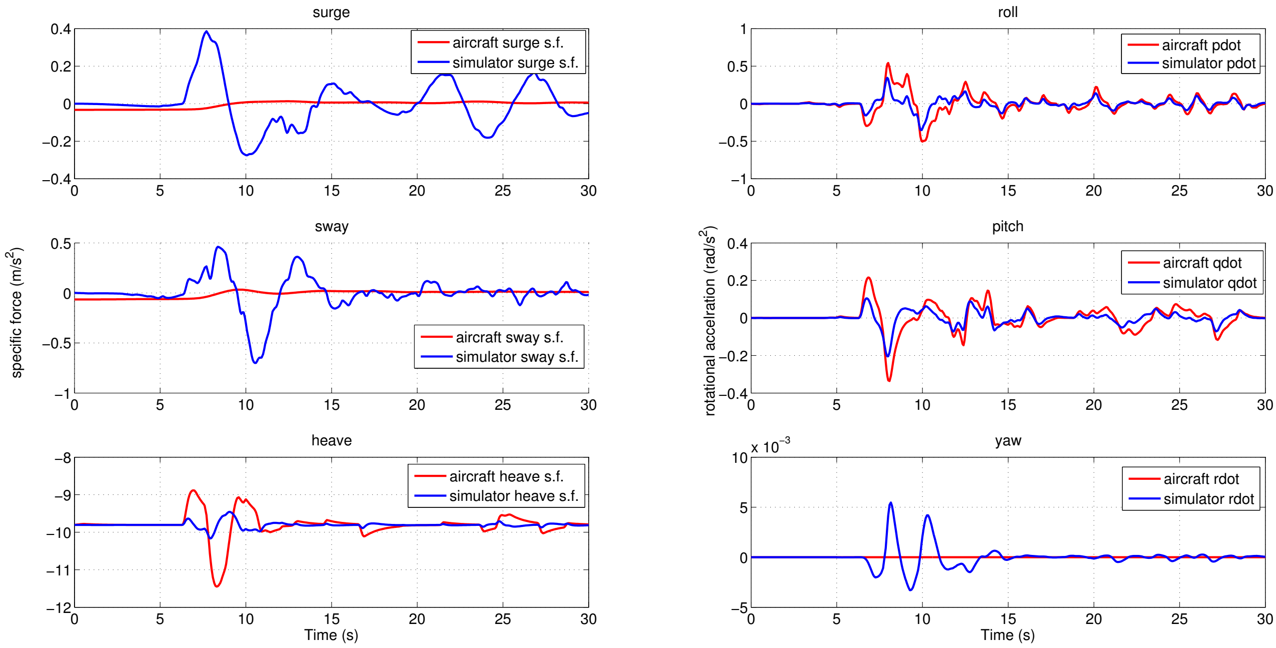

Figure C-3: Output for case 1

The surge cues are based on the body acceleration and effect of gravity. Both attributes are plotted. Base on the graph, the gravity (based on pitch) dominating the false cues while the body acceleration is trying to work against the false cues, hence improve it.

To fix the false cues, it can either increase the cueing from body acceleration (HP surge) or decrease the cueing on pitch. Note that there may be a point that if the pitch is too small that body acceleration will dominating the false cues. This will be further tested since body acceleration is also pitch dependent due to the transfer frame and the tilt coordination.

Same effect is found on sway and roll. The false cues on sway is also dominated by the roll attitude. (gravity). Either decrease this cues or increase body acceleration should help.

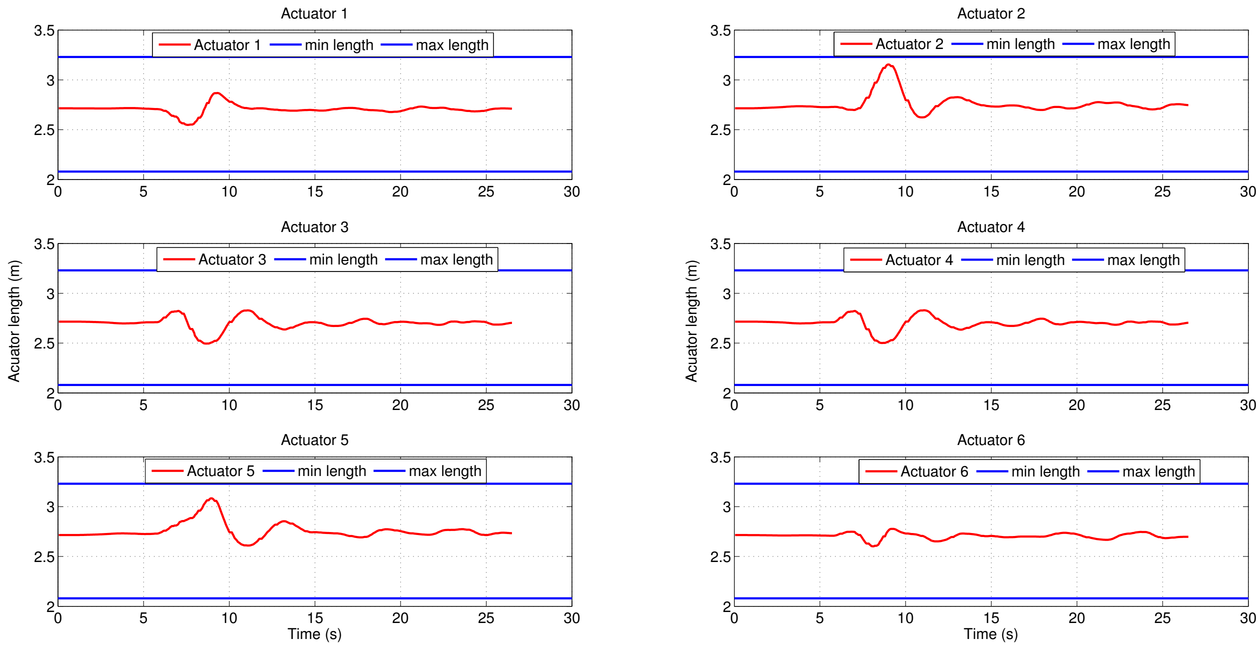

Figure C-4: Actuator length for case 0

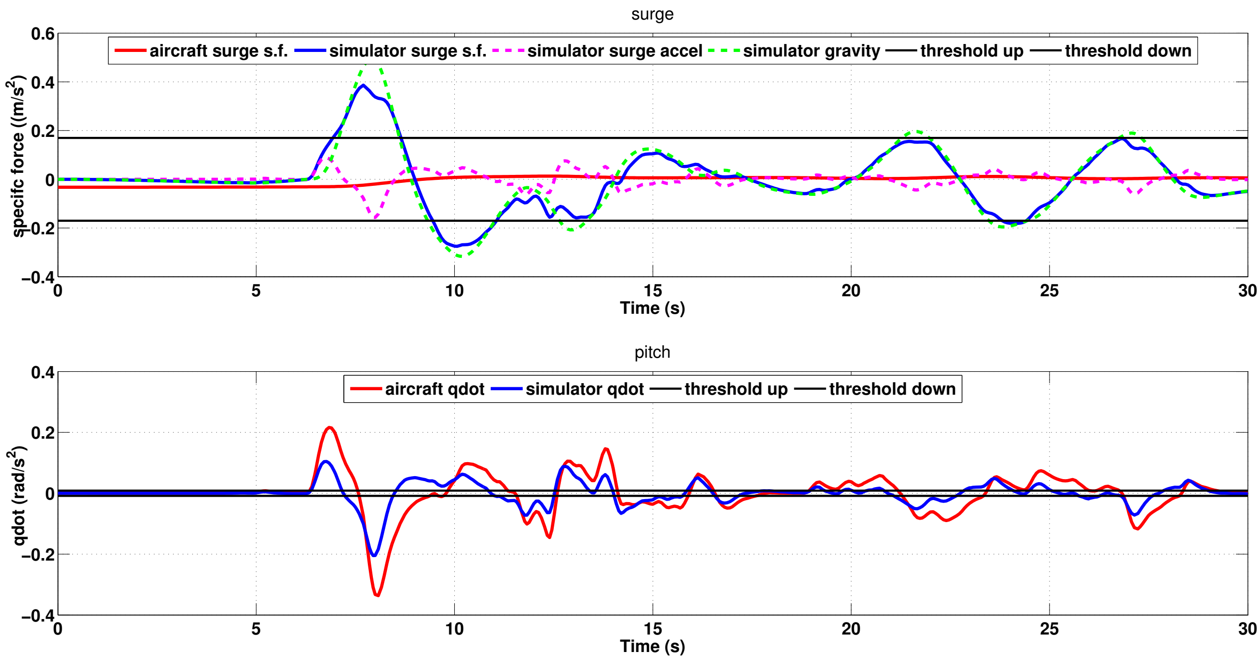

Figure C-5: Pitch and Surge for case 0

C-2-2 Case 0.5 Intermediate step

The surge and sway is improved by decrease the 2nd order break frequency while the pitch and roll are degraded by increase the break frequency from 1 to 1.5.

Table C-2: Case 0.5 : Mofdified Baseline

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	1.5	1.5	2.5	1.5	1.5	1	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	0	0	0.1	0	0	0	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

The result is shown in Figure C-6, this step is to verify the method to reduce false cues.

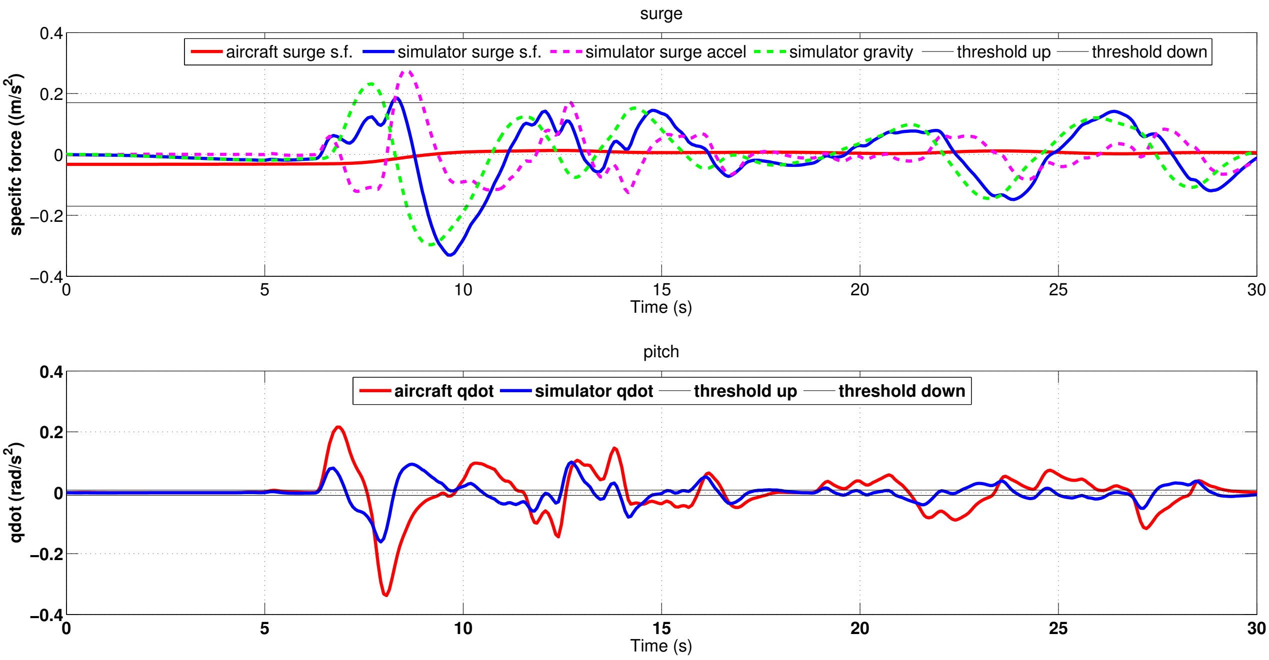

Figure C-6: Pitch and surge for case 0.5

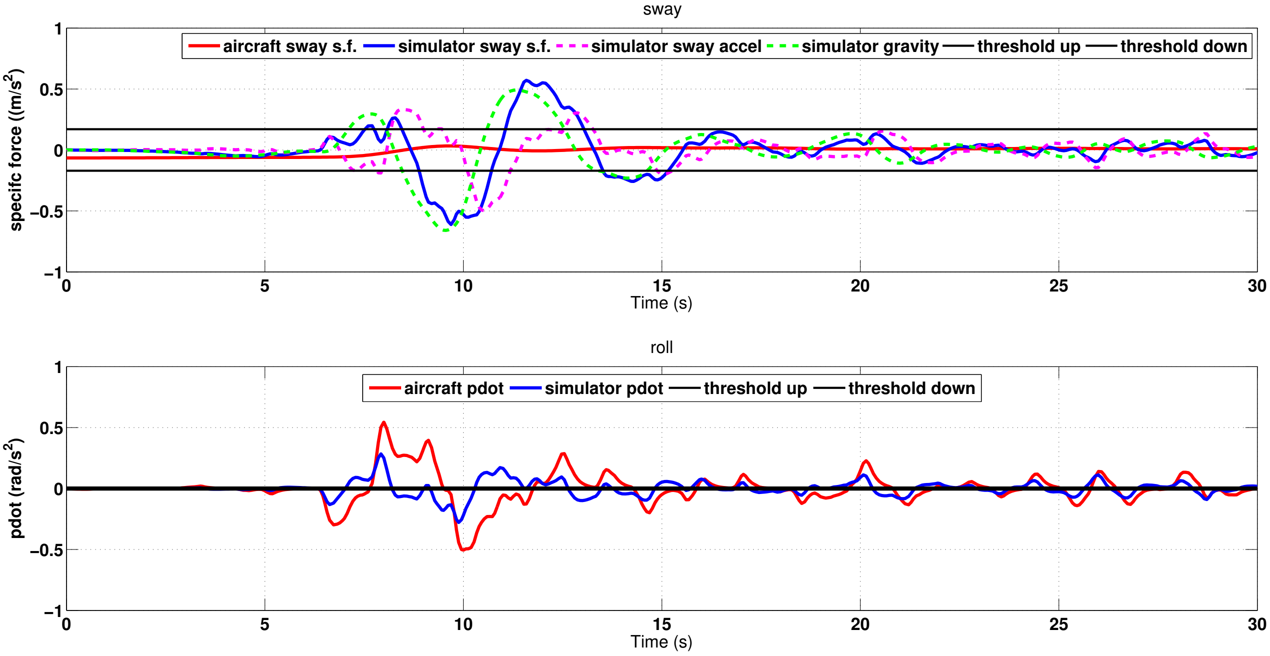

Figure C-7: Roll and Sway for case 0.5

C-2-3 Case1: Focus on pitch

Table C-3: Case 1 : Pure Pitch

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	1.5	1.5	2.5	1.5	1.5	1	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	0	0	0.1	0	0	0	-
ω_{n_lp}	4	4	0	0	0	0	-
switch	0	1	1	1	1	1	0

The motion filter is in favor of pitch due to the added dynamics. the surge cues are ignored in this case, so surge channel is off. Since we assume the specific force on surge is not noticed, the tilt coordination on surge is also off.

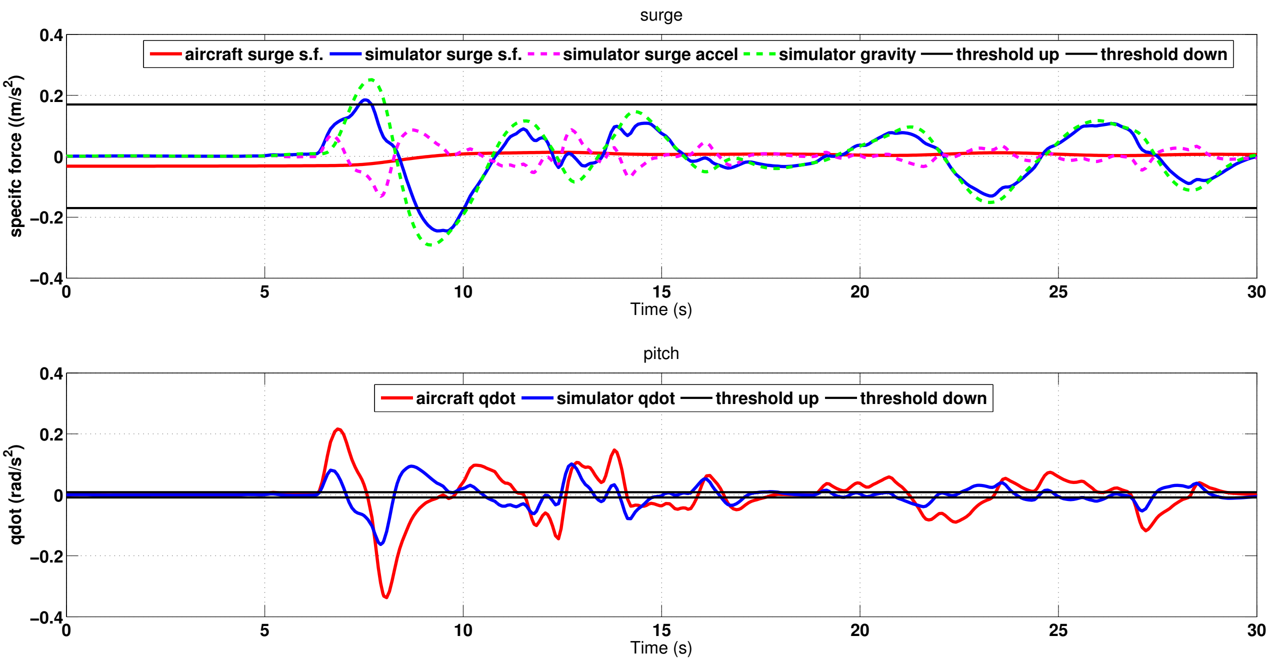

Figure C-8: Pitch and Surge for case 1

When turn off the surge, out of expectation, the false cues are actually reduced. The body acceleration based on the pitch actually works better than adding surge. In an ideal case, the body acceleration should be just opposite to gravity so that pilot feel nothing.

C-2-4 Case 1.2: 1st order filter on pitch

This can be improved further by using 1st order on pitch.

Table C-4: Case 1.2 : Pure Pitch

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	1.5	1.5	2.5	1.5	0	1	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	0	0	0.1	0	1.5	0	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	0	1	1	1	1	1	0

With 1st order pitch, the false cues are larger. In the extreme case for perfect pitch, the surge is off, if the surge can help the false cues, within the limit of simulator, it is possible to increase the surge to see if the false cues are reduced by keeping a very good pitch.

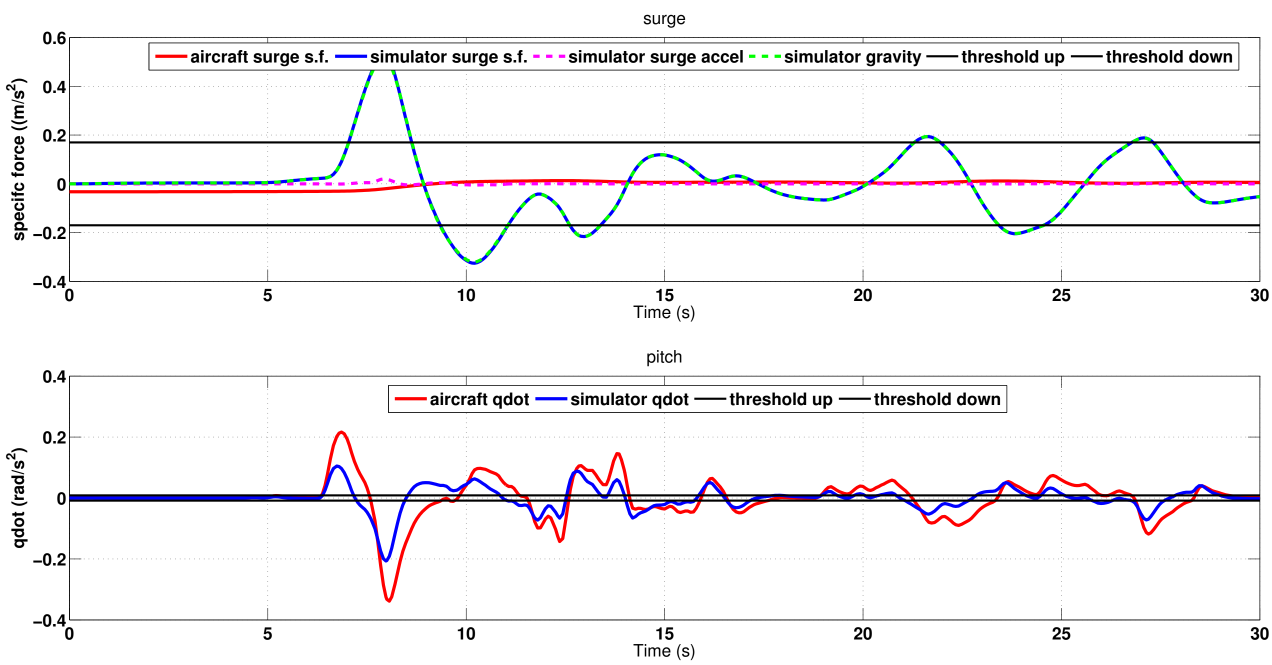

Figure C-9: Pitch and Surge for case 1.2

C-2-5 Case 1.3: Purely scaling: perfect pitch

By using 0 order (directly scaling) on pitch, the perfect pitch can be achieved by:

Table C-5: Case 1.3 : Pure Pitch

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	1.5	1.5	2.5	1.5	0	1	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	0	0	0.1	0	0	0	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	0	1	1	1	1	1	0

In this case, the pitch is almost perfect with a 0.7 scaling down. The workspace is within the limited. However, if in the surge is added, the limitation is violated badly due to the length of actuators.

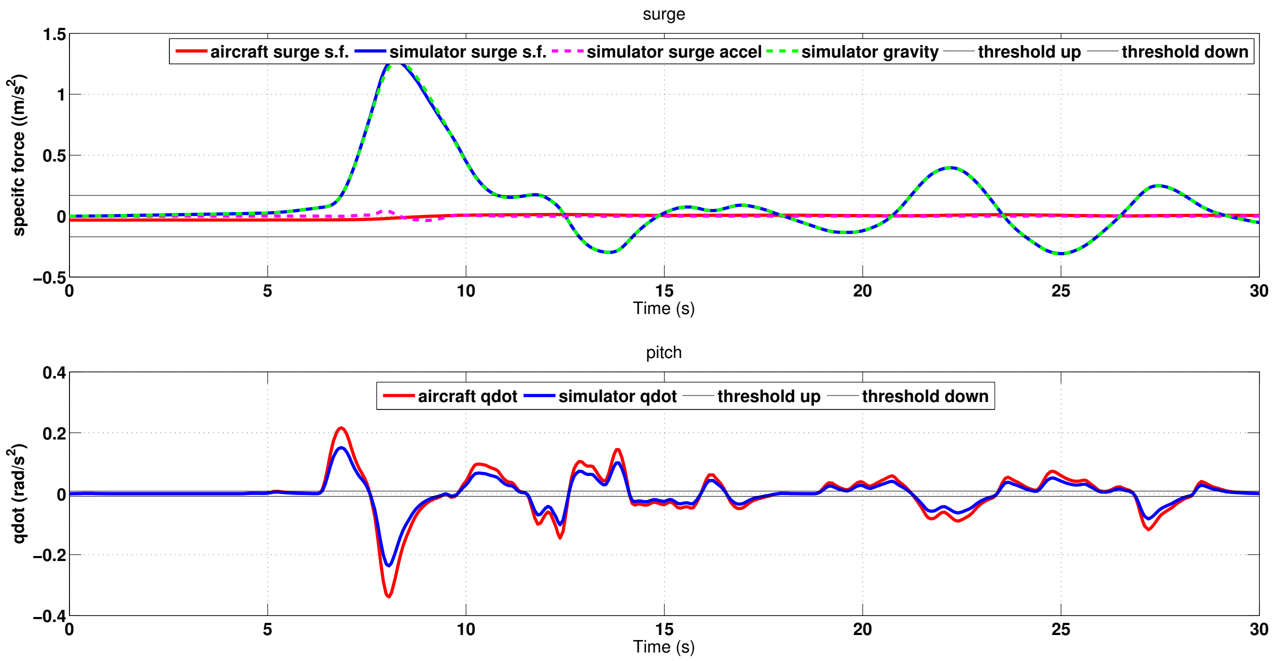

Figure C-10: Pitch and Surge for case 1.3

C-2-6 Case 1.4: Harmonized for pitch and roll

A tryout for same first order filter for both pitch and surge is used. In this case, the actuator length are all within the limits.

Table C-6: Case 1.4 : Pure Pitch

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	0	1.5	2.5	1.5	0	1	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	1.5	0	0.1	0	1.5	0	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	0

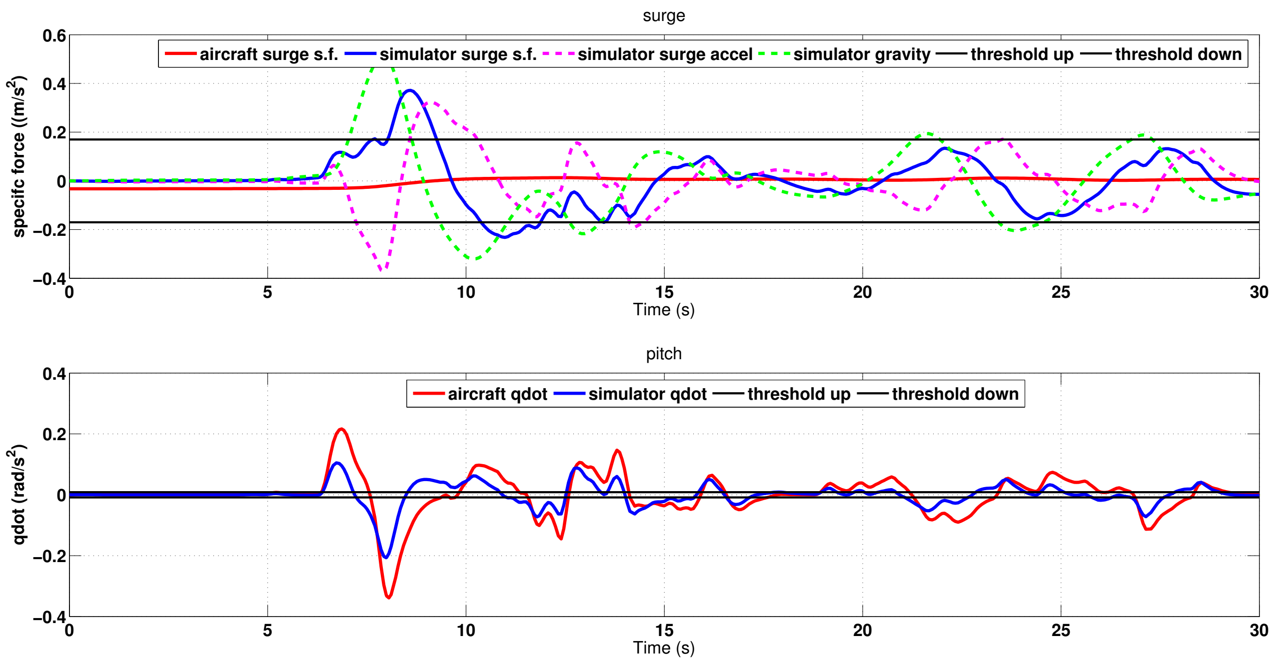

Figure C-11: Pitch and Surge for case 1.4

This is a harmonic case that same filter are used for surge and pitch, while the false cues are improved a lot, it is better than the case with 1st order pitch without surge. This filter can be used as a very good baseline, by adjust pitch and surge, the false cues can be tuned. The problem to this tuning is the break frequency for pitch should not be higher than 2 otherwise the added dynamics are passed out. The tuning of this setting is based:

- degrade pitch, can be done by decrease gain, increase washout

- the pitch is still the first priority, and the break frequency of pitch should ne lower than 2 rad/s
- Increase surge is limited by the work space of simulator

C-2-7 Case 2: Focus on surge

The purpose of this filter is to reduce the false cues on surge as much as possible, the first tryout is to use a 1st order filter on surge.

Table C-7: Case 2 : focus on surge

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	0	2	2.5	1.5	1.5	1.5	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	1.5	0	0.1	0	0	0	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	0

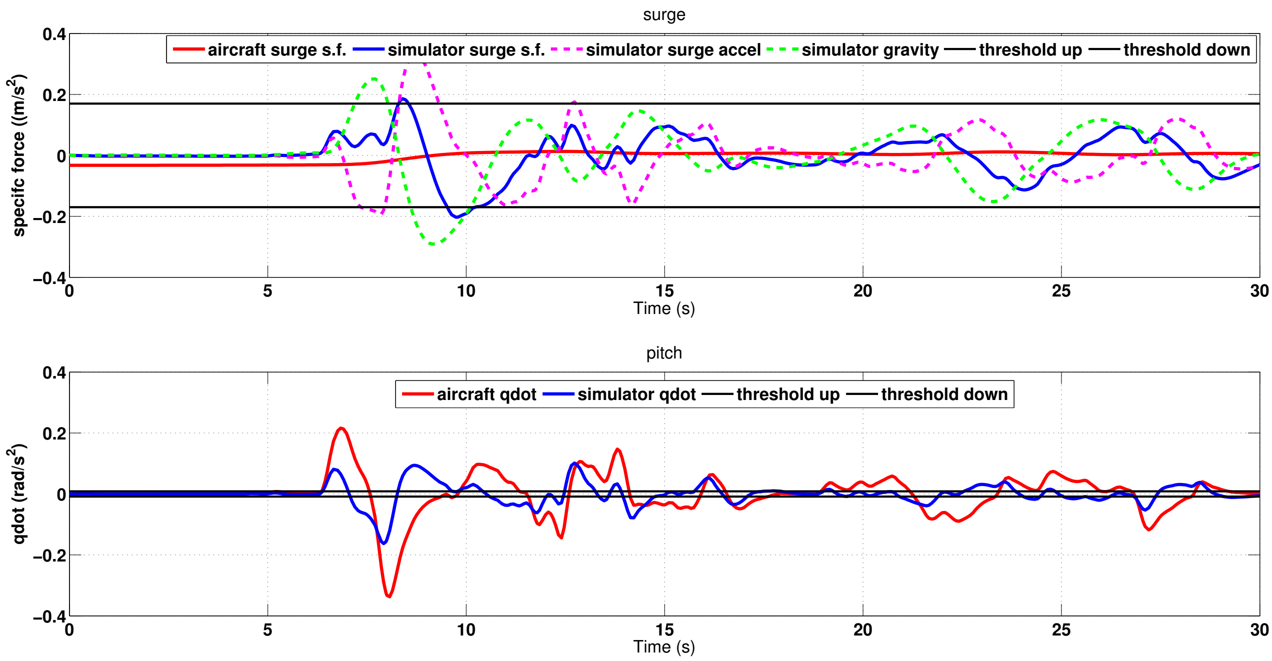

Figure C-12: Pitch and Surge for case 2

The false cues on surge are almost under threshold, but the problem is the pitch is degrading too much and make the whole setting in favor of surge.

C-2-8 Case 2.2: Minimum false cues

Table C-8: Case 2.2 : extreme surge

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	0	2	2.5	1.5	1.5	1.5	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	1	0	0.1	0	0	0	-
$\omega_{n_lp}p$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	0

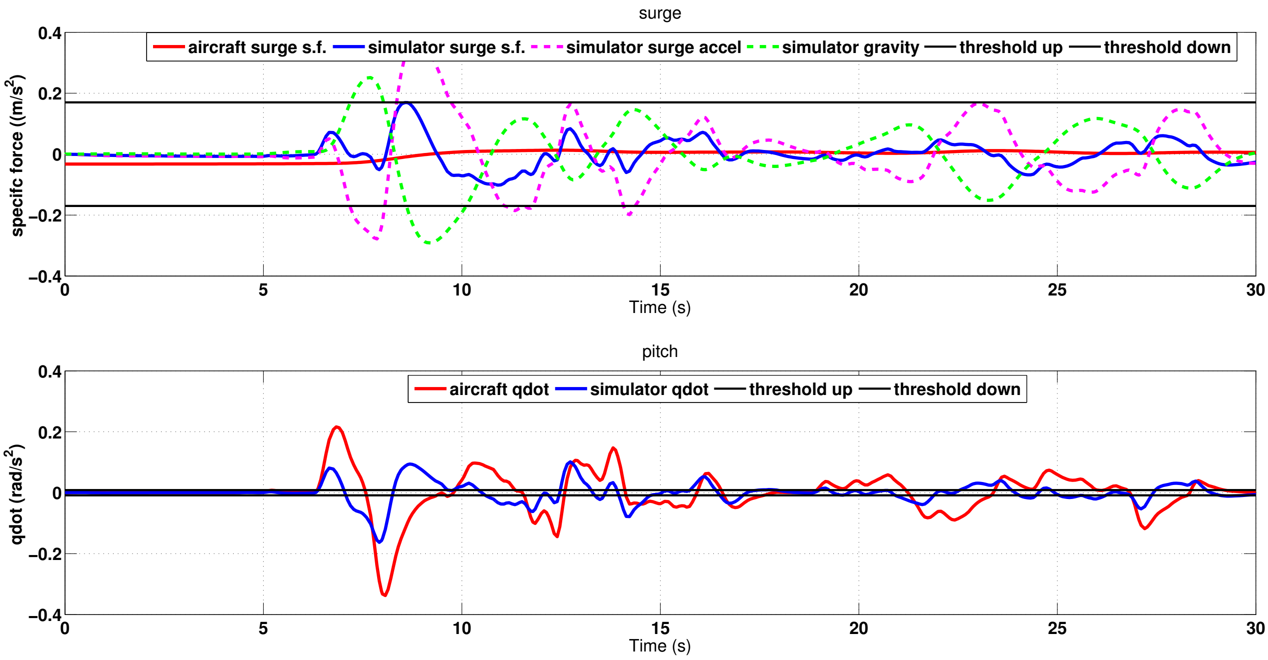

Figure C-13: Pitch and Surge for case 2.2

In this case, the false cues on surge are below the threshold. This is one of the extreme cases that the false cues are reduced to minimum. However, in this case, the tilt coordination is off. The effect of tilt coordination can be further investigated.

C-2-9 Case 2.3: Effect of low pass filter and tilt coordination

The pitch affect the surge during the transformation to body frame and effect of gravity, while the surge can only affect the pitch through the tilt coordination. In the previous case, the tilt is off. With the tilt coordination both on surge and sway. (LP with 4 rad/s break frequency), the filter is designed as shown in TableC-9

Table C-9: Case 2.3 : With Tilt Coordination

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	0	2	2.5	1.5	1.5	1.5	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	1.5	0	0.1	0	0	0	-
ω_{n_lp}	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

The surge and pitch are almost identical to the case without tilt. The rotational rate from tilt and from HP channel is hence plotted, note that those signal represent Euler angler rate, thetadot or phidot.

In this case, the rate from HP channel dominating the final output, it means the tilt does not contribute a lot. This can be adjust by tuning the LP break frequency or the tilt rate limit.

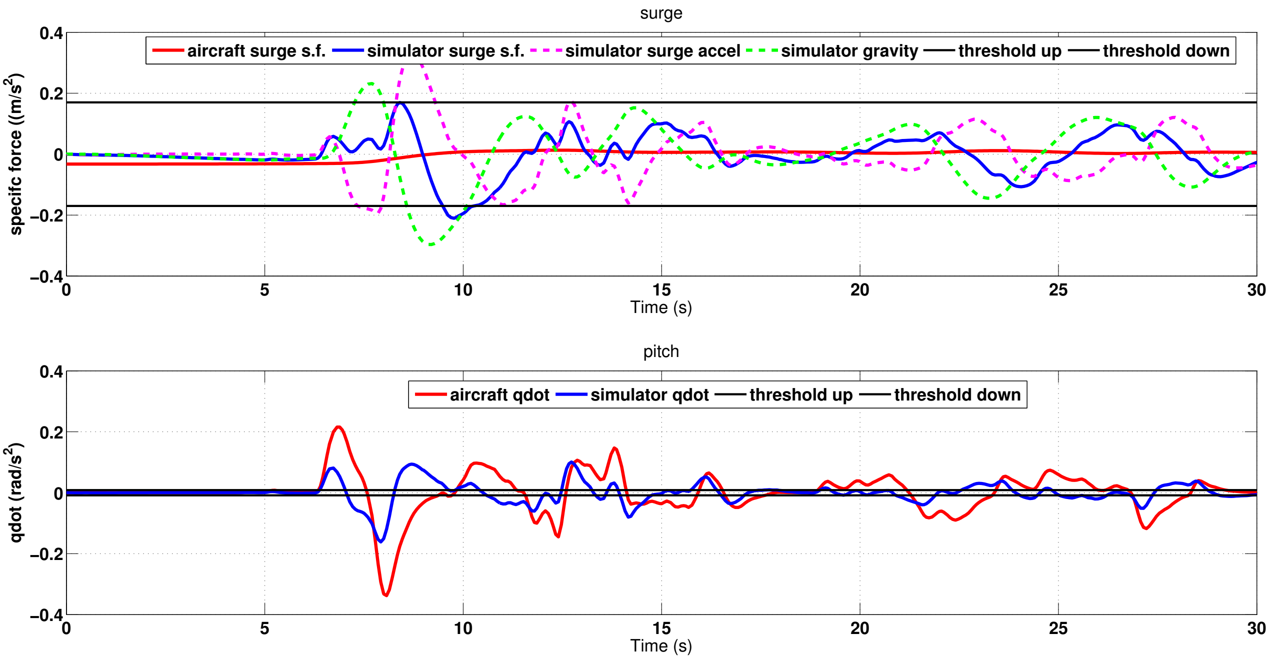

Figure C-14: Pitch and Surge for case 2.3

It is almost interstitial to Case 2. To investigate the effect of tilt coordination, figure C-15 is plotted.

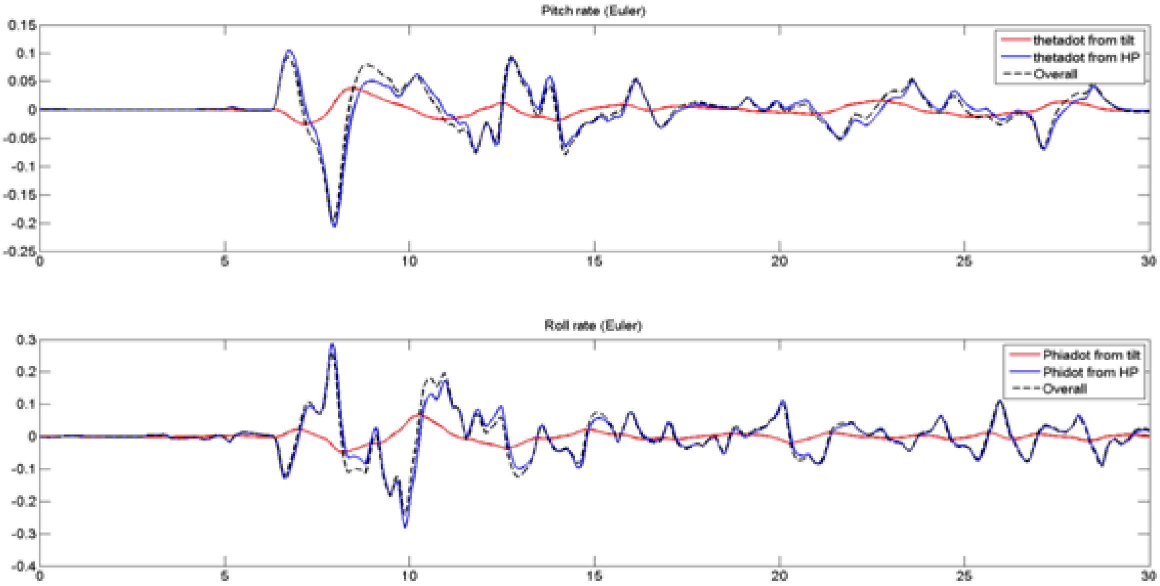

Figure C-15: Pitch and Roll rate for Case 2.3

It shows the contribute of high pass channel and low pass channel to the pitch and roll rate. It is clear that the high pass channel is dominating.

C-2-10 Case 3: Balanced case

Based on the previous test, the suitable baseline is 1st order on both translational and rotational. To make a balanced setting for both pitch and roll, besides heave, almost all other axis has same filter:

Table C-10: Case 3 : Balanced case

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Pitch	Yaw	tilt
K	0.7	0.7	0.5	0.7	0.7	0.3	-
ω_n	0	0	2.5	0	0	0	-
ζ	0.9	0.9	0.9	0.9	0.9	0.9	-
ω_b	1.5	1.5	0.1	1.5	1.5	1.5	-
$\omega_{n_l p}$	4	4	0	0	0	0	-
switch	1	1	1	1	1	1	1

The false cues on sway are more significant than surge. It is reasonable to degrading roll attitude. Note the increase of body acceleration is not recommended in this case, since first order filter for translational is already very extreme due to the limitation of simulator.

The question is, degrading pitch and roll can fix the false cues, but the false cues on this case, may be also acceptable. So this case can be tested by a pilot as the first baseline case.

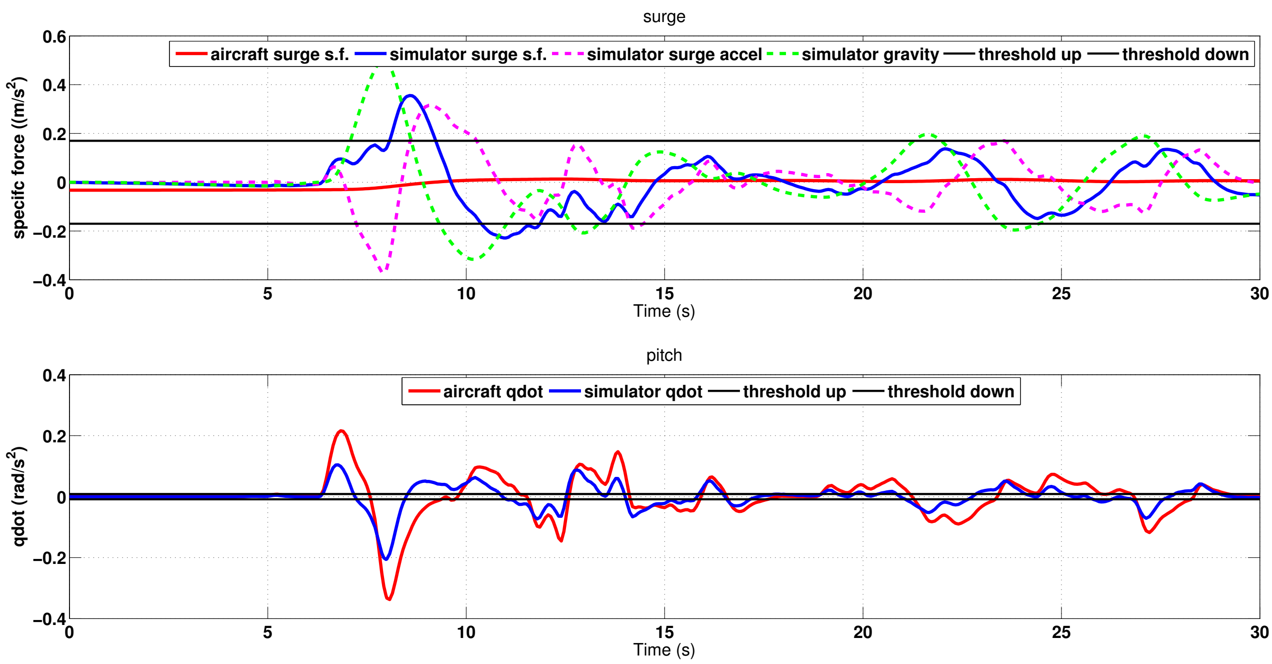

Figure C-16: Pitch and Surge for Case 3

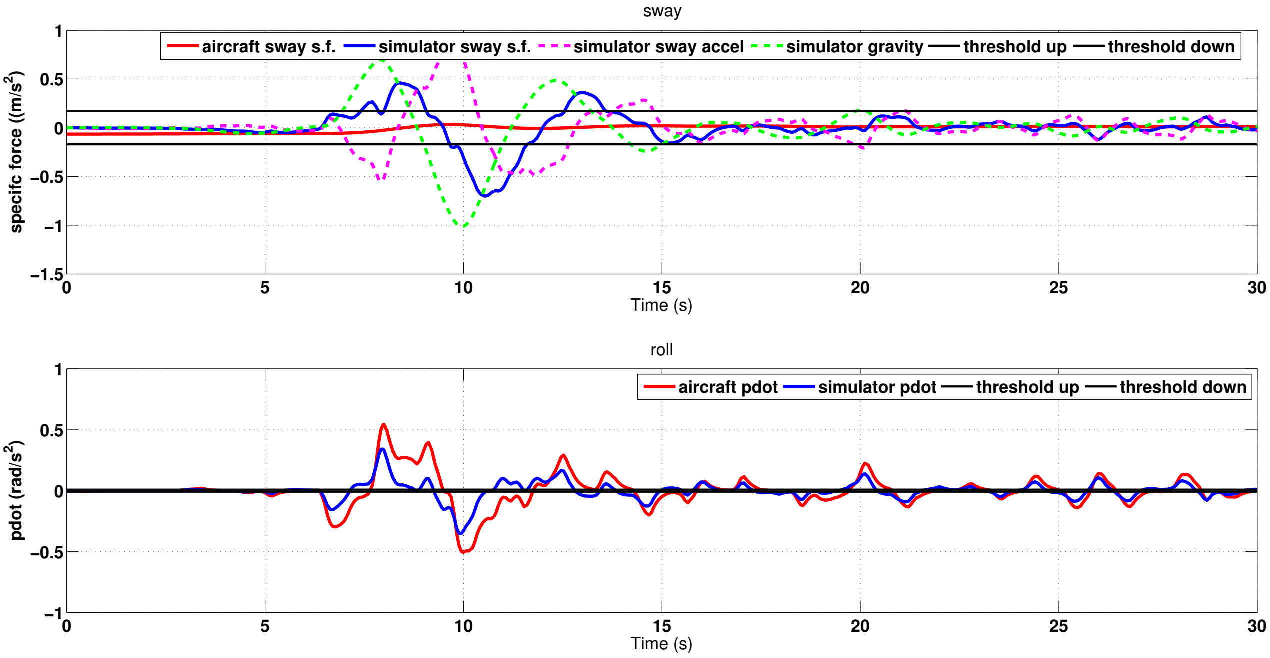

Figure C-17: Roll and Sway for Case 3

The main objective of tuning the motion filter is to find out a suitable filter for the task. Added dynamics is applied on pitch, so pitch is the most important axis. There are false cueing on translational axis due to the pitch and roll, while the cueing on body acceleration work against the false cues. So to fix it, either increase the cueing on body acceleration (HP channel for specific force) or decrease the rotational cueing (pitch and roll).

The body acceleration is also dependent on rotational cueing, it consist of the input from specific force in aircraft, and the effect of Euler angle. When the fx channel is off, the output of body acceleration due to the feedback simulator state is still work against the false cues, which has slightly better performance than a second order filter on translational axis, but not good as first order.

The tilt coordination does not help the false cues, in the method of directly derivation, the effect of tilt is almost neglected. A baseline motion filter setting is generalized: first order filter for all axis expect heave (case 3). This setting is harmonic, and already take balance between false cues on translational axis and the quality of rotational axis.

Further degrading of pitch and roll is possible to get less false cues (under threshold completely), while the difference on roll and pitch is still questionable, to be validated by a pilot. Testing on the noticeability of false cues are also the main task for a preliminary motion filter tuning. As in baseline case, the false cues are already quite small. In the end, three filters are chosen in the preliminary experiment: A good pitch (Case 1.2), A minimum false cues (Case 2.2) and a balanced case (Case 3).

Appendix D

Preliminary Experiment Result

This Appendix gives the result of the preliminary experiment. The objective of this preliminary experiment is to figure out the expected range of damping ratio for each frequency.

The experiment was performed with a randomized damping ratio per each frequency. An example is shown in Figure D-1. As showm in the figure, the blue lines are the unnoticed dynamics while the yellow line represent noticed dynamics. The red line is the critical case.

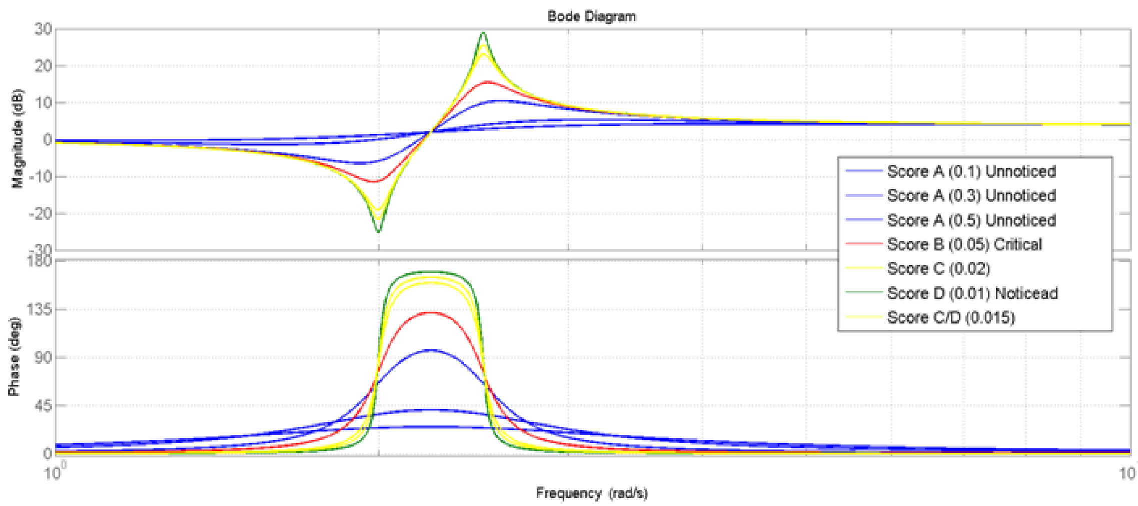

Figure D-1: Added Dynamics For frequency set 2 -2.5

The pilot rating for different damping ratio is shown in the figure. Damping larger than 0.1 will be unnoticed without doubts. While damping lower than 0.01 will be noticed.

Based on the ANR score:

- Score A : Did not feel any change
- Score B : Feel the change of dynamics but not affect the task
- Score C : Minimum adaptation is required
- Score D or above: Strategy changed

The boundary is designed to be the score B. While sometimes pilot are not sure between B and C, so in this case, the region between A and C will be the interesting area for the real experiment. In this frequency, the boundary is expected to be between 0.1 to 0.02.

The strategy to find out the boundary for this frequency set is hence: First try 0.1 to check if it is unnoticed. if so, randomly choose between 0.1 to 0.02 (0.02, 0.05, 0.07). Use 0.3 or 0.01 as a spot check. if 0.1 is noticed with a score D or worse, different strategy will be used. In this case, try randomly from 0.3, 0.5 and 0.9.

Table D-1: Designed Damping Ratioe

ω_z	ω_p	spot check (unnoticed)	Damping	spot check (noticed)
2	2.5	0.3	0.1 - 0.02	0.01
3	3.75	0.1	0.02 - 0.05	0.01
2.5	2	0.3	0.1 - 0.02	0.01
3.75	3	0.1	0.02 - 0.05	0.01
4	4	0.5	0.1 - 0.3	0.05
5	5	0.5	0.1 - 0.3	0.05
5.6	7	0.1	0.05 - 0.01	0.005
7	5.6	0.1	0.05 - 0.01	0.006

With the result from preliminary, the added dynamics as well as damping ratio is designed in Table D-1.

The plot in Figure D-2 shows all the frequency set of added dynamics that is tested during the check-out. For each set of frequency, the red line means the critical added dynamics (with Score B). While the green line and blue line shows the boundary that beyond these two line, the noticeability is quite clear (either noticed or unnoticed). The region in between is the area that pilot are not sure (Score C).

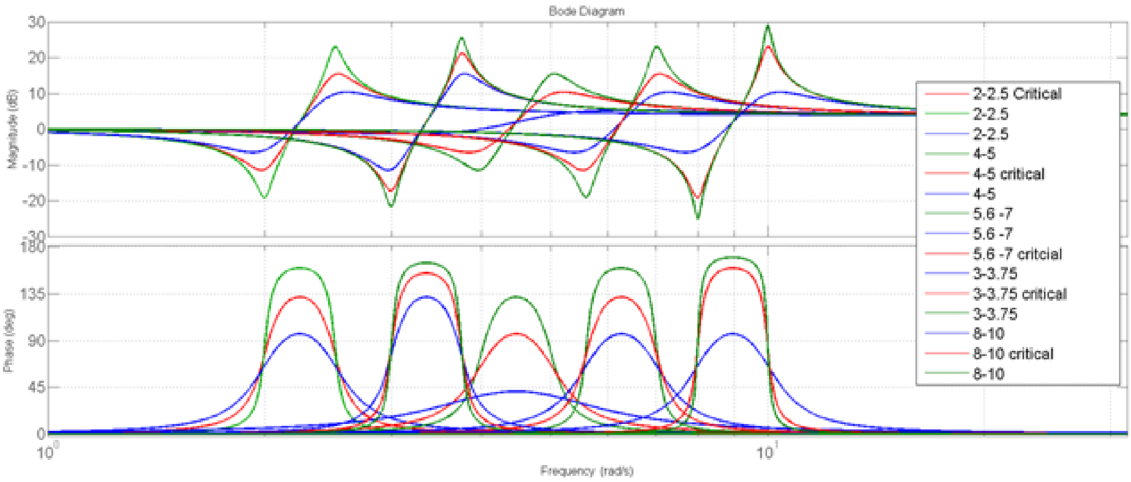

Figure D-2: All Added Dynamics

The other conclusion from preliminary experiment is that, to reduce time consumption, less amount of added dynamics will be used. By remove the high frequency 8-10 rad/s. As shown in D-3, the amount of sets of added dynamics is enough to develop the envelopes.

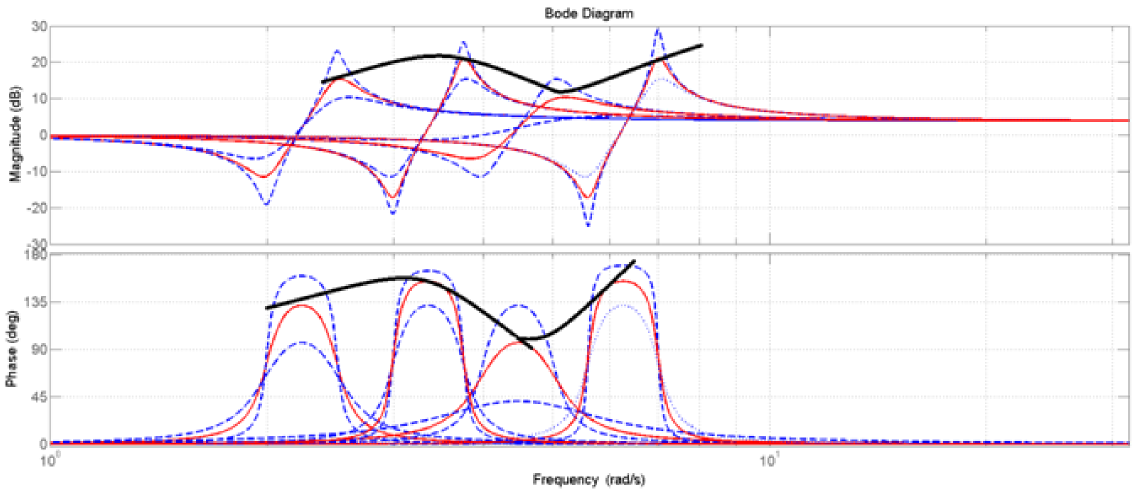

Figure D-3: Reduced Added Dynamics

Appendix E

Experiment Result Subject A

This Appendix lists all the result from the experiment performed by the first subject. Table E-1 to Table E-16 shows the result for 16 conditions. The order of the table is same as the order of experiment. The motion condition as well as frequency are randomized. For each table, there are five or six damping ratio, the subject flew each one two or three times, and a score was given for each damping ratio.

Table E-1: Experiment Result 3-3.75 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
3	3.75	on	0.025	C
3	3.75	on	0.1	B
3	3.75	on	0.05	B
3	3.75	on	0.01	D
3	3.75	on	0.015	C

Table E-2: Experiment Result 2.5-2 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
2.5	2	on	0.1	D-E
2.5	2	on	0.3	A
2.5	2	on	0.2	B
2.5	2	on	0.05	E
2.5	2	on	0.15	C

Table E-3: Experiment Result 5.6-7 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
5.6	7	off	0.1	A
5.6	7	off	0.05	A
5.6	7	off	0.02	A
5.6	7	off	0.01	B
5.6	7	off	0.005	D

Table E-4: Experiment Result 4-5 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
4	5	on	0.1	A
4	5	on	0.015	B
4	5	on	0.05	A
4	5	on	0.01	B-C
4	5	on	0.005	D

Table E-5: Experiment Result 3-3.75 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
3	3.75	off	0.025	B
3	3.75	off	0.1	A
3	3.75	off	0.05	B
3	3.75	off	0.01	D
3	3.75	off	0.015	C

Table E-6: Experiment Result 2-2.5 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
2	2.5	off	0.1	A
2	2.5	off	0.01	B
2	2.5	off	0.005	C
2	2.5	off	0.05	A
2	2.5	off	0.025	B

Table E-7: Experiment Result 4-5 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
4	5	off	0.1	A
4	5	off	0.3	A
4	5	off	0.05	B
4	5	off	0.01	C
4	5	off	0.005	D

Table E-8: Experiment Result 3.75-3 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
3.75	3	on	0.025	B
3.75	3	on	0.1	A
3.75	3	on	0.01	I
3.75	3	on	0.05	B
3.75	3	on	0.15	D

Table E-9: Experiment Result 7 -5.6 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
7	5.6	off	0.05	A
7	5.6	off	0.1	A
7	5.6	off	0.01	A
7	5.6	off	0.005	A
7	5.6	off	0.001	A-B

Table E-10: Experiment Result 2.5-2 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
2.5	2	off	0.1	E
2.5	2	off	0.3	A
2.5	2	off	0.2	B
2.5	2	off	0.05	F
2.5	2	off	0.15	D

Table E-11: Experiment Result 7 -5.6 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
7	5.6	on	0.05	B
7	5.6	on	0.1	A
7	5.6	on	0.01	B
7	5.6	on	0.005	B
7	5.6	on	0.001	C

Table E-12: Experiment Result 3.75-3 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
3.75	3	off	0.025	D
3.75	3	off	0.1	A
3.75	3	off	0.01	E
3.75	3	off	0.05	D
3.75	3	off	0.15	D-E

Table E-13: Experiment Result 5-4 without motion

ω_z	ω_p	Motion Condition	Damping	Rating
5	4	off	0.3	A
5	4	off	0.1	A
5	4	off	0.01	B
5	4	off	0.05	A
5	4	off	0.005	C

Table E-14: Experiment Result 5.6-7 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
5.6	7	on	0.1	A-B
5.6	7	on	0.05	B
5.6	7	on	0.02	B-C
5.6	7	on	0.01	C
5.6	7	on	0.005	D

Table E-15: Experiment Result 2-2.5 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
2	2.5	on	0.1	A
2	2.5	on	0.01	A
2	2.5	on	0.05	A
2	2.5	on	0.005	B
2	2.5	on	0.001	C

Table E-16: Experiment Result 5-4 with motion

ω_z	ω_p	Motion Condition	Damping	Rating
5	4	on	0.3	A
5	4	on	0.1	A
5	4	on	0.01	B
5	4	on	0.05	A
5	4	on	0.005	B

The ω_z and ω_p are the natural frequency for zeros and poles. The rating are the ANR score given by pilot. A score A means the dynamics was not noticed for sure. With a score C and above, pilot definitely felt the change of dynamics. The boundaries hence defined by the critical case B.

Appendix F

Data Analysis Subject A

F-1 Effect of Motion

The result of experiment is plotted in bode plot. As shown in Figure F-1. The green line is the dynamics not noticed, with score A, the blue line is the critical cases which has score B, the red line is the dynamics surely noticed by pilot, with score C and above.

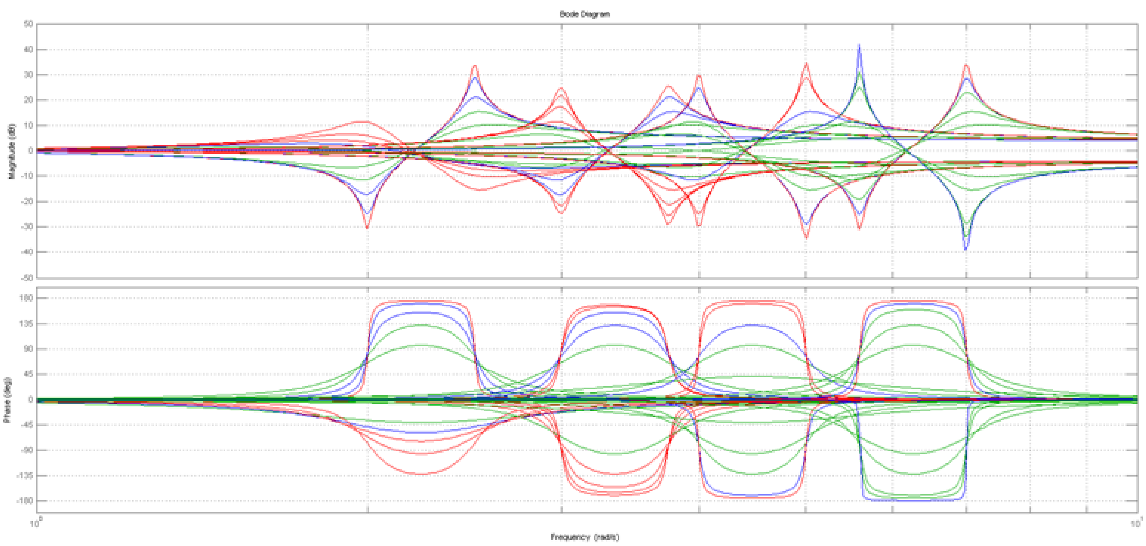

Figure F-1: All the added dynamics without motion

To clearly define the envelope, the critical cases are focused. Figure F-3 and F-4 shows the critical added dynamics without and with motion. The blue line is the critical cases for added dynamics with ω_p larger than ω_z, while the red line is opposite

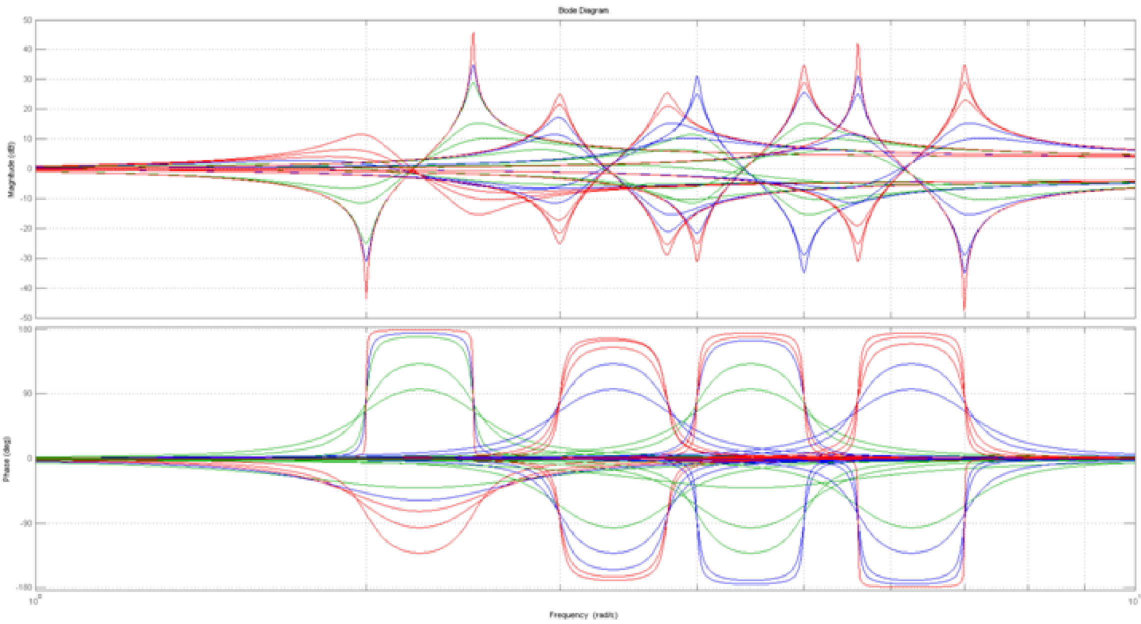

Figure F-2: All the added dynamics with motion

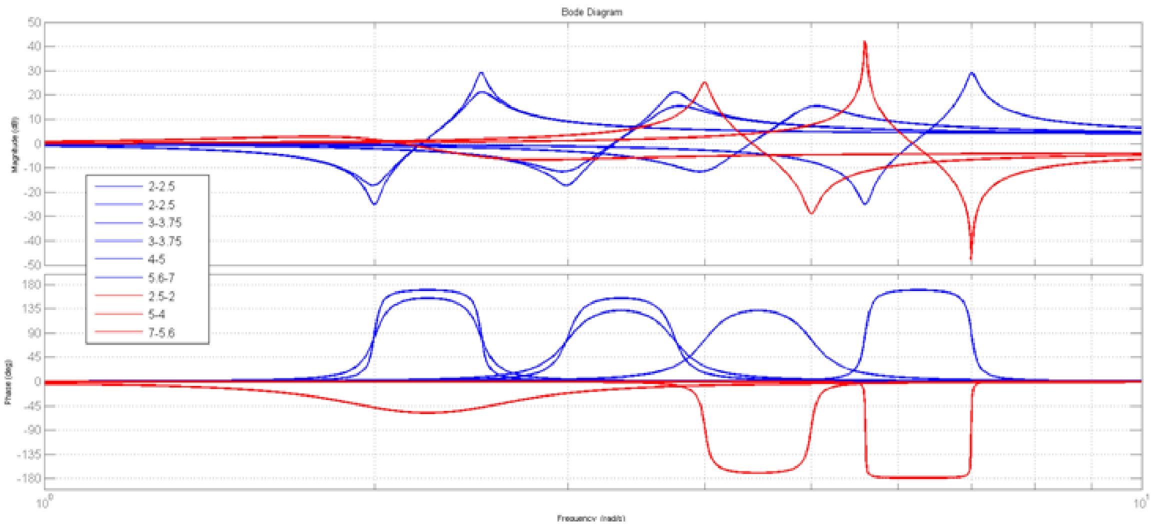

Figure F-3: Critical cases without motion

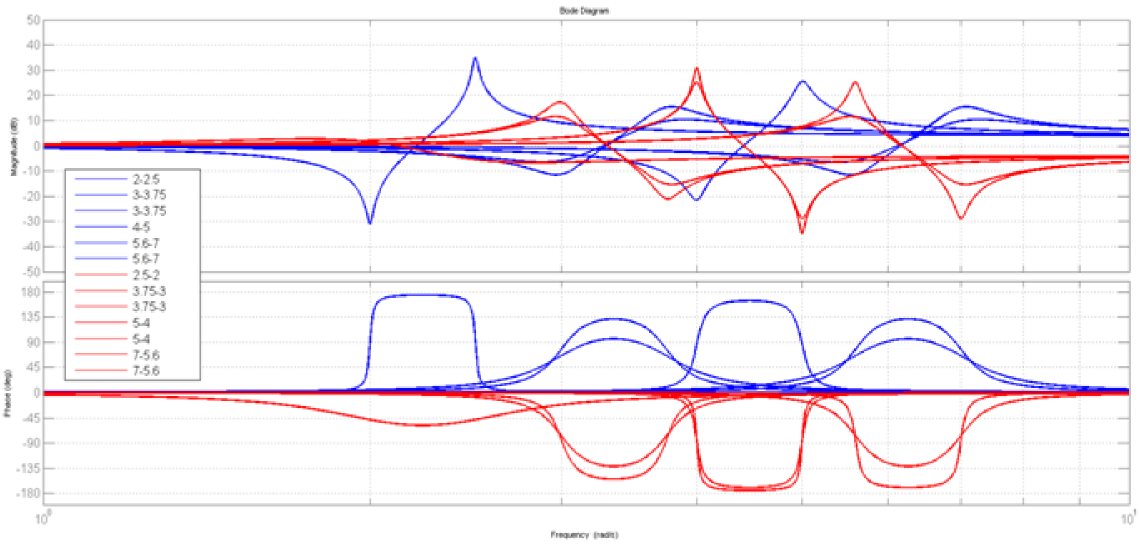

Figure F-4: Critical cases with motion

Based on the graph, it looks like motion has a effect on higher frequency part, which make pilot more sensitive to high frequency dynamics, the shape will be narrower in high frequency part. As mentioned, the effect of motion is significant for frequency from 4-5 and 5.6 -7, sometimes, inverse effect happened in lower frequency.

F-2 Effect of pole and zero

Before experiment, it assume that switch the pole and zero will not change the result a lot, hence the damping ratio used during the experiment is exactly same. (2-2.5 use same damping ratio as 2.5-2) however, during the experiment, big difference found.

In general, pilot is less sensitive to an added dynamics with higher ω_z (2.5 -2, 5-4..) for higher frequency, in case 7 - 5.6($\omega_z = 7$, ω_p=5,6), pilot almost feel nothing even the damping is almost zero. However, for lower frequency, pilot is more sensitive to added dynamics with higher ω_z,.

The difference can be due to the Gain used. The gain is used ω_p^2/ω_z^2, which means when the ω_z is higher, the gain is also smaller than 1. This can be explained why the difference in higher frequency is more obvious. since the Gain is chosen to be consistent with lower frequency.

At lower frequency, the difference between a lead/lag and lag/lead added dynamics is lager. This can also explained the asymmetric phase at low frequency.

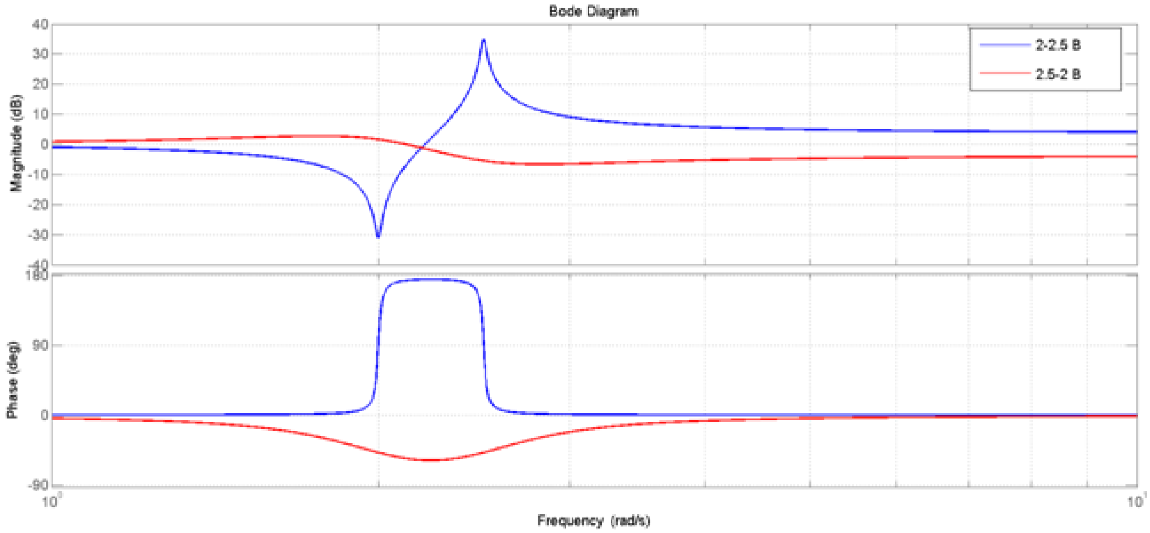

Figure F-5: pole and zero at lower frequency

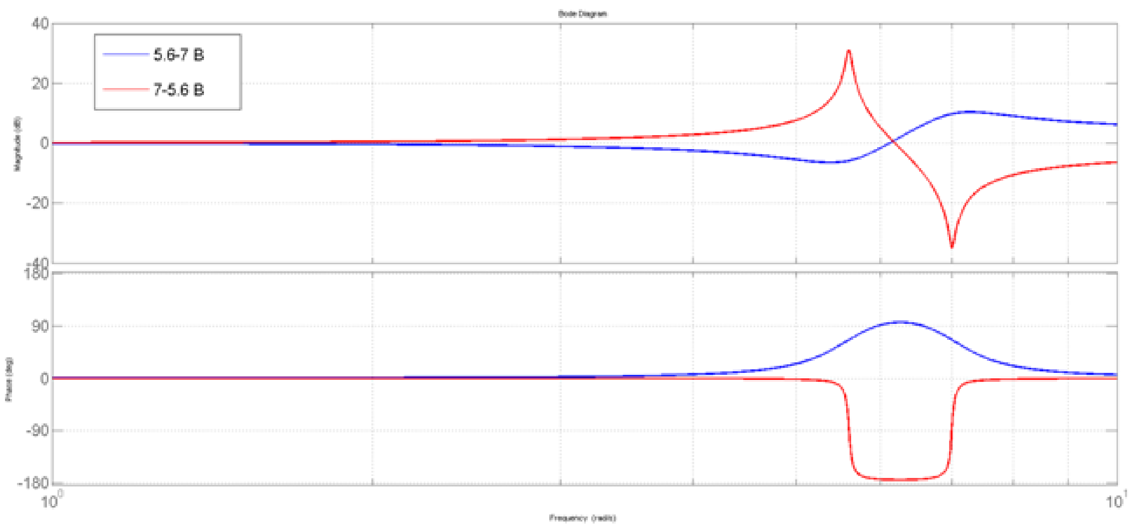

Figure F-6: pole and zero at lower frequency at higher frequency

Appendix G

Experiment Result Subject B

This Appendix lists all the result from the experiment performed by the second subject. Table G-1 to Table G-6 shows the result for 6 conditions. The order of the table is same as the order of experiment. The motion condition as well as frequency are randomized. For each table, there are five or six damping ratio, the subject flew each one two or three times, and a score was given for each damping ratio.

Table G-1: Experiment Result 2-2.5 with motion, subject B

ω_z	ω_p	Motion Condition	Damping	Rating
2	2.5	on	0.1	B
2	2.5	on	0.01	D
2	2.5	on	0.05	C
2	2.5	on	0.3	D
2	2.5	on	0.02	A

Table G-2: Experiment Result 3.75-3 without motion, subject B

ω_z	ω_p	Motion Condition	Damping	Rating
3.75	3	off	0.025	A-B
3.75	3	off	0.1	C
3.75	3	off	0.05	C
3.75	3	off	0.01	G
3.75	3	off	0.3	A
3.75	3	off	0.025	D

Table G-3: Experiment Result 5.6-7 with motion, subject B

ω_z	ω_p	Motion Condition	Damping	Rating
5.6	7	on	0.1	A
5.6	7	on	0.05	C
5.6	7	on	0.02	A
5.6	7	on	0.01	C-D
5.6	7	on	0.005	C

Table G-4: Experiment Result 3-3.75 without motion, subject B

ω_z	ω_p	Motion Condition	Damping	Rating
3	3.75	off	0.025	C
3	3.75	off	0.1	C
3	3.75	off	0.05	A
3	3.75	off	0.01	A
3	3.75	off	0.0025	A
3	3.75	off	0.005	B

Table G-5: Experiment Result 3.75-3 with motion,subject B

ω_z	ω_p	Motion Condition	Damping	Rating
3.75	3	on	0.025	I
3.75	3	on	0.1	A
3.75	3	on	0.01	H-I
3.75	3	on	0.05	A
3.75	3	on	0.025	A

Table G-6: Experiment Result 5.6-7 without motion, subject B

ω_z	ω_p	Motion Condition	Damping	Rating
5.6	7	off	0.1	A
5.6	7	off	0.05	A
5.6	7	off	0.01	A
5.6	7	off	0.001	G
5.6	7	off	0.002	A
5.6	7	off	0.005	A

Table G-7: Experiment Result 3-3.75 with motion, subject B

ω_z	ω_p	Motion Condition	Damping	Rating
3	3.75	on	0.025	A
3	3.75	on	0.1	A
3	3.75	on	0.05	A
3	3.75	on	0.01	B
3	3.75	on	0.005	H
3	3.75	on	0.0025	A

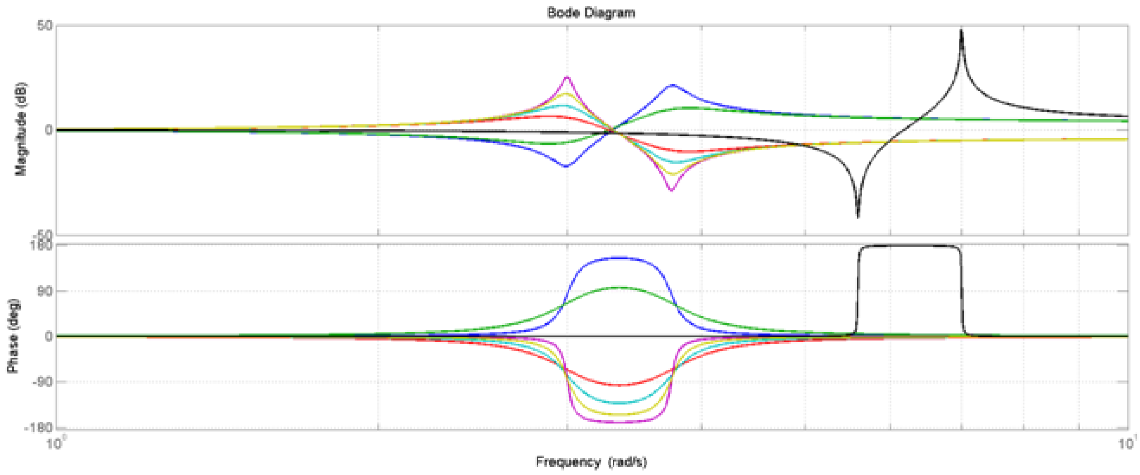

Figure G-1: Noticed dynamics: without motion

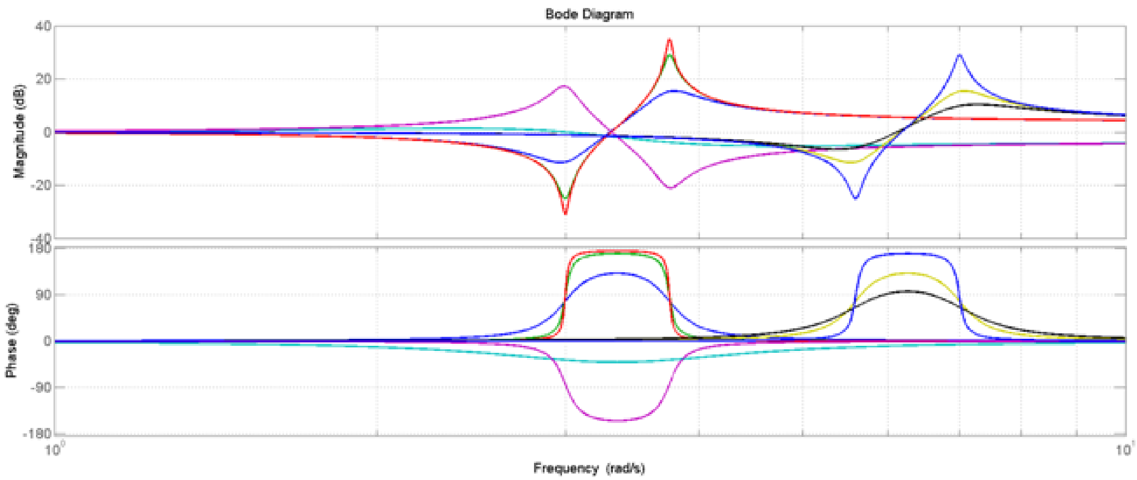

Figure G-2: Unnoticed dynamics: without motion

This data is not used in this study. The performance during the experiment is not consistent. Lots of inconsistency is found in the data. For example subject noticed a very well damped dynamics but did not notice a less damped added dynamics within the same frequency. The rating of Subject B had a much larger range compare to other subject. This is because of the inconsistency of performance. While the subject was in PIO or large drift, it was assumed that the equal performance is not attained. It results in the skipping of first few question and directly lead to a bad rating.

With all these data, it is impossible to find out a boundary between noticed and unnoticed added dynamics, the only way is to reject the inconsistent data. The rejected data are highlighted in the table. The reason to reject these data is that these ratings are out of expectation.The red lines are the noticed dynamics terms with highest damping, while the blue shows the unnoticed dynamics with lowest damping.

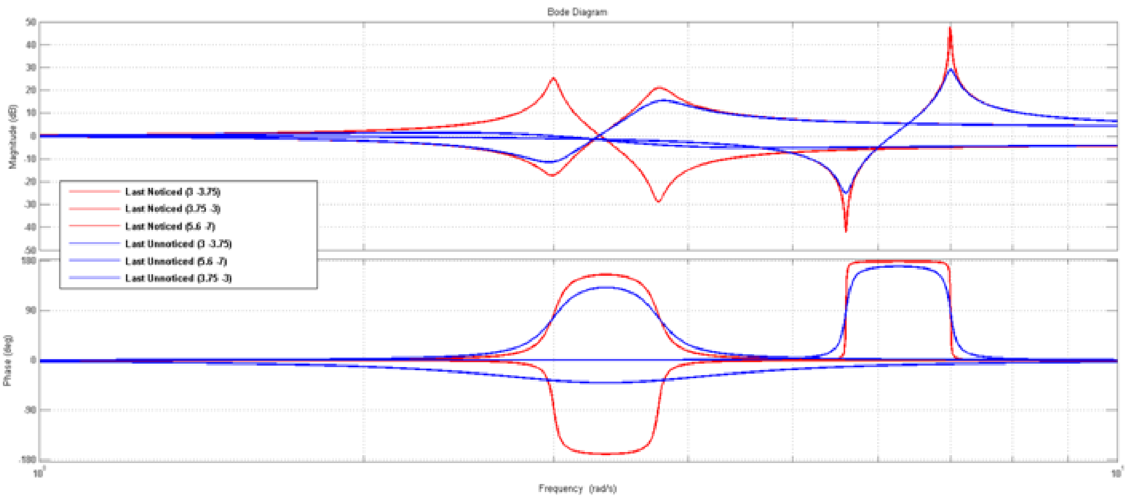

Figure G-3: Critical Added dynamics without motion

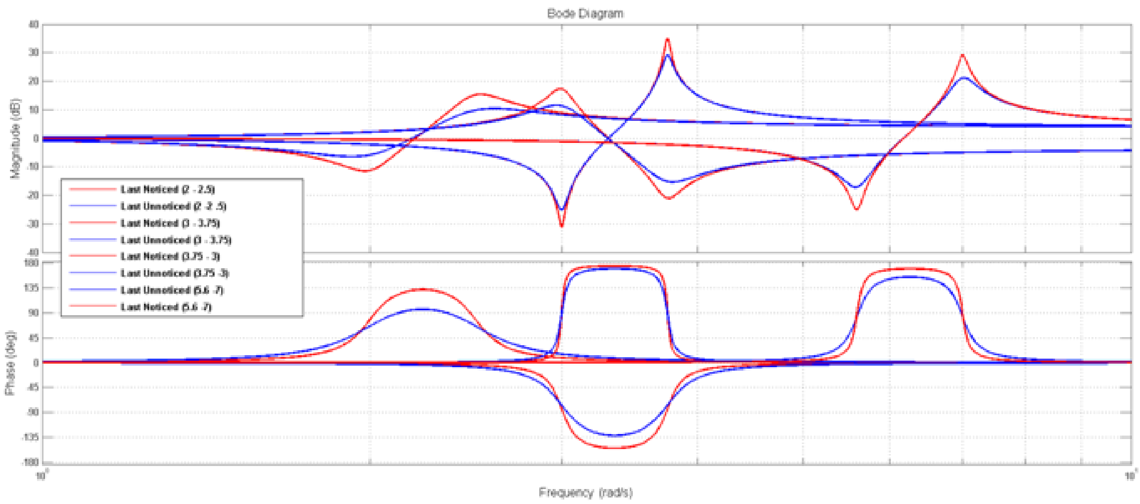

Figure G-4: Critical Added dynamics with motion

After rejecting the data, the effect of motion in higher frequency can be clear. The effect of motion on high frequency was obvious, with motion, the pilot was more sensitive the peak magnitude of critical cases dropped from 50/30dB to around 30/20dB when motion is on. However, the effect of motion on lower frequency (3 -3.75) is different, with motion, pilot is less sensitive. This is same as it was found in the data of the other subject. With these sets of data, there would be more confidence to recommend the further study to focus on the higher frequency range.

By switch the pole and zeros, the difference was not clear by only showing the graph. In this range of frequency (3- 3.75) pilot was a little more sensitive to the dynamics with larger ω_z(3.75 -3). With motion, this difference can be negligible. Comparing to the first subject, there are some similarities. Since in the middle range of frequency, the switch of pole and zeros does not have significant effect. So for the future research, to investigate the effect of poles and zeros of added dynamics, one should focus on either low frequency or high frequency.